Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-04/0-4260-4		

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF ADVANCE WARNING SYSTEMS FOR END-OF-GREEN PHASE AT HIGH SPEED TRAFFIC SIGNALS	September 2003 Resubmitted: January 2004
	6. Performing Organization Code
7. Author(s) Carroll J. Messer, Srinivasa R. Sunkari, Hassan A. Charara, and Ricky T. Parker	8. Performing Organization Report No. Report 0-4260-4
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project No. 0-4260
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Research: September 2001-August 2003 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Advance Warning for End-of-Green Phase at High-Speed Traffic Signals

16. Abstract

This report describes a research study that developed an effective advance warning for end-of-green phase at high-speed (≥45 mph) traffic signals in Texas. This report contains the research conducted, hardware developed, and field testing performed of the Advance Warning for End-of-Green System (AWEGS) designed by the Texas Transportation Institute for the Texas Department of Transportation (TxDOT). Two companion reports present guidance on the design, installation, and operation of AWEGS.

A series of advance warning technologies were tested over the two-year study. A base Level 1 technology was initially proposed using “trailing overlaps” to provide a fixed amount of advance warning of the end-of-green phase, but this method was rejected because it gave up existing dilemma zone protection. A new Level 1 technology, using average speed while still predicting when the traffic-actuated controller would gap-out, was substituted. More advanced AWEGS technologies (Level 2) added vehicle typing (car, truck) and individual speed measurement to better estimate when the signal controller would gap-out. AWEGS was field tested at two sites in Waco and Brenham, Texas. The Waco site was a high-speed, two-lane rural road. The second site was a high-speed four-lane divided highway located on the US 290 bypass of Brenham, Texas. AWEGS reduced red-light-running, during the targeted first 5 seconds of red, by 40 to 45 percent. Level 2 AWEGS is much preferred because it also minimizes negative impact on the existing traffic-actuated controller, and it provides new and effective dilemma zone protection for trucks and very high-speed cars.

17. Key Words	18. Distribution Statement
Advance Warning Flashers, AWEGS, Advance Traffic Control Signs, W3-4 Signs, Advance Traffic Warning Devices, Traffic Actuated Control	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	80	

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

DEVELOPMENT OF ADVANCE WARNING SYSTEMS FOR END-OF-GREEN PHASE AT HIGH SPEED TRAFFIC SIGNALS

by

Carroll J. Messer, P.E.
Research Engineer
Texas Transportation Institute

Srinivasa R. Sunkari, P.E.
Associate Research Engineer
Texas Transportation Institute

Hassan A. Charara
Associate Research Scientist
Texas Transportation Institute

and

Ricky T. Parker
Engineering Research Associate
Texas Transportation Institute

Research Report 0-4260-4

Project Number 0-4260
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at High-Speed Traffic Signals

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

September 2003
Resubmitted: January 2004

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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ACKNOWLEDGMENTS

This research was conducted during a two-year study under a cooperative research program between the Texas Transportation Institute (TTI), TxDOT, and FHWA. Michael Jedlicka of the TxDOT Bryan District was the project director (PD). Other TxDOT members of the project monitoring committee included Don Baker, Dale Barron, Glenn Campbell, Ted Copeland, Carlos Ibarra, Roy Parikh, Ismael Soto, and Doug Vanover. Robert R. Kovar and Tom Beeman of the Design Division were the program coordinators. Grant Schultz, Roelof Engelbrecht, Ricky Parker, and Kwaku Obeng-Boampong of TTI also contributed to the materials used in this report. Grant Schultz prepared an initial draft of the literature review. Ricky Parker made major contributions to the design of the back up flasher system together with field wiring and other related electrician services provided by TTI. Hassan Charara provided the software interface design for laboratory testing and program coding of the AWEGS run on the field computers. Kwaku Obeng-Boampong conducted all of the video data reduction and analysis for red-light-running of the AWEGS operations at the Waco and Brenham field sites.

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CHAPTER 1. INTRODUCTION

PROJECT OVERVIEW

Texas has become the second most populous state in America, and population growth continues at a rapid pace. Consequently, traffic signals are being installed more frequently at high-speed, high-growth rural intersections because of higher traffic volumes due to the resulting urban-to-rural migration. Most of these newly signalized intersections have posted speed limits above 45 mph and, in some instances, 70 mph. One major difficulty with traffic signal operation on high-speed approaches is the dilemma faced by approaching motorists when the downstream signal turns yellow. Should the motorists stop or proceed through the intersection? Crashes that may occur at these intersections result in high property damage and personal injury due to the high-speeds involved.

Research sponsored by the Texas Department of Transportation (TxDOT) has developed a new system named Advance Warning for End-of-Green System (AWEGS) for application to high-speed signalized intersections in isolated (non-coordinated) rural locations. This report contains the work the research team of Texas Transportation Institute (TTI) conducted to design, develop, install, and evaluate the new AWEGS. Companion research reports provide a manual for traffic engineers to use to design and install similar AWEGSs in Texas (*1*). TTI developed a second manual for traffic signal technicians to use as a guide for installation and maintenance of AWEGS (*2*). The remainder of this report contains the research objectives, theory of operations, and study results conducted at two field test sites in Waco and Brenham, Texas.

RESEARCH OBJECTIVES

This two-year research project had three primary objectives. These were to:

1. Develop designs for providing effective advance warning to approaching motorists of the end-of-green phase at high-speed and rural intersections;

2. Formulate effective traffic signal design strategies for supporting these devices that include the type and location of vehicle sensors; and

3. Develop practical traffic engineering manuals that effectively communicate the recommended application and installation guidelines, design features, and related traffic signal operations in high-speed and rural environments where traffic-actuated signal control is envisioned.

Additionally, research subsystems had to be developed to reliably test AWEGS prior to field implementation (AWEGS cabinet-in-the-loop), build a backup flasher system in case of system malfunction or power outages, and deploy a wireless red-light-running evaluation system at each field site using video data collection.

SCOPE OF RESEARCH

TxDOT directed this project to research the use of advance flashing beacons and/or other methods and develop a system to provide advance warning of the end-of-green signal phase to motorists and thereby eliminate the dilemma and sudden braking. The development of such warning devices would reduce the number of crashes, reduce pavement damage due to sudden braking, and reduce or eliminate drivers' dilemma approaching a high-speed signalized intersection.

The research team from Texas Transportation Institute proposed a two-year study to accomplish the above stated mission of the project. The study was funded by TxDOT for a total of $316,266. The funds were used in part to purchase six advance warning signs with flashing beacons, three industrial-grade computers, three backup flashers, one video imaging vehicle detection system (two cameras installed in Brenham), and other hardware installed at the two field sites. Local TxDOT districts funded and managed the installation of two AWEGSs. The two systems remain in place and operational under the supervision of local TxDOT district traffic engineering personnel.

CHAPTER 2. LITERATURE REVIEW

SIGNIFICANCE OF WORK

A primary goal of the Texas Department of Transportation is to make the highways in Texas as safe as possible. This goal is becoming more difficult as the population grows and suburban development spreads into adjacent rural locations. In addition, many rural speed limits have been returned to 70 mph with the recent elimination of the federal national maximum speed limit of 55 mph. Consequently, many warranted traffic signals are being installed at high-speed and rural intersections because of the large population growth. Most of these intersections have posted speed limits well above 45 mph. One major difficulty with traffic signals on high-speed approaches is the dilemma that a motorist faces when the signal turns yellow. Webster defines a dilemma as "*a.* a choice, or situation involving choice, between equally unsatisfactory alternatives, or *b.* a difficult or persistent problem" (*3*). The location of the dilemma zone on a typical approach is shown in Figure 1.

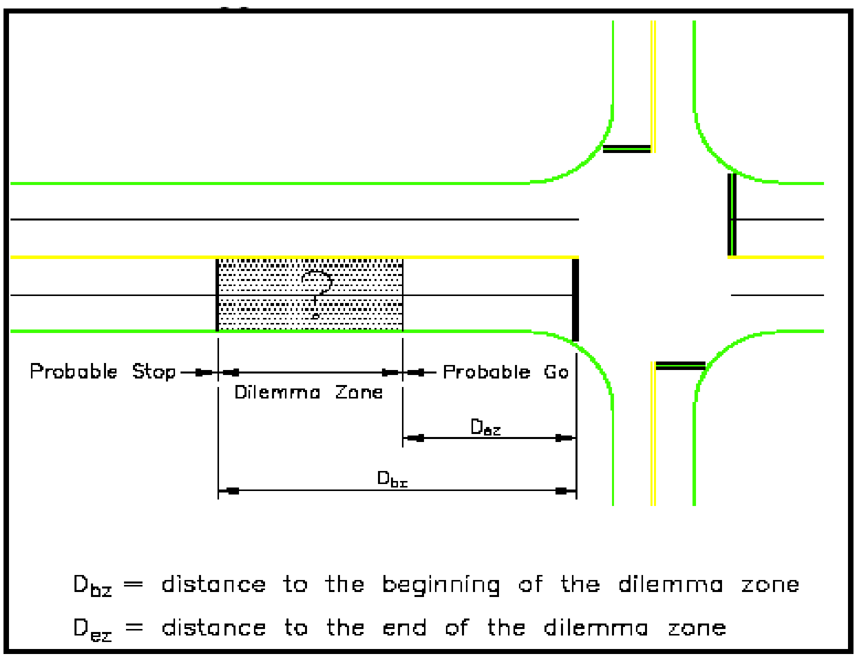


Figure 1. Dilemma Zone Boundaries on a Typical Intersection Approach.

At the start of the yellow interval, approaching motorists are faced with a decision to proceed through the intersection, or bring their vehicle to a safe stop. The decision to stop is easy for drivers far from the intersection at the onset of yellow. Similarly, the decision to continue to travel through the intersection is easy to make when the vehicle is close to the intersection. However, between these two opposite decision points exists a zone where the decision to stop or proceed is not as easy, even if the signal is timed according to national traffic engineering guidelines (*4*). Incorrect decisions here may result in severe crashes.

THE LITERATURE

The decision process faced by motorists as the signal turns yellow leads to potential red-light-running (RLR), which has become a significant safety problem throughout North America. Crashes that occur under these circumstances tend to result in increased property damage and personal injury, oftentimes fatalities. Retting et al. (*5*) reported that approximately 1 million collisions occur at signalized intersections in the United States each year. Of these collisions, engineers estimate that at least 10 percent can be directly attributed to red-light-running. One of the methods currently under investigation and used sporadically throughout the United States and Canada is the installation of advance flashing beacons and/or other methods to provide advance warning to motorists of the end-of-green signal phase, thus reducing or eliminating the dilemma faced by drivers. These installations have proved to be effective in several instances, but not without tradeoffs. Sayed et al. (*6*) indicated that effective advance warning flasher implementation has the potential to minimize the number of vehicles in the "dilemma zone," which in turn could lead to increased safety in this zone and a reduction in accident frequency, which warrants evaluation.

This literature review describes the background and research that has occurred with regard to advance warning flashers (AWFs) and the importance of this research to reduce RLR. In addition, this section outlines some warrants that have been identified for the installation of such devices. Finally, a summary of the research and the pros and cons associated with AWFs is presented. AWFs are basically equivalent to the Advanced Traffic Control Sign (W3-4) described in the millennium edition of the national *Manual of Uniform Traffic Control Devices* (MUTCD) of 2000 (*7*).

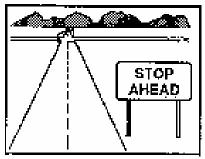
Installation of Advance Warning Flashers

The installation of AWF devices can be traced as far back as 1968 in Alberta, Canada. Installations of this type have increased over the years to the point where the City of Calgary now has more than 30 installations within its city limits. Throughout the United States and Canada, AWF installations have been documented to take on a number of different designs and practices. Bowman (*8*) has prepared a Synthesis of Highway Practice outlining the different advance warning devices that were not specifically identified in the 1988 MUTCD.

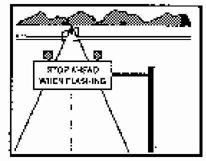
Transportation agencies have developed a wide variety of advance warning devices to address unusual safety, operational, or environmental conditions that cannot be adequately addressed using standard warning devices found in the MUTCD. The synthesis presents the results of a literature review and state-of-the-practice survey conducted to provide useful information on advance warning devices that were not specified in the MUTCD. Both active and passive devices intended for long-term use were included in this analysis (*8*).

Bowman (*8*) identified 10 different text messages used by 10 state agencies and five cities. The 10 different text messages and corresponding signs are depicted in Figure 2.

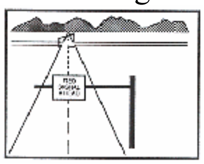
1. Stop Ahead



2. Stop Ahead When Flashing

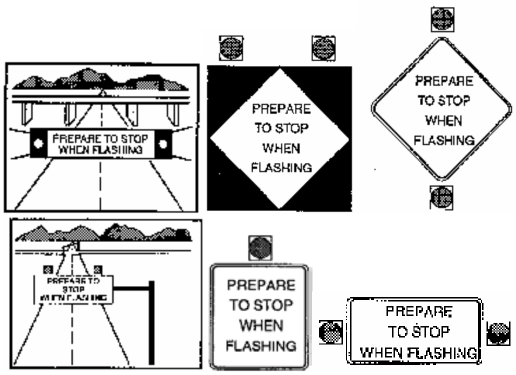


3. Red Signal Ahead

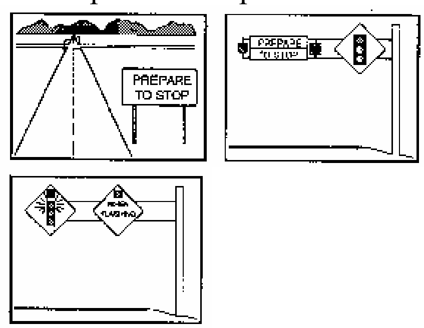


4. Signal Ahead Prepare to Stop When Flashing

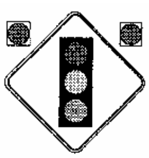
5. Prepare to Stop When Flashing



6. Prepare To Stop

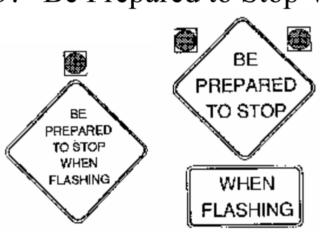


7. Signal Ahead sign supplemented with flashers



8. When Flashing Stop Ahead

9. Be Prepared to Stop When Flashing



10. Red Signal Ahead When Flashing

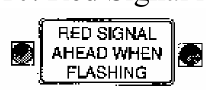


Figure 2. Various Advance Warning Signs Studied in NCHRP Synthesis 186.

The results of this NCHRP analysis indicated that the most widely used message was "Prepare To Stop When Flashing," which was used in six different configurations by five different states and one city. Of the 15 agencies that used the devices contained in this subcategory, three states and one city used more than one device to warn of signal changes. Some 23 percent of the agencies indicated that they used a device of this nature (*8*).

Several other studies have been performed over the years that have also looked at different text messages and sign installations. The results of these studies summarized the different sign types into three different categories. Sayed et al. (*6*) summarized these to include the following:

> "Prepare To Stop When Flashing (PTSWF): The PTSWF sign is essentially a warning sign with the text Prepare To Stop When Flashing complemented by two amber warning beacons 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 device is similar to the PTSWF sign except that the words Prepare To Stop When Flashing are replaced by a schematic traffic signal composed of a rectangle with solid red, yellow, and green circles. The flashers operate in the same manner as the PTSWF sign.
>
> Continuous Flashing Symbolic Signal Ahead (CFSSA): As the name suggests, this device is identical to the FSSA sign but it has flashers that flash all the time – the flashers are not connected to the traffic signal controller" (*8*).

Eck and Sabra (*9*) also looked at the different types of devices and indicated that there are many different variations of advance warning devices. They concluded that the flashing "Red Signal Ahead" sign, the PTSWF sign (and its variations), and flashing strobes are the three most commonly used advance warning devices. Pant and Xie (*10*) found that the PTSWF sign is the most commonly used sign in the state of Ohio and is preferred over other devices due to driver familiarity.

A review of Canadian practices provides some insight to an additional alternative in signing for advance warning installations. A summary of design and installation of AWF in the four western provinces of Canada (British Columbia, Alberta, Saskatchewan, and Manitoba) indicates that a combination PTSWF and FSSA has been put into practice through the years (*11*). Discussions with the City of Calgary and the British Columbia Ministry of Transportation indicated that their installations have evolved over the past 30 years from a standard PTSWF sign to a combination PTSWF and FSSA sign. The combination sign includes the symbolic "signal ahead" sign with the words "Prepare To Stop" along the bottom of the sign. These installations are typically installed overhead and include standard warrants and design criteria as discussed in more detail later in this literature review.

In addition to the research that has been done on the different types of signs used for advance warning of signals, Pant and Huang (*12*) as well as Sabra (*13*) performed driver surveys and studies to determine which of the different types of signs drivers reacted to best. Sabra (*13*) conducted a research investigation on the Federal Highway Administration (FHWA) highway driving simulator (HYSIM) using 60 test subjects to examine driver response to active advance warning systems (AAWS) at a high-speed signalized intersection. Measures of effectiveness included identification distance, reaction time, vehicle approach speed, and vehicle lateral placement measured on the HYSIM. The different AAWS evaluated included the PTSWF, the symbolic "Signal Ahead" sign with flashing lights, and a "Red Signal Ahead" sign with the "red" flashing.

The results of this analysis indicated that the symbolic "Signal Ahead" sign with flashing beacons had the greatest identification distance among all the test signs and was preferred by most drivers. The study found that the PTSWF sign confused subject drivers rather than helped them to modify their reaction, and this sign was the most incorrectly identified. Pant and Huang (*12*) also found as a result of their analysis that drivers did not always understand the correct meaning of the PTSWF sign; however, the motorists surveyed still preferred the PTSWF sign over other signs due to familiarity with the sign throughout the state.

In addition to the different text messaging on the signs themselves, Bowman (*8*) also outlined the different methods used by agencies for installation of the sign. The different methods included standard sign mounting on the roadside, span-wire mounting across the traveled way, mast-arm mounted signs, and, in some instances, sign bridge mounting. Sabra (*13*) studied the effects of different mounting locations as part of the HYSIM analysis, but concluded that in general the location of the sign did not have an impact on driver response.

The research conducted to date shows that there are many different types of installation for advance warning devices throughout the United States and Canada. These different installations make it difficult to compare one site to another because of the differences in design and installation. It is clear, however, that the PTSWF has been the most common installation throughout the United States.

Safety Impacts

One of the main purposes for the consideration of the installation of advance warning devices has been to improve safety at high-speed signalized intersections. Several research projects have been undertaken over the years outlining the effects of AWF installation on safety. The main method for determining safety has been in terms of accident reduction before and after installation. Agent and Pigman (*14*), Eck and Sabra (*9*), Gibby et al. (*15*), Klugman et al. (*16*), and Sayed et al. (*6*) all found that intersections with advance warning appear to have lower left-turn, right-angle, and in some instances, rear-end accidents.

Agent and Pigman (*14*) found that the use of an AWF should be limited to locations where either an existing or high potential accident problem exists, particularly a high percent of angle accidents. Gibby et al. (*15*) provided more detail indicating that high-speed approaches with AWFs had significantly lower total, left-turn, right-angle, and rear-end approach accident rates than those without AWFs. Gibby et al. also observed significantly lower ratios of nighttime accidents. The research performed by Klugman et al. (*16*) in Minnesota concluded that the use of AWF devices could be effective at reducing right-angle and rear-end accidents under certain situations, but device usage does not automatically increase the safety of all intersections. Sayed et al. (*6*) provided the most detailed accident analysis, indicating that AWF intersections showed 10 percent fewer total accidents and 12 percent fewer severe accidents. Negligible reductions were observed with respect to rear-end accidents. Sayed et al. found the reduction was not statistically significant at the 95 percent level.

Sayed et al. (*6*) also found a correlation between the accident frequency of AWF sites and the minor street traffic volumes. It was observed that when the minor street traffic volumes are low, the AWF sites have a higher frequency of accidents than non-AWF sites; however, with increasing minor street traffic volumes, the accident frequency for AWF-equipped intersections was found to be lower than at non-AWF sites. The specific results indicated that AWFs were effective at locations with a minor street Annual Average Daily Traffic (AADT) of 13,000 vehicles per day (vpd) or greater.

In addition to the comparison of accident reduction for intersections with AWF installations, Farraher et al. (*17*) collected data on the impact of red-light-running and vehicle speeds through the intersection. Farraher concluded that the installation of advance warning flashers provided a 29 percent reduction overall in red-light-running, a 63 percent reduction in truck red-light-running, and an 18.2 percent reduction in the speed of trucks through the survey intersection. Farraher et al. commented that although the data indicate that advance warning flashers are effective at the site studied, the number of overall violators and their speeds remained unacceptably high.

Another concern with AWF installation and safety is in relation to the potential for increased speeds as the advance warning device is activated. This is particularly true for the PTSWF and FSSA signs. Pant and Xie (*10*), and Pant and Huang (*12*) provided data from two separate studies in Ohio linking increased speeds at intersections with advance warning devices. Pant and Huang (*12*) found that an increase in speed at intersection approaches was common as the signal approached the red phase of the cycle. This was particularly true for tangent approaches and less of a concern for curved approaches where limited sight distance existed. Pant and Huang concluded that the use of advance warning devices, particularly PTSWF and FSSA signs, should be discouraged, as they were found to encourage high-speeds under some conditions. Pant and Xie (*10*) performed a follow-up study to this research and found once again that when flashers were off and the signal indication was clear, drivers faced with a PTSWF or FSSA sign generally increased their speeds in an attempt "to beat the light." Once again, this was particularly true on tangent approaches, and as such, installation of advance warning devices was discouraged, particularly on tangent sections.

The research performed to date indicates that intersections with AWFs have consistently provided lower overall accident rates and fewer severe accidents than intersections without the devices. These reductions, however, have not been shown to be statistically significant. The drawbacks of safety, however, are in the documented increase in red-light-running after the start of red and the increase in speeds approaching the intersection under certain conditions.

Selected Canadian Practice

AWF devices have been in operation in Western Canada for more than 30 years and are noteworthy for their documented experience and policies for advance warning devices. The City of Calgary together with the provinces of British Columbia and Manitoba have specific "warrants" for installation of AWF devices.

City of Calgary, Alberta

The City of Calgary has established criteria for the installation of AWFs within its city limits (*11*). The operational criteria and guidelines for installation are as follows:

- at all signalized intersections having a posted speed limit of 100 km/h;
- at the first signal into the city on routes where the posted speed limit is in excess of 70 km/h;
- on roadways having a speed limit in excess of 70 km/h where an accident hazard exists that is correctable through the use of advance warning signals; or
- on roadways where horizontal or vertical alignment causes restricted visibility of the approaching intersection.

British Columbia

Sayed et al. (*6*) outlined the following warrants for installation for British Columbia referenced from the British Columbia Engineering Guidelines (*18*). These applications warrants remained into 2001 (*19)*:

- posted speed limit on the roadway is 70 km/h or greater;
- view of the traffic signals is obstructed because of vertical or horizontal alignment (regardless of the speed limit) so that a safe stopping distance is not available;
- there is a grade in the approach to the intersection that requires more than the normal braking effort; or
- drivers are exposed to many kilometers of high-speed driving (regardless of posted speed limit) and encounter the first traffic signal in a developed community.

Manitoba

Manitoba policy (*20*) indicates that "Prepare to Stop" sign installations are required at approaches to permanent signalized intersections and should be installed on the primary roadway (main street) approaches, at any of the following:

- isolated rural intersections with approach speed limit of 70 km/h or greater;

- rural intersections at least 2 km away from nearest signalized intersection with approach speed limit of 70 km/h or greater;
- intersections at approaches to urban areas with approach speed limit of 70 km/h or greater;
- intersections within 1 km of 3 percent or greater downgrade with approach speed limit of 60 km/h or greater;
- intersections within 500 m of significant sight restrictions due to horizontal or vertical roadway alignment, etc. with approach speed limit of 60 km/h or greater; or
- intersections where "fail to stop" right-angle accidents exceed four per year on a three-year average with approach speed limit of 60 km/h or greater.

And on the secondary roadway (cross street) approaches, at any of the following:

- rural intersections with AADT approaching volumes of 2000 or more with approach speed limit of 70 km/h or greater;
- intersections within 1 km of 3 percent or greater downgrade with approach speed limit of 60 km/h or greater;
- intersections within 500 m of significant sight restrictions due to horizontal or vertical roadway alignment, etc. with approach speed limit of 60 km/h or greater; or
- intersections where "fail to stop" right-angle accidents exceed four per year on a three-year average with approach speed limit of 60 km/h or greater.

Ontario Ministry of Transportation

A detailed research program regarding advance warning and detection was completed in October 1998 for the Ontario Ministry of Transportation (*21*). This study included a thorough literature review, five field studies, crash data, benefit/cost analysis, and policy development. The research team included at least 10 individuals from Synetics Transportation Consultants, Inc. Their most important policy recommendation was that advance warning signing should be considered simultaneously with the type of detection system deployed. Guidelines similar to the above practices were supported.

Minnesota Department of Transportation Practice

The most recent American practice reviewed was developed by the Minnesota Department of Transportation (MnDOT) in 2000 (*22*). This guideline states that "AWF should only be installed in response to a specifically correctable problem, not in anticipation of a future problem. Generally, AWF implementation is appropriate only at high-speed locations. Before an AWF is installed, other remedial actions should be considered." The MnDOT guide continued with a taxonomy of potential problem categories for which application criteria and comment were provided: "the following guidelines generally apply only where the posted speed is 55 mph or higher by category and [criteria]:

- isolated or unexpected signalized intersection [>10 miles to next signal];
- limited sight distance [~AASHTO stopping distance, truck decel. reduced 20 percent];

- dilemma zone [~ITE stopping distance, truck decel. reduced 20 percent];
- accidents [not 1 or 2 above];
- heavy truck volume [grade >3 percent with > 15 percent trucks]; and
- engineering judgment.

The MnDOT AWF guide (*22)* is consistent with the previous research and traffic engineering practice on AWFs noted above.

LITERATURE SUMMARY AND ANALYSIS

Several agencies have identified advance warning for end-of-green phase at high-speed traffic signals as an important research topic for the 21st century. As traffic signals are installed more frequently at high-speed and rural intersections, the need to provide for safety is ever increasing. Several methods have been identified throughout the United States and Canada to provide advance warning for end-of-green phase.

The most common of these methods is the installation of advance warning devices that typically take one of three different designs. The first, PTSWF, provides a warning sign in connection with flashers activated prior to the signal indication turning to yellow and remaining activated through the green phase. The literature indicates that this is the most common type of advance warning currently in practice in the United States. The second type of advance warning is the FSSA sign. This warning serves the same purpose as the PTSWF, the only difference is in the sign design itself. While the PTSWF includes the words "Prepare To Stop When Flashing," the FSSA includes a symbolic "signal ahead" sign with flashing yellow lights, once again linked to the signal controller. A combination PTSWF plus FSSA sign is also in use in all of the four western Canadian provinces. This combination sign provides the symbolic signal reference with the "Prepare To Stop" wording providing advance warning of the upcoming signal indication. The final advance warning device is the CFSSA, which mirrors the FSSA sign in design, but does not include an activated flashing device. Instead of an actuated device, this system includes a constant flashing yellow light to help warn the driver of an approaching signal.

Several studies have been performed to compare and contrast the pros and cons, as well as the warrants for installation of advance warning devices. A summary of the main points is illustrated in Table 1.

Table 1. Summary of Previous AWF Studies.

Summary of Previous Advance Warning Flasher Study Results	
Pros	Cons
Reduction of Dilemma Zone	Increased speed at intersection
Reduction in accidents	Increased cost
Reduced driver reaction time	Requires a need to educate the public
Increased driver expectancy	Increase in extended red-light-running
Increased warning for signalized areas	
Reduction in overall red light violations	
Reduction in truck speeds	

The potential to provide effective advance warning devices for high-speed roads in Texas is worth developing. Existing research shows that there are advantages that have been identified with advance warning installation. These advantages can help to reduce accidents, increase overall intersection safety, and provide a safe and efficient transportation system. As noted in the research reviewed, however, installation of advance warning devices has not always produced the positive results anticipated at all intersections. Consequently, the application, design, and operation of advance warning systems need to be carefully employed for specific site conditions.

2000 MUTCD

The MUTCD was initially published in December 2000 (*7*). A first revision was published in June 2001, and a second revision is scheduled for late 2003. The MUTCD provides national design and operations guidance for AWEGS applications in America. The following materials relevant to AWEGS applications were extracted from the 2000 MUTCD:

Section 2C.26 Advance Traffic Control Signs (W3-1, W3-2, W3-3, W3-4):

Standard: The Advance Traffic Control symbol signs include the Stop Ahead (W3-1a), Yield Ahead (W3-2a), and Signal Ahead (W3-3) signs. These signs shall be installed on an approach to a primary traffic control device that is not visible for a sufficient distance (defined in a table) to permit the road user to respond to the device.

Option: An Advance Traffic Control sign may be used for additional emphasis of the primary traffic control device, even when the visibility distance to the device is satisfactory. A warning beacon may be used with a Signal Ahead (W3-3) sign.

A BE PREPARED TO STOP (W3-4) sign may be used to warn of stopped traffic caused by traffic control signals or in areas that regularly experience traffic congestion.

Standard: When a BE PREPARED TO STOP sign is used in advance of traffic signals, it shall be used in addition to a Signal Ahead sign.

Option: The BE PREPARED TO STOP sign may be supplemented with beacons.

Guidance: When the beacon is interconnected with a traffic control signal or queue detection system, the BE PREPARED TO STOP sign should be supplemented with a WHEN FLASHING plaque.

Only in the second revision of the 2000 MUTCD was the W3-4 BE PREPARED TO STOP advance traffic control sign actually shown in a pictorial display. Apparently, some debate existed within the national committee as to whether it should be a three-line or four-line sign. The three-line sign is depicted therein, and this design was selected for use as the AWEGS' advance warning sign. Advance warning for unexpected and problematic queuing at traffic signals seems to be the primary application expected for the new W3-4 sign. The proposed application of the W3-4 sign for mitigating red-light-running in this project would appear to be an extension of the intended use permitted by the Manual (*7*).

CHAPTER 3. PROBLEM SPECIFICATIONS FOR ADVANCE WARNING SYSTEM FOR END-OF-GREEN IN TEXAS

INTRODUCTION

Every new system design, such as AWEGS, should have a clear statement of the (traffic) problem that it is trying to efficiently address. All system designs have a finite scope of expected service and tradeoffs between various features, functions, and costs. All designs are limited by the resources of time and technology, and AWEGS is no exception. This chapter presents a description of the traffic problems being addressed by AWEGS and provides general guidance for its application based on the literature on the subject and our field experiences to date. This guidance material might be used in the future to develop a specific warrant for AWEGS applications once more field experience is obtained.

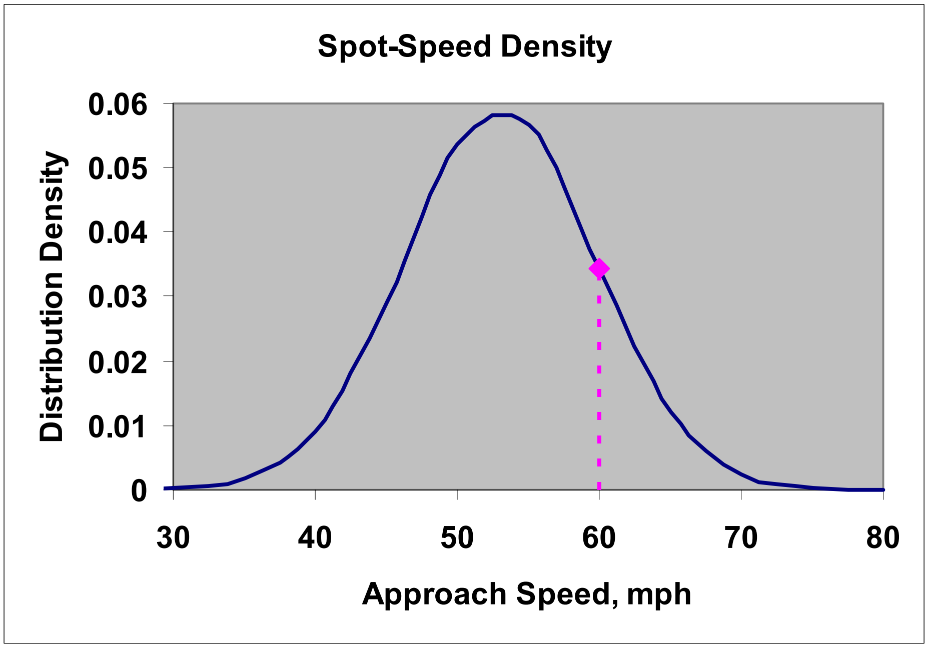
DESIGN PROBLEM SPECIFICATIONS

The goal of AWEGS operations is to get drivers approaching a traffic-actuated signalized intersection at high-speed to slow down to a speed so they can safely stop when the signal turns yellow and then red shortly thereafter. Yellow lights are not generally timed for these high-speeds (i.e., usually illegal speeds above the speed limit). A flashing warning (e.g., beacon) is activated to warn approaching motorists when AWEGS detects the traffic signal phase is about to end, usually in about 5 seconds. An additional function was added to (Level 2) AWEGS to minimize dilemma zone exposure to trucks and high-speed cars when the signal is operating in the green dwell state during light traffic.

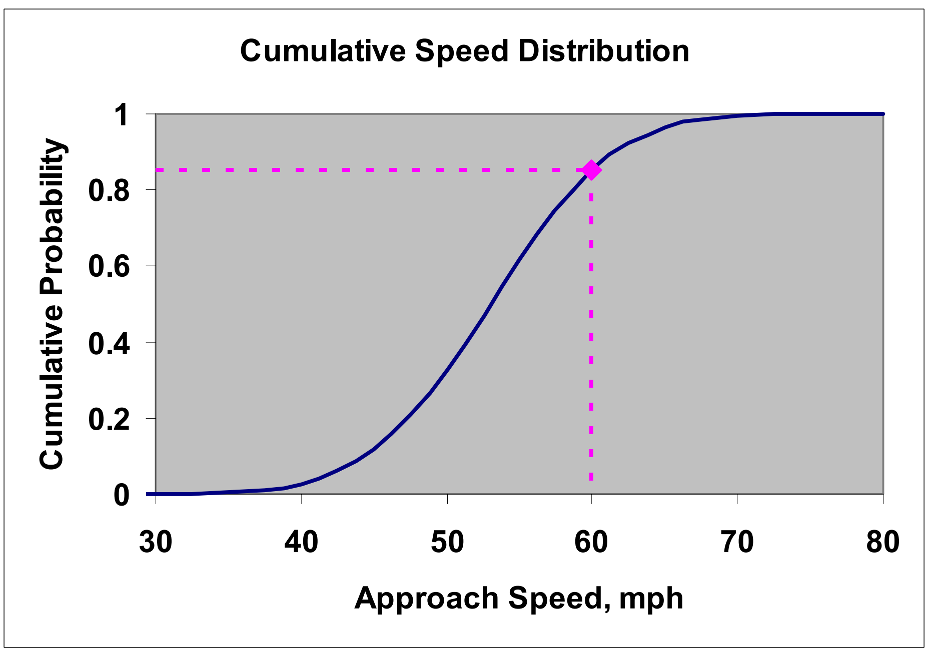
Traffic

Important inputs to the design of AWEGSs include the characteristics of traffic flow of speed of traffic, traffic mix, and degree of interruption by adjacent traffic signals. Our AWEGS design assumes that the arrival traffic flow (1) is located in Texas, (2) is isolated from adjacent traffic signals (non-coordinated), (3) has mixed traffic of cars (and pickups) and trucks, and (4) has mostly free-flowing speeds that are normally distributed.

Spot-speed studies should be conducted using procedures similar to TxDOT's *Procedures for Establishing Speed Zones* (*23*). Two basic spot-speed parameters are needed for each high-speed approach: the mean (50th percentile) speed (mph), and the 85th percentile speed (mph), as used for speed zoning. The term "approach speed" used herein is synonymous with the 85th percentile speed of a spot-speed study, which is frequently used as a guide to set speed limits on rural highways, setting yellow warning signal intervals, and for choosing signal detector design speeds. An example distribution of spot-speeds for a high-speed rural highway is shown in Figure 3 for a mean (50th percentile) speed of 53 mph and an 85th percentile speed of 60 mph. Note that 15 percent of the traffic will be traveling at speeds exceeding the 85th percentile speed, and some may find stopping on red difficult unless warned of the impending loss-of-green signal in advance.



a. Distribution density of approach spot-speeds.



b. Cumulative distribution of approach spot-speeds.

Figure 3. Example of High-Speed Traffic Not Covered by Dilemma Zone Detection.

Dilemma Zone Detection Guide

Our AWEGS was designed primarily to improve the safety at traffic-actuated signals designed to provide high-speed dilemma zone protection in Texas. Multiple inductive-loop detector layouts along the approach to the signal provide this dilemma zone protection up to the design speed. The detector layout varies with approach speed, as described in draft design guidelines originally developed for TxDOT around 1990 and updated circa 1996 (*24*). These draft guidelines, called Nader's Guide in this report, are presented in Table 2. Inductive-loop detectors (ILDs), operating in the presence mode, are presumed when using these guidelines. Nader's Guidelines (*24*) were extended from 55 mph to 70 mph when the 55 mph national maximum speed limit was repealed in 1996.

Table 2. Nader's Guide for Detector Installation for High-Speed Approaches. (24)

Approach Speed, mph	Distance from Head of Detector to Stopline at Intersection, feet			Stopline Area Detector [a]	Passage Gap, seconds
	CDA[b] 1	CDA 2	CDA 3		
45	330	210	---	6′ x 40′	2.0
50	350	220	---	6′ x 40′	2.0
55	415	320	225	6′ x 40′	1.2
60	475	375	275	6′ x 40′	1.4
65	540	430	320	6′ x 40′	1.2
70	600	475	350	6′ x 40′	1.2

[a] Presence on red; then delayed (no) call on green following first gap-out.
[b] Dilemma Zone Detectors

Traffic engineers typically assume that the design speed for signal timing and design is the 85th percentile approach speed of free-flowing vehicles. The speed limit is also frequently based on the 85th percentile approach speed, for it represents the maximum speed judged safe for specified (existing) speed-zoning conditions by reasonable and prudent driving public. In recent times, the specification of design speed has become less specific to existing traffic conditions, but the fact remains that traffic engineers face a tradeoff among many operational measures in selecting any speed value for design.

Increasing the design speed at traffic-actuated signals leads to longer signal cycles, more sluggish traffic operations, and increased traffic delays. Traffic engineers know that these negative consequences should also be minimized where possible. The upshot of this paradox is that about 15 percent of the arrival traffic in free-flowing conditions, which are exactly as assumed, would be traveling faster than the design speed of the dilemma zone detection system. These high-speed motorists could benefit from a warning when a green signal ahead is about to change so that they could slow down to a safe approach speed.

Most dilemma zone detection systems used on Texas highways are based on existing conditions similar to those assumed in Nader's Guide. These existing conditions generally include: (1) passenger cars only, (2) level grades, and (3) no change in roadway design, among other possibilities. Upgrading the pavement quality will likely result in an immediate increase in travel speed. It is very expensive to readjust multiple-loop dilemma zone detector designs to best fit current conditions to maximize the safety provided, so traffic engineers may increase the "passage gap" in the signal controller unit above those recommended in the original design; e.g., the right-hand column of Table 2. This gap adjustment (usually an increase) usually aids only the slower motorists. It does not aid high-speed motorists. Moreover, increasing the passage gap increases: (1) the sluggishness of the signal operation, (2) traffic delay, and (3) the propensity of the signal phase to "max-out," thereby losing all dilemma zone protection and green split control.

Trucks

Recent federal legislation aside, trucks are 20 times heavier and more difficult to stop than passenger cars. Publications from 1994 (*25*) and 1998 (*21*) concluded that large trucks decelerate at approximately 70 percent of passenger car rates. MnDOT (*22*) assumes trucks decelerate to a quick stop at 80 percent of passenger cars. In the geometric design of crest vertical curves of highways, this increased stopping sight distance of trucks is presumed to be overcome by the nearly 5-foot increase in truck driver's eye height as compared to cars. No such compensation exists for truck drivers to the onset of the yellow at a traffic signal. Moreover, trucks' lower deceleration capability is not directly considered in signal timing or most dilemma zone detector layouts, including Nader's Guide. Thus, most truck drivers could benefit from having advance warning for the end-of-green.

ADVANCE WARNING FEATURES

Advance warning of end-of-green systems have been widely deployed in North America for more than 30 years, using the detector and controller technology of the day. The previous literature review and analysis shows that advance warning systems are meritorious of field deployment and testing.

Figure 4 presents design features of our AWEGS for high-speed traffic signals. A Level 2 AWEGS, having two advance detectors per approach lane, is shown in Figure 4. AWEGS receives vehicle actuations from inductive loop detectors (ILDs) strategically placed along the approach roadway to the intersection. Video detection systems could probably be used in a similar role. Video detection offers directional flow features which could be also used to minimize false calls for cross-street green caused by turning traffic at intersections lacking barrier island channelization.

Traffic signal controllers typically deployed at high-speed rural intersections in Texas operate in the full traffic-actuated mode. The green for a cross-street approach is called only on detected traffic demand, and the signal green can terminate either because large gaps in the traffic stream are detected (i.e., gap-out) or because of the green reaching its maximum allotted time under heavy traffic demand (i.e., max-out). An active advance warning system that warns the motorist about the termination of green should do so safely and consistently. This means that advance warning should be provided in a consistent manner when either the controller gaps-out or maxes-out. It is essential to provide a consistent warning to the drivers to ensure driver respect for the AWEGS.

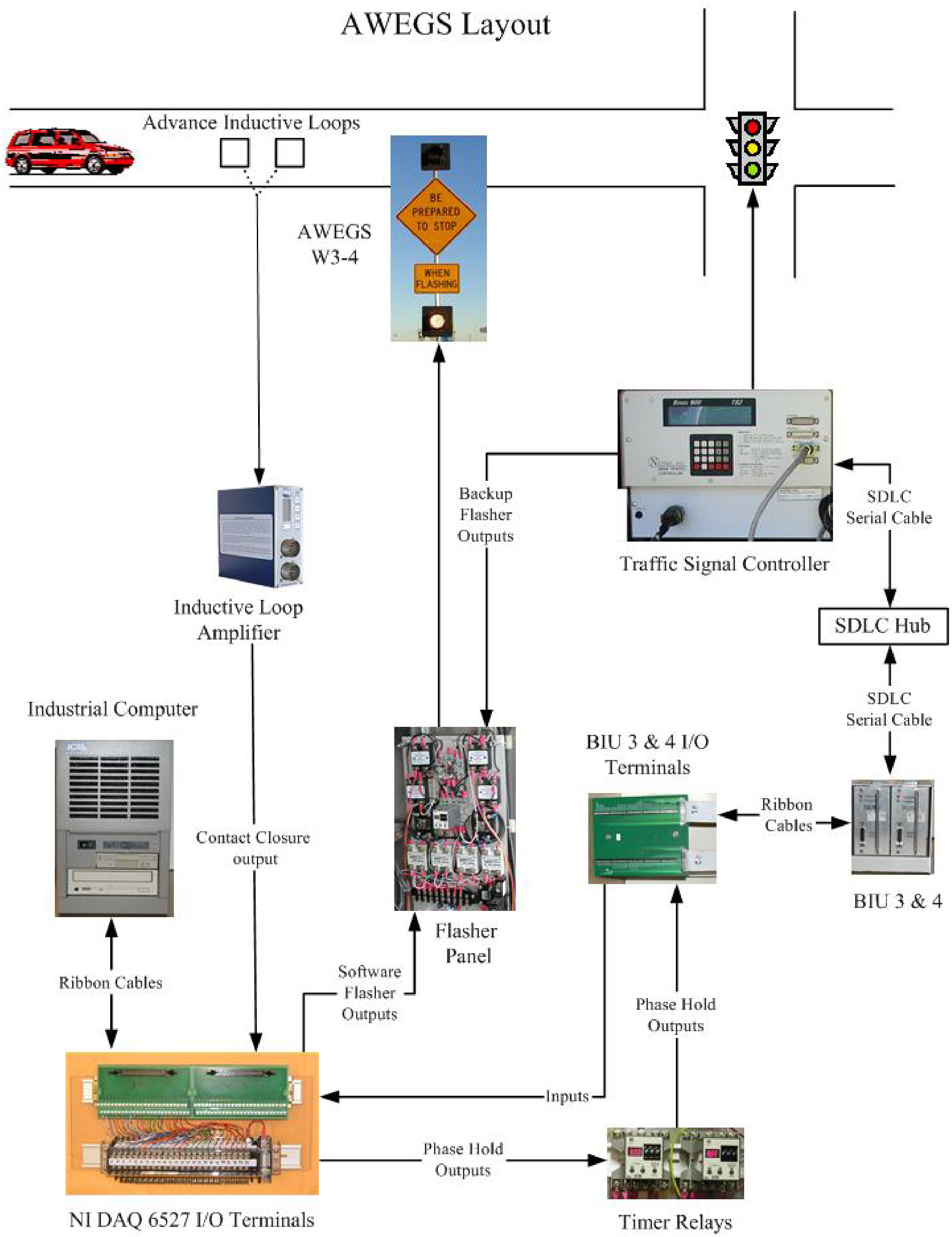


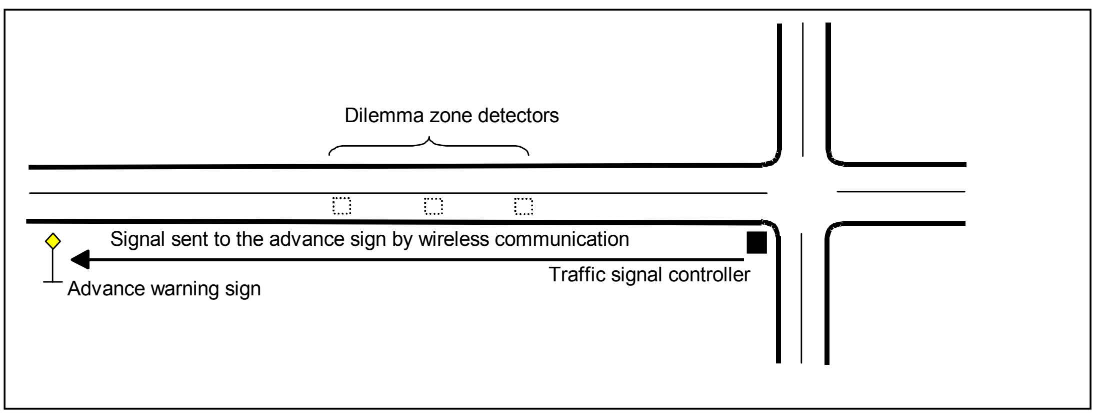
Figure 4. Design Features and System Connections for AWEGS.

ADVANCE WARNING TECHNOLOGY LEVELS

Three technology levels of advance warning devices/systems were originally envisioned for development, deployment, and testing in this research. Level 0 contained state-of-the-art (or practice) advance warning devices with no major development cost. Level 1 would feature the detection and response to the “average” arriving vehicle, and Level 2 would provide speed estimation of individual vehicles and differentiation between cars and trucks. An overview of the features of these advance warning technology levels follows.

Level 0 – Existing Technology

This state-of-the-practice advance warning device/system would routinely activate when the end-of-green signal for the protected high-speed approach is eminent. A timed “trailing overlap” of about 5 seconds would follow the terminating arterial (actuated) signal phase gapping-out so that advance warning flasher operation could be implemented. After this timed overlap expired, the signal phase would end with the start of yellow. Figure 5 illustrates the timed-overlap method (Level 0) for providing advance warning for traffic-actuated signals. The main features (and advantages) of this basic technology are that no advanced detection is needed, no major technology development would be needed, and system installation within the signal cabinet is minimal.



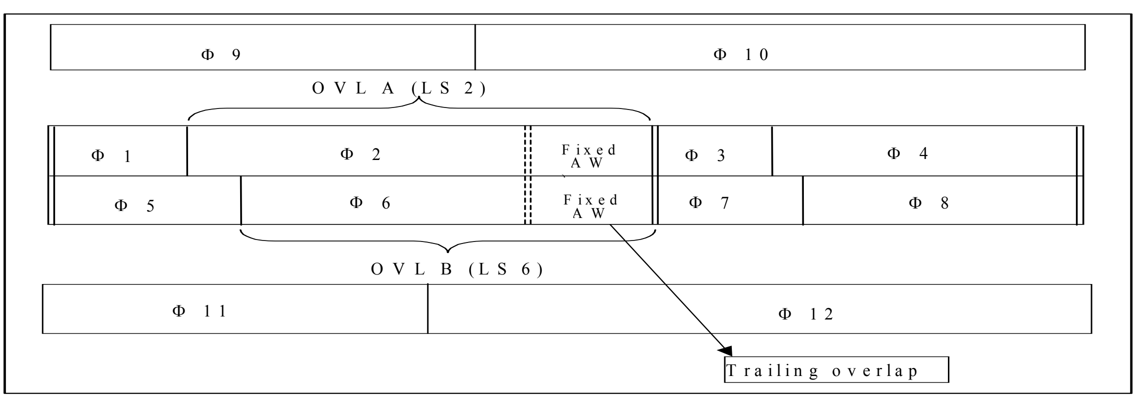


Figure 5. Possible Layout and Ring Structure for Level 0 with Trailing Overlaps.

Some existing traffic signal controllers have incorporated advance warning logic *(19)*. However, none of the signal controllers used by TxDOT has trailing overlap advance warning logic explicitly built in. Moreover, the routine loss of dilemma zone protection, provided by TxDOT's widely used advanced detection design (or as provided by Nader's Guide), causes this method (Level 0) for routinely providing advance warning for end-of-green to be judged unattractive for routine implementation in Texas. A decision was made not to field test Level 0 in this research project.

Level 1 – Single Detector Advance Detection and Basic Modeling Technology

This technology level features the advance detection in real time of individual vehicles arriving on the approach. However, neither the individual type of vehicle nor its speed is determined. Thus, all vehicles detected are presumed to be traveling at the average speed and in need of warning of any imminent end-of-green. As used here, advance detection implies a location upstream of TxDOT's typical dilemma zone detectors, and not a technology level. Estimation of future phase gap-out between arriving vehicles is considered the principal technical challenge of Level 1 systems since the exact arrival time of vehicles to the TxDOT detectors is not known.

The paradoxical upshot of this relatively simple Level 1 AWEGS design is that it provides a very conservative AWF operation because the original location of the approach's detector (later to be named the ADA detector) is based on the assumption that the design approach vehicle is traveling very fast (that is, at the 99th percentile speed), but individual projected travel times are based on the estimated average space-mean speed. This conservative advance warning system causes more traffic delay and less efficient signal operation to occur than would a Level 2 system. Figure 6 conceptually illustrates the deployment of a Level 1 advance warning system.

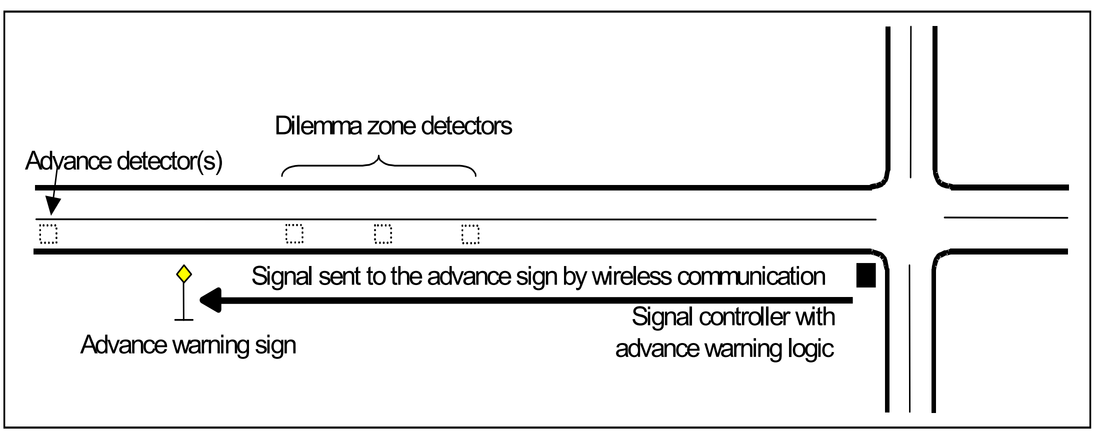


Figure 6. Level 1 – Advance Detection Technology Layout.

Level 2 – Vehicle Detection, Speed Estimation, and Vehicle Classification

Level 2 AWEGS builds on Level 1 technology by adding knowledge regarding the general type (car, truck) of vehicle and its individual speed. This additional information is obtained by placing a second advance detector (BDA) at a strategic location downstream from the initial advance detector needed for Level 1. Both AWEGS advance detectors are also strategically located upstream of TxDOT's dilemma zone detectors, presumed to already be installed at the signalized intersection of interest. Figure 7 presents the general layout of a Level 2 AWEGS.

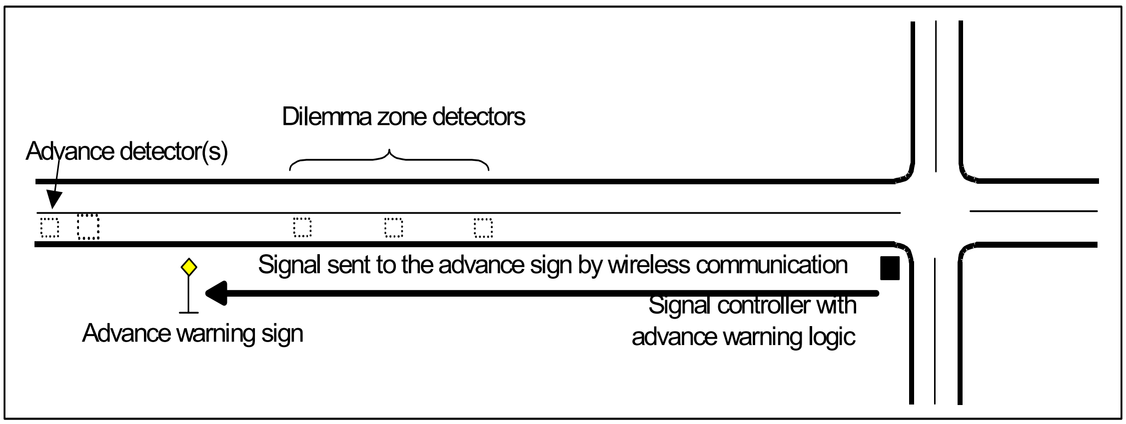


Figure 7. Generalized Layout of a Level 2 AWEGS.

ADVANCE WARNING SIGNS

The type of advance warning device used by AWEGS could range from simple ground-mounted W3-4 signs with flasher beacons to more complex cantilevered electronic matrix signs. Figure 8 presents examples of these advance warning sign options. Recall the prior advance warning signing options noted previously in Figure 2. The deployment and evaluation of such advance warning signs will be described in the following chapters. Figure 8a is the W3-4 sign installed at our test site in Waco. The vertically mounted flasher beacons provide the active warning element. Their design (and their backup system design) proved to be a fairly complex problem because nominal off-the-shelf flash drivers, commonly used in signal cabinets, do not provide the immediate full-flash capability desired for AWEGS applications. Figure 8b depicts an overhead advance warning sign mounted on a large cantilevered sign support structure. Less costly mast-arm designs are also frequently used to support overhead advance traffic control warning signs with attached warning beacons.

a. Pole-mounted AWEGS (W3-4) in Waco (left) and Brenham (right), Texas.

b. Cantilevered electronic matrix warning sign located in Marshall, Texas.

Figure 8. Examples of Advance Warning Signs Used in Texas.

CHAPTER 4. THEORY OF AWEGS OPERATIONS

OVERVIEW

AWEGS was designed to provide advance warning for end-of-green for high-speed, rural intersections. A minimum of interference with the existing traffic-actuated signal's operation was desired. For this research, a MUTCD-compliant W3-4 advance traffic control sign was selected to provide the advance warning message. Advance detection was placed ahead of existing TxDOT detectors (usually by Nader's Guide) to provide look-ahead time to identify arriving vehicles. Two research technology designs, Level 1 and Level 2, were developed and investigated. Level 1 used one advance detector (ADA) to monitor the arrival of vehicles. Level 2 added a second detector just downstream of the ADA detector to measure each vehicle's speed (travel time) and vehicle type (car, truck). As the research progressed from Level 1 to Level 2 systems, the features of Level 1 became the backup design for Level 2 when and if one of the two advance detectors failed. A typical detector layout for one two-lane, divided 60 mph approach of a Level 2 AWEGS is presented in Figure 9. The remainder of this chapter provides the details of the operational theory and development of AWEGS. Companion reports provide the recommended design methodology (*1*) and signal installation for field applications (*2*).

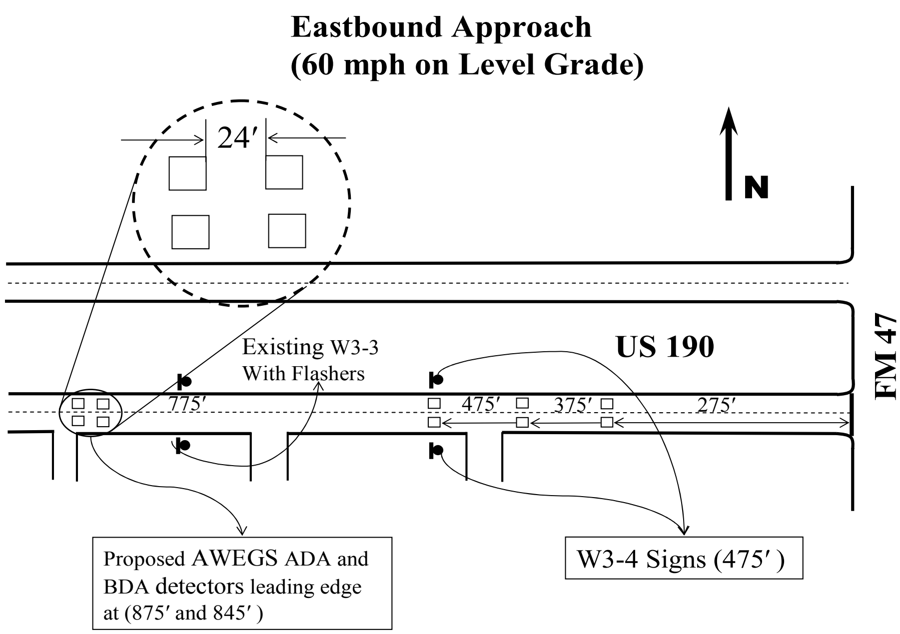


Figure 9. A Generalized Layout of a 60 mph AWEGS in Texas.

DETECTOR FUNCTIONS

AWEGS employs three basic operations of forecasting, surveillance, and monitoring. As noted in Figure 9, for Level 2 systems, there are two detector groups for each arterial approach phase " ***i*** " ***per lane***. These are the:

1. ADA ***i*** and BDA ***i*** detectors (forming a speed trap); and the
2. CDA ***i*** detectors (i.e., TxDOT's dilemma zone detectors).

The tasks assigned to these detector groups are described in subsequent sections.

The CDA multiple-loop detector layout, widely known in Texas as "Nader's Guide" and defined previously in Table 2, provides high-speed dilemma zone protection using traffic-actuated control. AWEGS monitors the input status of these existing multiple loops. AWEGS then tries to estimate the control output (gap-out of the traffic-actuated controller) given the same local detector inputs and data files (of passage gaps, minimum greens, maximum greens, etc.) that the traffic-actuated controller uses. The TxDOT CDA detectors have uniform spacing between them (see Table 2). One important local operational question is "What passage gap is actually being used by the local district traffic engineer in the signal controller?" Our field experience suggests that the coded passage gap may be larger than that recommended in Nader's Guide (*24*). Moreover, the spacing between the detectors also may not be as indicated in the Guide for a particular site and approach speed because of local engineering judgment.

A. Forecasting—of phase gap-out time from the ADA/BDA detectors, which would later be measured by the controller at the CDA detectors (a forecasting task):
   1. Using only the ADA detector – a constant-speed, Level 1 technology.
   2. Using the ADA and BDA detectors – a speed-based, Level 2 technology.
   3. Output: Flash W3-4 sign beacons for AWNG time. No phase hold.

B. Surveillance—of impending phase gap-out by controller (a watch-dog alarm task). There are two main cases where this status condition seems to occur:
   1. An error has occurred between the predicted effective passage gap for vehicle *j* and the measured effective gap over the CDA detectors, and a call for service exists against this phase which is ready to gap-out.
   2. The arterial through phases (say Phases 2 and 6) have gapped out and now are in Green Rest during light traffic conditions; then suddenly a conflicting call (hopefully a true call) for service arises, usually from the cross street, but sometimes from the opposing left turn. Effective ways are provided in AWEGS for dealing with these conditions. Level 2 technology, which is speed based, reduces the frequency of occurrence of the former case for error; whereas, the unpredictable (in real time) latter event is routinely handled by careful timing and application of the delay function during not-green, which is available with inductive-loop detection (either in the detector amplifier or controller unit).
   3. Output: AWEGS response depends on whether any approach traffic is located between the ADA advance detector and the CDA detectors. Outputs include:
      a. Case 0 — no arrival traffic is detected traveling in zone of detection (no traffic arriving is a function of approach traffic volume).
         Output: Flash W3-4 sign with onset of call. No phase hold.

b. Case 1—Arrival traffic is detected traveling in the zone of detection:
   Output: Level 1—Flash W3-4 sign, and hold phase green for a constant time, usually about 5 seconds.
   Output: Level 2—Flash W3-4 sign, and hold phase green *only if* vehicle is in its dilemma zone, based on its vehicle type and speed. This is a major benefit of Level 2 technology in that holds are placed only if they appear to be needed to minimize dilemma zone problems.

C. Monitoring— of all inputs and status of the traffic-actuated controller to determine any impending (within next 0.2 seconds or so) missed phase.
   1. Gap-out of the signal controller by monitoring CDA detector inputs and signal controller status (a monitoring task), or
   2. Any impending max-out of arterial signal phase (a watch-dog task);
   3. Output: Flash W3-4 sign beacons for all or remaining AWG time and Hold phase for same duration only if arrival traffic is operating in zone of detection of phase. This response essentially adds a trailing overlap to the impending end of the phase when the W3-4 sign has not already been turned on.

Level 1 technology provides major advantages compared to Level 0, where a trailing overlap would be applied to each phase termination, thereby loosing all dilemma zone protection and increasing traffic delays. When Level 1 AWEGS estimates that the signal controller is about to gap-out the phase (say within the next 0.2 seconds), then Level 1 AWEGS checks to see if the approach is clear from the ADA detector to the stopline. If clear, then no action is taken (in particular no hold is placed on the ending phase which might further delay traffic stopped at the intersection and loose dilemma zone protection of traffic that might arrive during the hold time). The phase should gap-out shortly thereafter with the flash synchronized to start with yellow onset (judged a more desirable visual scene to more distant motorists approaching the signal), instead of possibly 0.2 seconds earlier.

Level 2 provides the additional gap-out feature of variable hold times. The main efficiency advantage during imminent gap-out ("fire" conditions) is the determination of whether a hold is needed, based on the approach vehicle's type and speed, to provide dilemma zone protection. Typically, cars would have to be traveling faster than the design speed of the CDA detector set (Nader's Guide) for them to need a hold and be located very close to the CDA detectors; most faster trucks located in the ADA-CDA zone would merit a hold be place to allow them to reach the CDA detectors.

COMMON TEXAS PRACTICE

Texas Department of Transportation does not currently have an official high-speed detection system plan or standard layout. However, a detection layout developed by a former TxDOT traffic engineer is widely used in the field. As noted previously in Table 2, this unofficial practice is known herein as Nader's Guide (*24*). Both field sites where our AWEGS were deployed used this layout. The development and assumptions of Nader's Guide are unpublished, but it has been researched by others to some extent (*25*, *26, 27*).

Nader's Guide provides two or three high-speed detectors per approach, depending on speed. These detectors are 6-foot by 6-foot ILD operating in the presence mode. A stopline area detector may be installed to detect local driveway calls where both intersecting highways are major roads. Otherwise, a minimum recall is usually placed on the major road, and the stopline detectors for it are omitted. Spacing and distance from the intersection stopline increase with approach speed (i.e., the speed limit or the 85th percentile speed, if known to be higher). The ILDs are assumed to be operating in the presence mode without delay for the phase's passage gap shown for each approach speed.

Analysis of Nader's Guide

Nader's Guide for detector layout commonly found today on Texas highways is significantly different from that used by many Texas traffic engineers in prior decades (*4*). Whereas the design shown in Table 2 has uniform spacing between detectors for a given speed (*24*), the prior multiple-loop design (*4*) had variable spacing between the detectors. The prior multiple-loop design operated much like a speed sieve, gapping-out only those vehicles that could safely and would likely stop based on their individually measured speeds, as those motorists approached the intersection. The speed-sieve result was achieved by systematically reducing the spacing between the detectors (sometimes as many as five detectors for high-speed approaches) as the loops were installed in the roadway proceeding toward the intersection. It is unknown why this change was made (*26*). Current Texas practice will basically gap-out all vehicles traveling less than the critical speed for existing conditions, especially at low-volume conditions.

The AWEGS design developed in this research is based on the traffic operations expected to arise from the deployment of Nader's Guide detector layout. As noted above, both field sites in this research used the layout. While we have analyzed the method to better design and operate AWEGS in the field, neither optimization nor improvement of Nader's Guide has been attempted, based on the scope of this research. Some data and guidance are provided, however, regarding potential gap-out impacts of size of passage gaps on the traffic signal controllers in the field.

The critical speed, or slowest speed that will not gap-out for each detector speed group used in Nader's Guide, can be readily calculated based on the noted uniform spacing between detectors and given signal timing. The basic formula is:

$$v_c(fps) = \frac{X_i - X_{i+1} - L_d - L_v}{PGap} = \frac{S_v - L_{d+v}}{PGap} \cong \frac{S_v - 22}{PGap} \qquad (1)$$

where:

v_c	=	critical gap-out speed for Nader's Guide, feet per second, fps;
$PGap$	=	passage gap of traffic-actuated controller phase, seconds,
S_v	=	spacing between detectors for approach speed group, v , feet; and
L_d, L_v	=	length of detector (6 feet) and vehicle (16 feet), respectively, feet.

The probability of an arriving vehicle gapping-out while traveling between the first (CDA1) and second (CDA2) detectors during light traffic (assuming no other vehicle being in the detection zone) is the probability that the vehicle's speed is less than the critical speed, or

$$\Pr obGO(v_c) = \Pr ob(v \le v_c), v \Rightarrow N(v_m, \sigma) \qquad (2)$$

where it is assumed that arrival speeds, v, are normally distributed with a known mean, v_m, and standard deviation, σ, of speeds. For this analysis, a coefficient of variation ($cv = \sigma / v_m$) of 0.13 was assumed.

An analysis of two cases—Nader's Guide and the Institute of Transportation Engineers (ITE) driver behavior parameters widely used (*28*) for timing yellow change intervals—are given in Table 3. It is assumed that the design speed is the 85th percentile speed. For example, for a 45 mph approach (design) speed, the critical speed that will hold the phase green against conflicting calls (with a 2.0 second passage gap) is 33.41 mph. Traffic is traveling at speeds less than this critical speed is 10.58 percent, and therefore these vehicles would be expected to gap-out between the CDA1 and CDA2 detectors. Most critical is the 70 mph design with a passage gap of 1.2 seconds, which has a critical speed of 58.52 mph, where 34.76 percent of the traffic would gap-out while crossing the Guide's layout. Here 32.32 percent of the traffic would be exposed to potential deceleration rates exceeding ITE design guidelines for signal timing (nearly 96 percent of those gapping-out).

Table 3. Analysis of Texas Practice Compared to Institute of Transportation Engineers Criteria for Signal Change Interval Timing.

85th percentile Approach Speed, mph	Nader's Guide [a]		ITE Design Criteria [b]		Coverage of ITE Criteria	
	Critical Speed, Mph	Probability of Gapping-Out [c]	CDA2 Safe Stopping Speed, mph	Arrivals Exposed to ITE Stop, percent	CDA2 Cover Passage Gap, seconds	Prob. Gap-out with Full Cover
45	33.41	0.1133	25.16	11.08	2.66	0.0022
50	36.82	0.1034	25.88	10.26	2.85	0.0007
55	41.48	0.1341	32.35	12.88	1.54	0.0047
60	37.99	0.0152	35.49	0.95	1.50	0.0051
65	50.00	0.1647	38.41	15.90	1.56	0.0051
70	58.52	0.3476	40.66	32.32	1.73	0.0039

[a] Nader's Guide as shown in Table 2 (*24*).
[b] ITE perception-reaction time T = 1.0 seconds, acceptable deceleration rate = 10 fps^2 (*28*).
[c] Assumes approach speeds distributed normally with a coefficient of variation of 0.13.

A graphic examination of the probability of a single arrival gapping-out while traveling over Nader's Guide is presented in Figure 10. For example, the probability that an arriving vehicle taken from a normal distribution of speeds would gap-out while driving over a 45 mph design speed layout (= 85th percentile approach speed) would be 11.33 percent when the passage gap set in the controller is 2.0 seconds. Figure 10 shows the gap-out probability increases to 66 percent if the passage gap were reduced to 1.6 seconds.

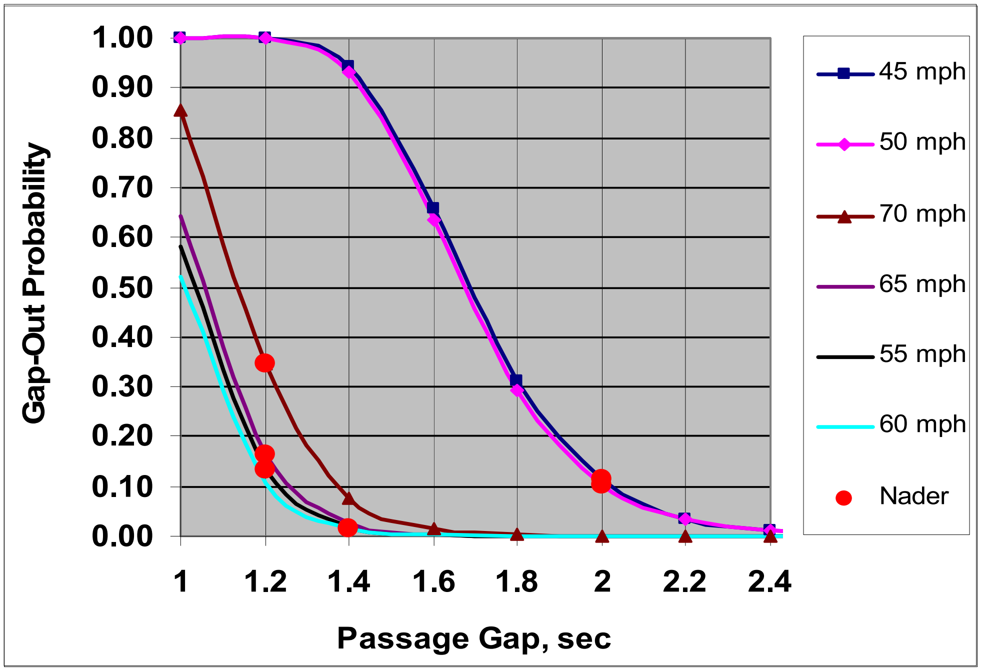


Figure 10. Gap-Out Probability of Nader's Guide as a Function of Passage Gap.

An examination of Table 3 and Figure 10 provides several revealing results. There are inconsistent gap-out probabilities (column 3) across the speed ranges in Nader's Guide, being much larger at the higher speeds of 65 to 70 mph. Low speeds of 45 and 50 mph have a remarkably higher gap-out probability than the other speeds for a given passage gap. There are similarly high percentages of vehicles exposed to "unsatisfactory" stopping possibilities, based on the ITE stopping criteria (column 4) with 32.32 percent (column 5) of those vehicles arriving at an approach speed of 70 mph being so exposed upon phase gap-out in light traffic. During low traffic volumes, 34.76 percent all gap-outs will occur between the first (CDA1) and second (CDA2) detectors. In order to fully cover all vehicles potentially exposed to unsatisfactory stopping conditions following gap-out (that is, from being in their respective dilemma zones as defined from the above ITE criteria), the passage gaps listed in column 6 would be needed to provide reliable service, as a minimum, given Nader's Guide for detector spacing.

An important finding when full ITE coverage is provided by using the passage gaps of column 6 of Table 3 is that almost no vehicles for any speed would then likely gap-out the arterial phase (column 7) while traveling over the detectors. This no intermediate gap-out result would produce longer maximum allowable headways (MAH), thereby increasing the cycle time and resulting traffic delays at the intersection (*25*). This situation is truly a design dilemma within Texas practice. Our two field study sites (at Waco, having a 60 mph approach speed, and at Brenham with a 70 mph approach speed) both were observed to have

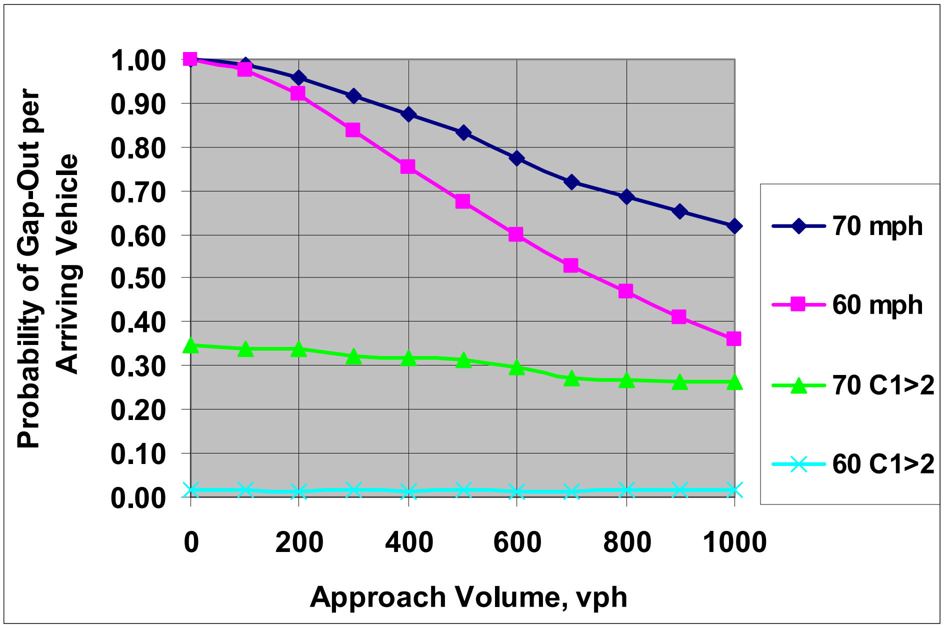
2.0 second passage gaps installed for their respective arterial phases. This timing reflects the field adjustment traffic engineers may apply where Nader's Guide has been by engineers to specify the original dilemma zone detection layout.

Simulation Studies

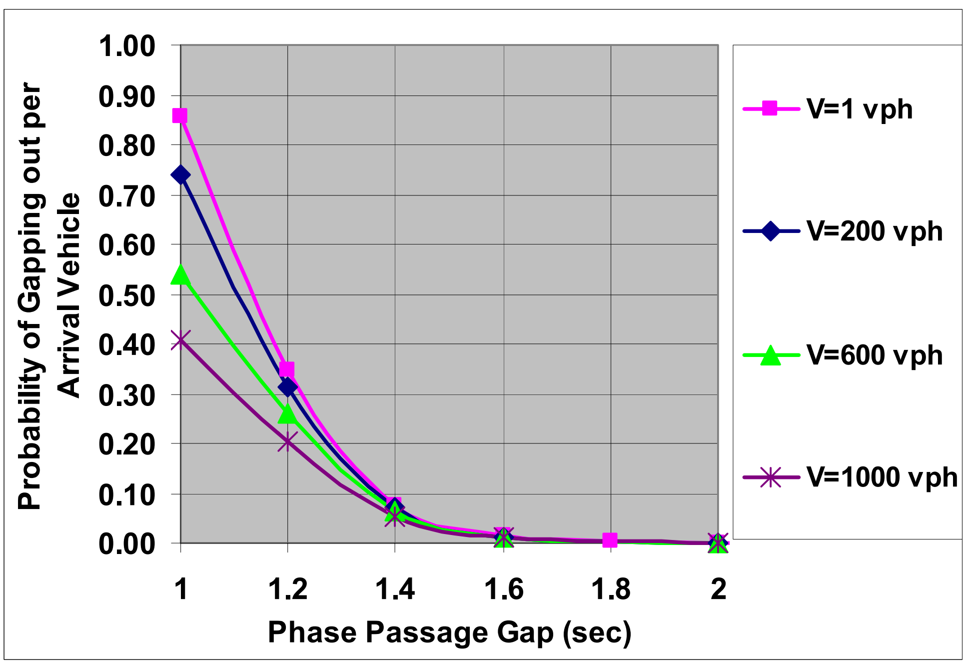
Computer simulation studies using Excel were conducted to further examine these issues and to determine the effect traffic volume has on gap-out probabilities of common Texas practice using Nader's Guide. In these simulation studies, it was presumed that the signal phase did not extend to its maximum green time allowed. Two design speeds of 60 mph and 70 mph were also studied. Again, the primary reason for conducting these simulation studies was to guide the development of AWEGS.

The simulation results for Nader's Guide detection system (of Table 2) were developed in graphic form to expedite analysis. Figure 11a presents gap-out characteristics for the 60 mph and 70 mph approach (design) speeds for a 200 vph approach volume. The upper two speed-based curves in Figure 11 a show the overall gap-out probability per arriving vehicle of the detector set using the passage gaps in Nader's Guide; whereas, the lower two curves depict comparative gap-out results only between the first two detectors (CDA1 –> CDA2). The 70 mph design was shown to be much more likely to gap-out a vehicle crossing the first two detectors than would the 60 mph design. Figure 11b provides simulation results of the same intra-detector (CDA1 –> CDA2) probabilities as related to the size of passage gap and approach traffic volumes for the 70 mph design speed case. Increasing the size of the passage gap is seen to significantly reduce the intra-gap-out probability, together with increasing traffic volumes.

It is noted that increasing traffic volume decreases the likelihood of either system gapping-out for any randomly arriving vehicle. However, Texas practice designs clearly will have many slower vehicles falling through the cracks than will the 2.0-second timing, particularly for the 70 mph case where about 30 percent or more of the arriving vehicles would be expected to fall through as would be expected from Table 3. The 2.0-second gap timing will almost never gap-out between the CDA detectors. In fact, the two lower curves of the 2.0-second fix are indistinguishable from zero probability. However, the 2.0-second fix will more likely extend the phase to maximum green in higher volumes, also an undesirable outcome, as can be inferred by comparing the total gap-out probabilities given by the upper speed-based curves between the two figures.



a. Simulation results for 60 and 70 mph approach speeds.



b. Simulation results for 70 mph approach speed for various volumes.

Figure 11. Probability of Phase Gap-Out per Randomly Arriving Vehicle for Nader's Guide Detection as Related to Approach Volume and Passage Gap from Simulation.

Summary

The upshot of these simulation results is notable for designing AWEGS in Texas. Traffic operations to be expected from signalized intersections using Nader's Guide are very sensitive to passage gap timing for some speed groups, and their individual MAH are very different, which makes predicting gap-outs challenging. If the passage gap set in the controller produces a critical speed which contains a sizeable percentage of arriving vehicles, then a proportionate number of those vehicles will gap-out between the first two detectors. Such a short gap will produce a highly variable MAH. Long passage gaps will likely cause vehicles to gap-out only at the end of the detector set near the stopline. This setting produces a very low likelihood of gapping-out between the multiple-loop CDA detectors.

Consequently, two types of gap-outs may descriptively occur—the crack-outs and the trail-outs—depending on the speed of the vehicle and passage gap set in the controller for the phase. It appears (from Figure 11) that most will be the trailing type if the 2.0-second passage gap currently employed in the controllers at the two study sites exists. The simulation studies indicate that passage gaps of 1.6 seconds or greater produce little chance of inter-detector gap-out (no falling through the cracks) using Nader's Guide. Thus, a reliable estimate of the overall passage gap and maximum allowable headway for any design speed can be estimated, given that longer passage gaps are (likely) used in the controller.

ESTIMATION OF NADER'S EFFECTIVE PASSAGE GAP

For AWEGS to be able to predict that a traffic-actuated signal controller is going to gap-out a phase currently extending in green against conflicting traffic demand, the effective passage gap of any detector design must be estimated for any given traffic speed and passage gap set in the controller. Theoretically, this situation was a major challenge in the research and development of AWEGS. To begin, it is assumed that passages gaps will be used to minimize intra-detector gap-out, as noted in Table 3 and from field observations. It is also known that a general relationship exists between traffic flow theory of traffic headways (elapsed time between arrivals of vehicles at a point for a given speed) and operational passage gaps between vehicles, assuming that ILDs are measuring their arrival. We now can assume (for specified conditions) that Nader's Guide layout will act like a very long present loop for most passage gaps set. The basic relationship in (maximum) headway terms is (*25, 26, 27*):

$$MAH = P + Gap = \frac{l_{dz} + l_v}{v_{sh}} + PassGap \qquad (3)$$

where:

MAH	=	maximum allowable headway for a given condition, seconds;
P	=	presence time (average) over the initial detector, seconds;
l_{dz}, l_v	=	length of detection zone and vehicle (average) being measured, feet;
v_{sh}	=	average space-mean speed of holding traffic, feet per second; and
$PassGap$	=	passage gap (estimated to be) set for signal phase of interest, seconds.

Understanding the cause-effect of Equation 3 is critical to understanding how AWEGS works. If *PassGap* is set in the controller, then MAH is the resulting critical traffic headway that would gap-out the phase. That is, any vehicle following another vehicle at a headway greater than MAH would not hold the extending phase green, and the yellow warning interval would begin. Please note that l_{dZ} is a function of speed in Nader's Guide and does not vary consistently with speed. The speed, v_{sh}, is very difficult to calculate, so the Excel simulation was used to calibrate the above model form to Nader's design conditions. Initial studies examined only the 60 and 70 mph design conditions, as depicted in Figure 12. Observations of the small differences for the two speeds permitted averaging the results using statistical regression. The following linear regression equation was developed:

$$MAH = 2.46 + 1.31 PassGap \tag{4}$$

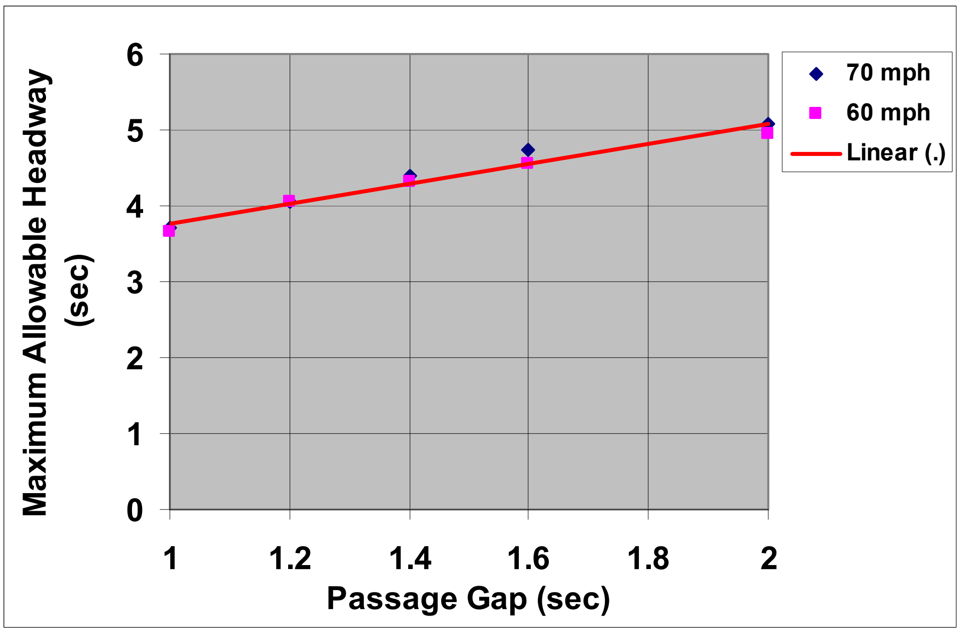


Figure 12. Estimated Maximum Allowable Headway as Related to Passage Gap Set in Controller for 60 and 70 mph Design (Approach) Speeds for Nader's Guide Detection.

Equation 4 produces results very similar to those previously estimated by Bonneson et al. using the same speeds in Nader's Guide (*27*). These results somewhat verified the Excel simulation modeling, and the model development continued along the same lines keeping the objectives in mind. AWEGS needs an equivalent single-detector passage gap from which to estimate an impending gap-out condition, given the *PassGap* set in the controller, and local site parameters. That is:

$$MAH = \frac{l_{dz} + l_v}{v_{sms}} + PassGap \cong \frac{l_{dz} + l_v}{1.467 * V_{85AW} / 1.17} + PassGap \quad (5)$$

where:

$V_{85AW} =$ design speed (85th percentile approach speed) of AWEGS for a given Nader's Guide layout and presumed local 85th percentile speed, mph.

If the length of the detection zone (l_{dz}) is defined as

$$l_{dz} = (n_d - 1) * \Delta X + l_d = (n_d - 1) * (CDA_2 - CDA_1) + l_d \quad (6)$$

then the effective passage gap ($PassGap_{AWEGS}$) of Nader's Guide can be found from

$$MAH = \frac{(n_d - 1)(CDA_2 - CDA_1)}{v_{sh}} + \frac{l_d + l_v}{v_{sh}} + PassGap$$

$$MAH - \frac{l_d + l_v}{v_{sh}} = PassGap_{AWEGS} = \frac{(n_d - 1)(CDA_2 - CDA_1)}{v_{sh}} + PassGap \quad (7)$$

Level 1 Effective Passage Gap

Thus, the effective passage gap to be used in AWEGS for Level 1 technology can be estimated, here assuming a three-detector dilemma zone set, from

$$PassGap_{AWEGS} = \frac{CDA_3 - CDA_1}{v_{sh}} + PassGap = \frac{CDA_3 - CDA_1}{1.467 * V_{85} / 1.17} + PassGap \quad (8)$$

From which is developed the method for estimating an equivalent single-detector passage gap as used in Level 1 AWEGS:

$$PassGap_{AWEGS} = \frac{0.800 * (CDA_3 - CDA_1) * (1 - Pgout)}{V_{85}} + PassGap \le n_d * PassGap \quad (9)$$

where:

$PassGap_{AWEGS} =$ effective passage gap used in Level 1 AWEGS, seconds:
CDA_i = distance to stopline of detectors $i = 1,2,3$ in Nader's Guide, feet;
n_d = number of detectors in a set { i } in Nader's Guide;
V_{85} = design (or 85th percent-tile approach) speed of the detector set, mph.

1.17	=	calibration factor from 85th percentile to 50th percentile speed, and conversion from time- to space-mean speed. This value was determined from simulation as a theoretical value of 1.1212 plus some adjustment for multiple activations, even at low volumes. A 7 mph standard deviation in speed was assumed for this calculation; and
Pgout	=	probability of detector layout gapping-out per arriving vehicle, given its design speed and controller *PassGap,* which is assumed to be zero.

Level 2 technology measures the speed of all arriving vehicles. If the average speed of the traffic stream increased on an approach for a given detector layout (and design speed), the average travel time over the layout would decrease, and the effective passage gap would therefore decrease if the original traffic speeds were all greater than the critical speed for gap-out of the loops. Equation 9 suggests this inverse relationship. However, if the original traffic speeds were too slow for the design in place, then increasing the traffic speeds would result in fewer gap-outs such that the overall average passage gap might increase for a while, and then it would begin to decrease as noted above.

A complex theoretical model of this process has been developed but is considered beyond current needs. Suffice it to note that all current AWEGS operations assume that the original passage gaps set in the controller are sufficient to provide a minimal intra-detector gap-out probability. An Excel spreadsheet was developed which provides application guidance on this subject beyond what is suggested from Figure 12. This spreadsheet is available at http://ceprofs.tamu.edu/cmesser, subdirectory AWEGS.

TRAVEL TIME APPLICATIONS IN LEVEL 2

The main feature of Level 2 technology in AWEGS is the measurement of an individual vehicle's travel time (or speed) across the upstream AWEGS trap detectors, ADA and BDA. A typical detector layout for AWEGS Level 2 was presented in Figure 9. The recommended head-to-head spacing $\left(X_{ADA} - X_{BDA}\right)$ between the ADA and BDA ILDs is 30 feet, as shown in Figure 9. Thirty feet should be long enough to provide accurate travel time measurement, given the computer's scan rate. The recommended gap spacing between the detectors is 24 feet. One might call these detectors speed-trap detectors such that speeds of individual vehicles could be calculated from

$$v_i(t) = \frac{X_{ADA} - X_{BDA}}{ttAB_i} = \frac{30'}{ttAB_i} \qquad (10)$$

but the AWEGS design question is: "Why calculate speed?" Except for providing the engineer some reference to local speed zones and travel speeds, there is little reason to use speed directly in a traffic signal control system. For example, most traffic signal technicians call traffic signal controllers timers basically because controllers work almost exclusively with times of and between local traffic events: phase times, yellow times, gap times, etc. Likewise, AWEGS Level 2 works only with time, not a derived speed.

DYNAMIC PREDICTION OF CRITICAL PASSAGE GAP

AWEGS needs accurate estimates of (1) the time gap between arriving vehicles and (2) the signal controller's effective critical gap for the given CDA detector pattern and passage gap set in the controller for the phase. The overall problem of predicting if and when the downstream traffic-actuated signal controller may gap-out an existing green phase between arriving vehicles, when conflicting calls for service exist, is composed of two steps: (1) a forecast of the likely critical passage gap and (2) a follow-up prediction of the actual gap once the next arriving vehicle is detected, assuming the gap-out question remains. As vehicles arrive at the ADA/BDA advance speed-trap detector set, their projected arrival time at the CDA1 detector is predicted, as depicted in Figure 13. Since the arrival time or speed of the next arriving vehicle is not immediately known, a forecast (a back calculation) of the critical arrival time for the next vehicle is made, assuming it would be traveling at the average speed of traffic. The corner points of the trapezoidal shapes are calculated as described below. Projection lines from a vehicle are not coincident because traffic gaps must account for vehicle length. Predicted event times are immediately updated as new arrival data become available to AWEGS.

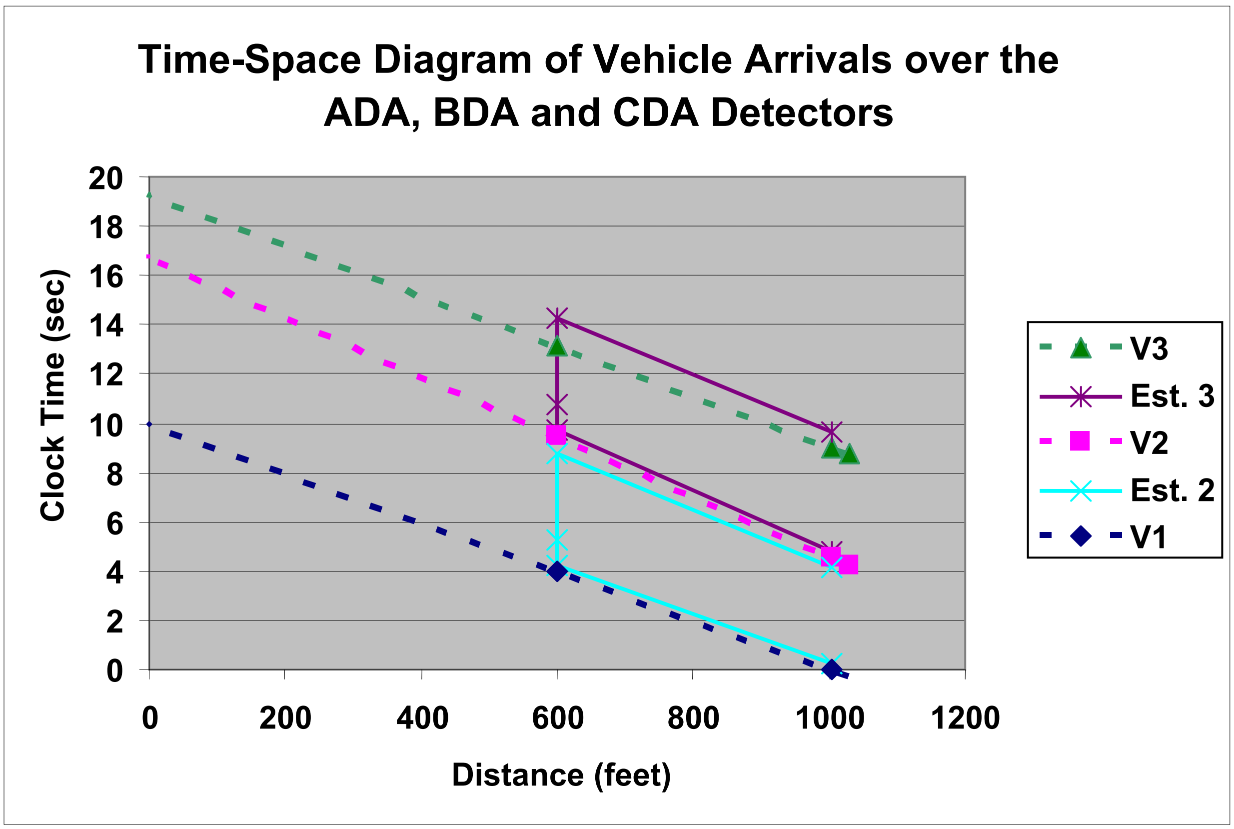


Figure 13. Example of Time-Space Diagram of Vehicle Arrivals and Forecasted Gaps between Vehicles.

Forecast of Gap between Vehicles

Estimation of the actual headway gap between two vehicles, *i* and *i-1*, per lane can be determined from the prediction of arrival times (*AT*) of vehicles at the CDA detector set and the application of basic safe car-following logic, as follows:

$$AT_{i@CDA} = T_{i@BDA} + ttBC_i \tag{11}$$

subject to a minimum safe car-following headway and related gap at the CDA1 detector of:

$$AT_i \geq AT_{i-1} + MinSH \geq AT_{i-1@CDA1} + P_i + MinSGap \tag{12}$$

where P_i is the presence time of vehicle *i* as measured while traveling over the ADA detector.

We assume that all high-speed approach vehicle detectors are of the same design and length. AWEGS uses the latter formulation (Equation 12) to better account for long trucks with the *MinSGap* set at a nominal value of 1.0 seconds. The design requires that the travel time between the advance speed-trap detectors and the standard TxDOT dilemma zone detectors ($ttBC_i$) of each detected vehicle be estimated in real time.

1. Travel Time

The travel time of every vehicle crossing the ADA to BDA detectors is measured in milliseconds, ms, from which travel times associated with vehicle *i* are determined from:

$$\begin{aligned} ttAB_i &= measured\ travel\ time(ms) \\ ttBC_i &= \frac{X_{BC}}{X_{AB}} * ttAB_i \end{aligned} \tag{13}$$

where the predicted travel time from the BDA to CDA detectors is directly proportional to the respective travel distance ratio as determined from the locations of the detectors.

2. Critical Arrival Time at CDA1

Assuming that vehicle *i* has arrived at the BDA detector prior to AWEGS deciding that the active green phase will soon gap-out (as noted below, or has just gapped out), the arrival time of vehicle *i* at CDA1 (the leading dilemma zone detector) is compared to the critical phase gap-out time. The question of extending the phase, or gapping-out the phase is resolved from:

Extend:

$$AT_i \leq CGAP_{i@CDA1} = AT_{i-1} + P_{i-1} + PassGap_{\phi} \tag{14}$$

Gap-out:

$$AT_i > CGAP_{i@CDA1} = AT_{i-1} + P_{i-1} + PassGap_{\phi} \tag{15}$$

where $PassGap_N$ is the effective single-detector passage gap for the signal phase, as used in Level 1 technology (see Equation 9)

3. Critical Lag Time at ADA

However, AWEGS may have already decided (with a high confidence at low to moderate volumes) that the downstream signal phase will soon gap-out (against a conflicting call) because vehicle *i* did not arrive at the BDA detector by its critical gap time. AWEGS will wait only so long for the next vehicle to arrive. The critical wait (hot) time set for the ADA detector is estimated from:

$$CHotT_{i@ADA} = CGAP_{i@CDA} - MTAC_{i-1} \tag{16}$$

where *MTAC* is the current mean travel time, as measured by AWEGS, from the ADA to CDA detectors. Vehicles arriving at the ADA detector before their hot time but traveling slower than the average speed might not arrive at the CDA detector soon enough to extend the phase. All vehicles traveling faster than the average would hold the phase in green. This is a major operational improvement of Level 2 over Level 1 (constant mean speed) technology.

Estimating the Current MTAC

AWEGS provides an exponential smoothed running average of the expected travel time (*MTAC*) downstream between the ADA and CDA1 detectors. Adaptation to current long-term traffic and environmental conditions is a design objective. Adjustment to time of day impacts, such as related to hourly volume changes, light-to-dark-to-light visibility conditions, and day of week effects, are anticipated together with those weather-related environmental impacts due to rain, ice, sleet, and snow. Short-term traffic effects, such as due to platooning, may also be sensed. Significant improvement in speed prediction is expected as errors in the original database (presumed to be collected from a prior traffic study) grow due to aging of the database and as local conditions routinely change. The exponential smoothing method used is as follows:

$$MTAC_i = MTAC_{i-1} + BETA * (ttAC_i - MTAC_{i-1}) \tag{17}$$

where *BETA* is the exponential smoothing (sensitivity) factor, and whose inverse represents the "sample size." A *BETA* of 1 would imply that the current estimate of the true mean (a sample size of 1) would be that of the last vehicle measured. A *BETA* of 0.0 suggests that the current estimate of the mean would remain the original value stored in the database ($MTAC_0$) i.e., an infinitely large sample size would be collected before a new value is estimated. AWEGS currently uses *BETA* = 0.05, or an equivalent sample size of 20 vehicles. The lower the *BETA* value, the lower the sensitivity to current traffic conditions. *BETA* values as low as 0.01 appear equally attractive. Experience may suggest a better starting value for *BETA*, or later adjustments to the value. Travel times used to estimate *MTAC* are taken only when the downstream signal is green.

Another important AWEGS design feature is how it responds to detector failure or otherwise questionable detector input data. But what constitutes a detector failure? Quality control limits are defined to assist in this determination.

Quality Control Limits

The ability of travel time and speed measurements to represent normal traffic flow is defined in AWEGS by upper and lower quality control limits. Measured speed and travel time could be too high or too low to likely be a true measurement of actual unimpeded through-traffic operations. Low-speed traffic may be detected that is (a) turning into or out of local driveways, (b) turning at the downstream intersection, or (c) arriving on red behind a stopped queue. Moreover, lane changing or passing may also affect travel time measurements. Providing warning for end-of-green for high-speed through traffic is a specific goal of AWEGS, so high-speed traffic should be retained and addressed. Only unlikely super high-speed measurements are considered suspect, and they are reset to the upper speed control limit.

The basic assumption of AWEGS quality control of real-time measures is that individual and sample mean travel times collected approximately 10 seconds travel time upstream of signalized intersection during green are normally distributed. Following some preliminary study of field data and simulation results, a *ProbT* (a rejection probability) = 0.00135 (or a *t* or *z* statistic of 3.0) producing one rejected low and one rejected high vehicle in a sample of 740 arriving vehicles) has been selected as the confidence level.

We assume that the local district traffic engineer would have the following spot-speed traffic data available to him/her for each direction of flow along the high-speed roadway approximately 1000 feet in advance of the signalized intersection of interest. As an example:

Mean (50^{th} percentile) speed, mph =	55.9
85^{th} percentile speed, mph =	62.7

The usual speed zoning sampling criteria would seem appropriate: at least 125 free-flowing vehicles. These data should also be used to establish the original locations of the ADA and BDA detectors and to check the correctness of the locations of TxDOT's CDA detectors. From the above field data coded into the system, AWEGS calculates the following statistics and quality control criteria:

Standard Deviation: *SIGMA* = (V85-V50)/1.04 [=6.538]
Coef. of Variation: *CoV* = *SIGMA*/Mean Speed [=0.117]
ALPHA = *ProbT***CoV* [=0.351]

AWEGS general form for setting upper and lower quality control limits also employs *BETA*:

$$LL = \frac{ttM_d}{(1 + ALPHA * \sqrt{BETA_d})} \qquad LL = \frac{ttM_{s/BC}}{(1 + 0.351 * \sqrt{0.05})} = 0.927 * ttM_{s/BC}$$

$$UL = \frac{ttM_d}{(1 - ALPHA * \sqrt{BETA_d})} \qquad UL = \frac{ttM_{s/BC}}{(1 - 0.35 * \sqrt{0.05})} = 1.085 * ttM_{s/BC}$$

where *BETA* = 1 for individual vehicle measurements, and *BETA* = 0.05 for exponentially smoothed running averages shown above, given the mean travel time from B to C.

Calculation of a space-mean travel time from a spot-speed study requires adjustment from time-mean (spot) speed to space-mean speed (and corresponding reciprocal adjustment to related travel times). AWEGS adjusts the base mean travel time by:

$$V_s = V_t(1 - CoV^2)$$

$$ttM_s = \frac{X_d}{V_s} = \frac{X_d}{(1 - CoV^2)V_t} = \frac{1}{1 - CoV^2} * ttM_t$$

$$ttM_{s/AC} = SMSF * ttM_{t/AC}$$

$$SMSF = \frac{1}{(1 - CoV^2)}$$

$$V_s = (1 - 0.117^2) * V_t$$

$$V_s = 0.986 * V_t = 0.986 * 55.9$$

$$V_s = 55.1\, mph$$

$$ttM_{s/AC} = 1.014 * ttM_{t/AC}$$

where:

V_s	=	space-mean speed, fps;
V_t	=	time-mean speed, fps;
ttM_s	=	space-mean travel time, seconds;
ttM_t	=	time-mean travel time, seconds;
CoV	=	coefficient of variation of speeds (here assumed to be 0.117); and
$SMSF$	=	space-mean speed factor (here *SMSF* =1.014).

Predicting Critical Gap of Arriving Vehicle

AWEGS Level 2 processing of the gap-out question continues as described above until either AWEGS determines that the phase will gap-out (i.e., predicts a "fire" state) or another vehicle is noted arriving on the ADA detector. Once its time of arrival and speed (travel time) are determined, only one small decision process error could possibly occur, if gap-out has been forecasted, assuming a true conflicting call. It is possible that this is a very fast vehicle (unknown to AWEGS until this moment) which has arrived at ADA just after its $CHotT_i$ time, but it can still get to the downstream CDA1 detector before its $CGAP_{i@CDA1}$ time. AWEGS has no way of knowing that such a high-speed vehicle will arrive just after deciding that the phase will soon end (i.e., the $T_{i@ADA} > CHotT_{i@ADA}$). This likelihood is very low and is estimated to be less than 1 percent of these termination cases at an arrival volume of 400 vph within a travel time delta of 1.0 seconds. Level 1 also faces this same problem, so Level 2 operation adds no deficiency.

Metamorphosis—Method of System Protection from a Detector Failure

A system that depends heavily on quality data inputs from two traffic detectors located in the roadway, as Level 2 AWEGS does, should be designed to operate effectively should one of the ADA/BDA detectors per lane either: (a) fail, due to a mechanical problem, or (b) miss detecting a passing vehicle. AWEGS is so designed using the above quality control limits. An exogenous mean travel time is always available from the basic input data for each approach. Should either one of the ADA/BDA detectors fail, then a long travel time since last activation would be calculated, and this travel time would be rejected by the upper travel time limit. AWEGS is programmed to replace the false long travel time with the mean travel time for that vehicle. Should the detector failure continue over an extended period of time, then the resulting running average will slowly drift toward the stored mean travel time for the approach (as if it were operating with Level 1 technology). Should one detector fail on each approach, AWEGS will slowly change from a Level 2 to a Level 1 system, as if it were in a state of metamorphosis. Should the problem detector begin working again, AWEGS will then slowly return to a Level 2 system without reprogramming or recoding any data.

Super high-speed vehicle calculations (very short travel times being measured) are also likely to be false, but the AWEGS design response reflects possible consequences of them being true, however unlikely The super-short travel times are replaced with the current lower limit travel time, which would reflect a very fast but still plausible speed being measured. In this regard, it is important that trucks do not lose measured loop presence as they travel over the individual inductive loops, thereby producing erratic and/or misleading speed measurements.

VARIABLE HOLD TIME

One of the major advances of the speed-sensitive Level 2 technology provided in AWEGS is the capability of efficiently addressing potential dilemma zone issues facing very high-speed traffic approaching the intersection on green while simultaneously minimizing the frequency and magnitude of phase hold times applied by AWEGS to the signal system. These targeted speeds could be well above the speed limit. Level 1 operation can not determine a very fast vehicle from a very slow vehicle.

Level 1 provided an inefficient phase hold signal operation. To ensure adequate end-of-green warning was provided for high-speed traffic using Level 1 technology, *all* approach traffic was assumed to be high-speed traffic when a phase was predicted to end; i.e., its condition was now judged hot. A fixed phase hold of about 5.0 seconds was placed on the hot actuated phase, i.e., one that was dwelling in green rest (gapped out but no conflicting call exists), and then a cross-street call is suddenly detected. For a phase hold to be placed on a hot phase, at least one approach vehicle must be detected between the ADA and CDA1 detectors when the conflicting call was received.

The idea of providing dilemma zone protection for only very high-speed traffic (say from the 85th percentile speed up to the 99th percentile value) was not an original AWEGS design objective. However, providing this protection was relatively easy and served as a rational basis for minimizing the frequency and duration of phase hold times needed (and provided). Several past researchers had noted long fixed phase holds as being operationally problematic in their previous advance warning designs (*21*, *25, 27*).

This new variable hold capability greatly reduces the likelihood of the traffic-actuated phase extending to maximum green, wherein all dilemma zone protection would be lost and much unnecessary delay caused the motoring public when traffic volumes are high. In addition, dilemma zone protection for truck traffic can also be readily provided to a large extent by judicious selection of the space gap between the 6-foot by 6-foot ILDs used for the ADA and BDA speed-trap detectors.

Dilemma Zone Protection

Numerous research papers have been written regarding dilemma zones. The interested reader might start with recent works from Canadian researchers (*21*) and by Bonneson and McCoy (*25*). An advance warning system that can also minimize the number of vehicles in their dilemma zone at yellow onset is also likely to reduce red-light-running (*27*). Dilemma zones can be defined as time-based or space-based zones. Most researchers usually show space-based zones so that approach detection can be located along the roadway (*27*). However, equivalent time-based dilemma zones are more useful for AWEGS. Time-based dilemma zones have a leading- and trailing-edge travel time to the intersection defined for each vehicle's speed/travel time as:

1. Leading Edge, sec:

$$ttDZ_{le} = T_{PRle} + \frac{v}{2d_{le}} = T_{PRle} + \frac{X_{AB}}{2 * d_{le} * tt_{AB}} \qquad (18)$$

2. Trailing Edge, sec:

$$ttDZ_{te} = T_{PRte} + \frac{v}{2d_{te}} = T_{PRte} + \frac{X_{AB}}{2 * d_{te} * tt_{AB}} \quad (19)$$

where the new variables are defined in Table 4. The dilemma zone for a vehicle is the time domain between the leading and trailing edges of the zone.

Table 4. AWEGS Parameters Recommended for Determining Dilemma Zones of Drivers in Cars or Trucks Approaching Traffic Signals at High-Speed at Yellow Onset.

Vehicle Type	Vehicle Length, feet	Leading Edge *Le*	Trailing Edge *te*	Leading Edge *Le*	Trailing Edge *Te*
		Perception-Reaction Time $T_{PRle,}$, seconds	Perception-Reaction Time T_{PRte} , seconds	Deceleration, 95 percent Stop, d_{le} , fps^2	Deceleration, 5 percent Stop, d_{te} , fps^2
Car	< 24	1.2	0.5	8.9	16.0
Truck	$24	1.2	0.5	6.2	16.0

Several points should be noted regarding the above dilemma zone formulations. First, the latter equations do not use speed directly; they use only measured travel times from the ADA to BDA detectors. Second, every vehicle (and driver) will have its own dilemma zone depending on its speed (travel time) and type of vehicle. Third, if trucks can be distinguished from cars, then truck dilemma zones can be identified for a given speed since acceptable truck deceleration rates have been estimated to be about 70 percent of those of cars (*21*, *25*). A recent Minnesota reference assumes trucks decelerate at 80 percent of cars (*22*). Drivers' perception of yellow onset, decision to stop or go, and reaction times are presumed to be the same by vehicle-driver type. Table 4 presents recommended AWEGS values for T_{PR} and $d_{u/ll}$ calibrated at 55 mph from other research (*25*).

AWEGS will identify a passing vehicle as a truck when both the ADA and BDA detectors (per lane) are simultaneously activated, and a car, otherwise. The break point for vehicle length in Table 4 was chosen to ensure that four-door crew cab ¾-ton pickup trucks with front bumper guards and rear trailer hitches, commonly found in Texas, will be classified as cars and not trucks. In a small survey, some of these larger four-door crew cab pickups were measured to be about 21 feet long (the largest measured was 21.4 feet) and many full-size sports utility vehicles are about 20 feet long. In addition, a vehicle traveling 80 mph will travel 2.35 feet in 0.020 seconds (two computer periodic scan intervals), so the gap spacing between the ADA and BDA detectors should be at least 23.75 feet (23.75 = 21.4 + 2.35), or rounded up to 24 feet, as shown. This detector design correctly identified every vehicle in a total sample of about 50 vehicles from a traffic stream having about 15 percent trucks at our rural Waco site. A large pickup pulling a horse trailer would be classified as a truck, as desired, and so would be most single-unit trucks. Shorter detector spacings of 18.8 and 19.5 feet installed at our Brenham field site usually classified large SUVs, full-size cars, and crew cab pickups as trucks, which is not the desired outcome.

AWEGS dilemma zone applications are illustrated in Figures 14 and 15. Figure 14 provides plots of the resulting travel time dilemma zone boundaries as related to Nader's Guide sometimes used by TxDOT for CDA1 detector locations, based on a design speed equivalent to the 85th percentile approach speed. Figure 15 shows the recommended ADA/BDA detector trap location is also adequate to provide dilemma zone protection for the fastest trucks likely to be encountered.

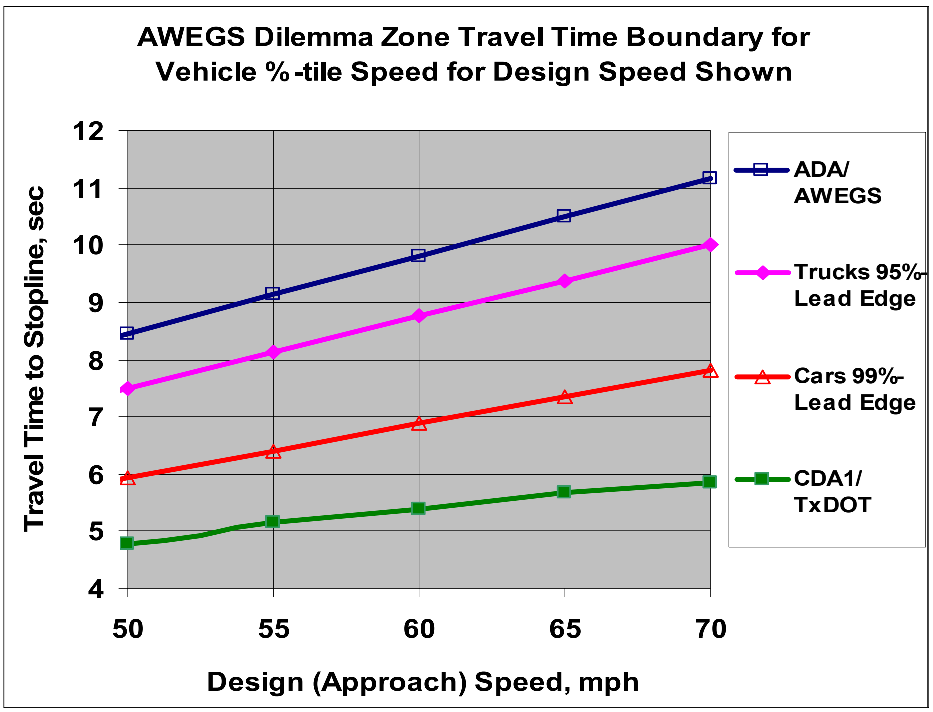


Figure 14. Travel Times to Stopline for Various AWEGS Design Elements.

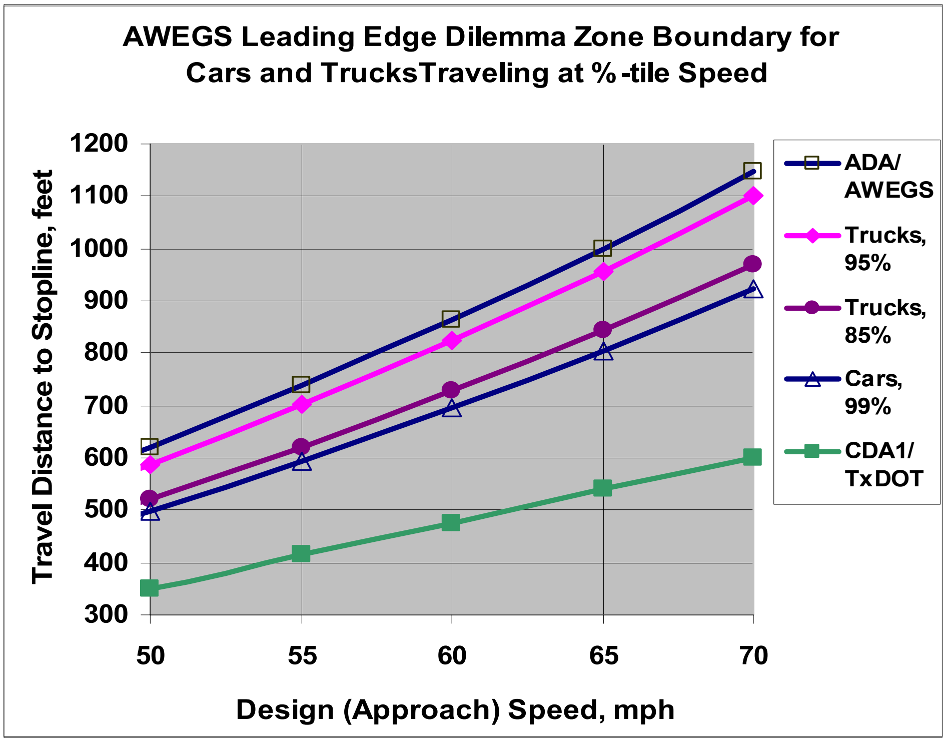


Figure 15. Distance to Stopline for Various AWEGS Design Elements on Level Grade.

VARIABLE PHASE HOLD

A phase hold is applied only for those few vehicles currently inside their dilemma zone but have not yet arrived at the CDA1 detector, which would then automatically extend the phase. AWEGS does not try to determine when the subject vehicle has actually arrived at the CDA1 detector; rather, a hold of sufficient time is placed on the extending green phase to permit such arrival. The variable phase hold is calculated from:

$$HOLD = ttDZ_{le,i} - tt_{CDA1,i} + \varepsilon \qquad (20)$$

where:

$HOLD$ = variable phase hold time for the subject through phase, seconds;
$ttDZ_{le,i}$ = travel time from leading edge of dilemma zone to stopline, seconds;
$tt_{CDA!,i}$ = travel time from CDA1 (TxDOT) detector to stopline, seconds; and
ε = a 1.0 second buffer to ensure coverage of vehicle to CDA1 detector.

An example of the variable hold process is illustrated in Figure 16 for a 60 mph design speed detector layout. Here a high-speed 67 mph vehicle is 0.40 seconds into its dilemma zone, when the conflicting call is received, and needs 0.58 second variable-phase hold for it to arrive at the CDA1 (TxDOT) leading dilemma zone detector. Once detected by the controller, detection across the remaining CDA (TxDOT) detectors will automatically extend the phase.

The following chapter describes the field studies conducted to evaluate the AWEGS previously described at two real-world study sites located in Texas. Extensive laboratory testing of the proposed hardware designs was conducted at TTI's Gilchrist laboratory using cabinet-in-the-loop technology before AWEGS was deployed at the two sites. Details of cabinet-in-the-loop testing are described elsewhere (*29*).

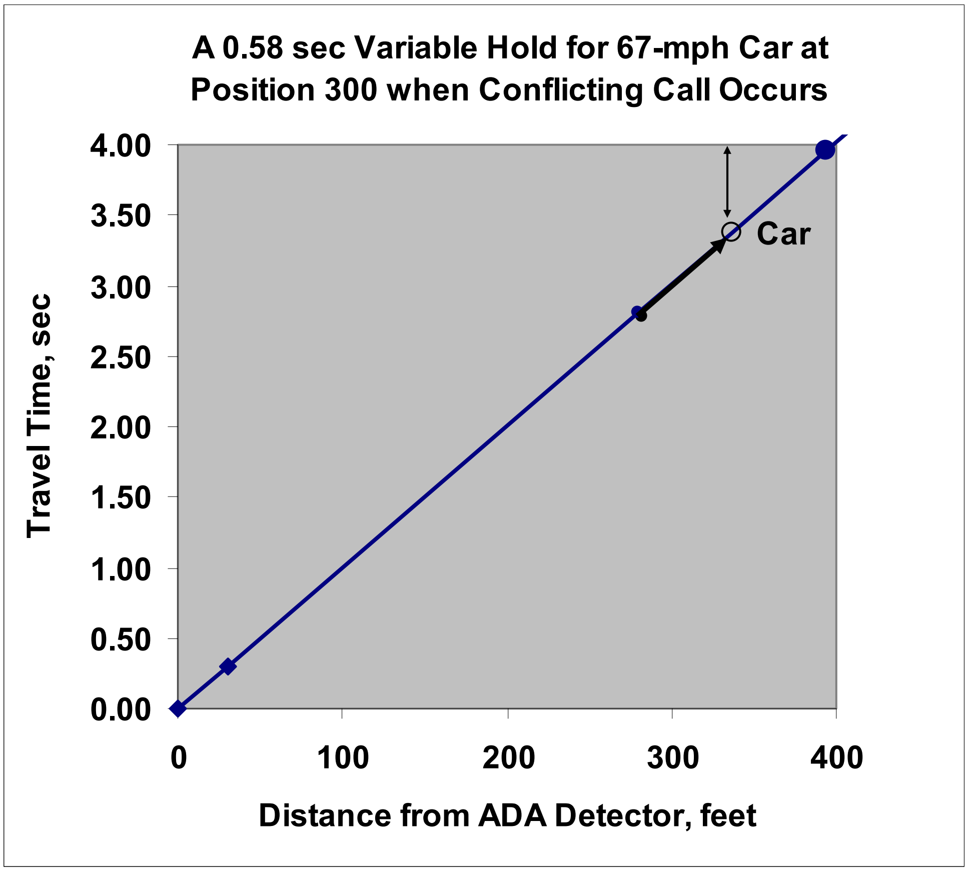


Figure 16. Example of a 0.58 Second Phase Hold for a 67 mph Arriving Car for a 60 mph Design Speed Detector Layout.

CHAPTER 5. FIELD EVALUATION OF AWEGSS

STUDY SITES

Researchers deployed two AWEGSs in the field and evaluated their performance. Two field sites were chosen as study sites due to their known potential for red-light-running. The first site was at the signalized intersection of Texas 6 and FM 185 about 6 miles west of Waco. Existing dilemma zone detection 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. Figure 17 illustrates this two-lane undivided site. Figure 8a shows one AWEGS sign installed and operating at the Waco site.

Figure 17. Westbound TX 6 Approach near Waco before AWEGS.

The second AWEGS site was at the signalized intersection of US 290 and FM 577 along the US 290 bypass in southeast Brenham. Figure 18 shows this (US 290) four-lane, divided road. Two advance warning signs, one on each side of the roadway, were placed for each approach of US 290, as can be seen in Figure 19. The local dilemma zone multiple-loop design was for a design speed of 70 mph using Nader's Guide.

Researchers conducted two types of AWEGS technology evaluations. First, the performance of AWEGS operating under Level 1 (no speed measurements) and Level 2 (with speed measurements and other features) technology were compared and contrasted so that the features and tradeoffs between the two systems could be clearly demonstrated and understood. Second, the overall traffic performance of the Level 1 and Level 2 systems were compared to traffic conditions before AWEGS was installed. Massive databases were collected by the AWEGS computer system at each site for many days to assist in this evaluation. Red-light-runners were detected using video imaging vehicle detection systems (VIVDS) at the Waco and Brenham sites.

Figure 18. Eastbound US 290 Approach in Brenham before AWEGS.

Figure 19. Westbound US 290 Approach in Brenham after AWEGS Installed.

OPERATING PERFORMANCE

The function of AWEGS is to provide an advance warning before the end-of-green of the arterial phases to high-speed approach traffic. The system monitors almost all of the detections at the intersection, detections on the advance detectors on the arterial approaches, and the signal controller status. Based on the detector activity, AWEGS then predicts the termination of green about 5 to 6 seconds in advance for each arterial approach and starts flashing the advance warning beacons.

In order to ensure that a vehicle is not in its dilemma zone at the termination of green, sometimes AWEGS places a phase hold for special cases. In Level 1 implementation, AWEGS used only one advance detector. Hence, the system was likely placing more holds, and they were all between 4.5 to 5.0 seconds long, since travel times were fixed and based on the off-peak space-mean speed. However, in Level 2 implementation, AWEGS used both advance detectors, and it was more intelligent in placing phase holds. These phase holds should be far fewer in number and shorter in duration in Level 2 than in Level 1.

AWEGS attempts to provide an advance warning for the end-of-green of about 5 to 6 seconds. AWEGS makes decisions on termination of green based on several assumptions regarding vehicle detection and operation. However, motorists do not always drive in a predictable manner. They sometimes slow down on an approach, and sometimes they speed up. To overcome this variability of driver behavior, the system monitors the signal controller to provide high-quality prediction. If the prediction is proving to be false, AWEGS has to catch up with the controller operations to warn the vehicle by delaying the termination of green when the vehicle is in the dilemma zone by placing a phase hold. Sometimes the advance detectors may detect the first vehicle of a platoon. Under the right conditions, AWEGS may start flashing the beacons after protecting the lead vehicle of the platoon because of conflicting calls. AWEGS does this because it has no way of knowing a platoon of vehicles is oncoming. This situation can result in advance warning of more than 5 to 6 seconds because the subsequent vehicles in the platoon may extend the phase.

Sometimes no advance warning on the arterial may be provided. This usually will happen because no advance warning is really necessary. This may happen when a call suddenly comes on a conflicting phase when there are no vehicles on the arterial approaches (as may happen during off-peak periods). Here, no need exists to provide any advance warning for the arterial approaches.

Sometimes the system is unable to distinguish a real detection on a detector from a false call. For example, a real detection on a side-street stop bar detector is a vehicle waiting for a green on the side street. A false detection on the same detector is a left-turning vehicle from the arterial going over the same detector during an arterial left-turn movement. With ILD, the amplifier in the cabinet is unable to distinguish this detection as being a false call. Hence, the AWEGS reacts to this false detection as if it were a true call, and AWEGS may immediately start flashing if conditions are right. However, the system usually soon recognizes the false call and stops flashing the beacons when it is safe to do so. This unnecessary flashing can be minimized by providing good intersection geometric design initially and improved directional detection capabilities

This situation sometimes leads to false calls and may result in a large variation in the warning time provided to approaching motorists, and this case may even cause some false flashing. However, the AWEGS has been designed to minimize this variation in warning time and ensure that it does not have an adverse impact on approaching motorists.

Phase Holds

In order to better understand system performance, six days of detailed data were examined from the Level 1 and Level 2 AWEGS operations in Waco together with Level 2 implementation in Brenham. Researchers analyzed these data to determine the hold patterns, the number of phase terminations, and the pattern of the advance warning being provided per typical day. Table 5 illustrates the statistics observed in Waco regarding the number of phase holds and the mean duration of phase holds. The table also illustrates the number of phase ends for each approach.

Table 5. Number of Phase Holds and Phase Ends in Waco.

Level 1 - No Speed Measured								
	Phase 2 (Leading Through)				Phase 6 (Leading Through)			
Day	# of Holds	Mean Hold, sec	Std. Dev	Phase Ends, #	# of Holds	Mean Hold, sec	Std. Dev	Phase Ends, #
Sunday	126	4.947	0	857	105	4.667	0	849
Monday	146	4.947	0	999	152	4.667	0	984
Tuesday	122	4.947	0	946	172	4.667	0	944
Wednesday	154	4.947	0	974	159	4.667	0	975
Thursday	151	4.947	0	968	170	4.667	0	975
Friday	151	4.947	0	1057	165	4.667	0	1046
Average	**142**	**4.947**		**967**	**154**	**4.667**		**962**
Level 2 - Speed Measured								
	Phase 2 (Leading Through)				Phase 6 (Leading Through)			
Day	# of Holds	Mean Hold, sec	Std. Dev	Phase Ends, #	# of Holds	Mean Hold, sec	Std. Dev	Phase Ends, #
Sunday	5	1.714	0.828	1033	5	1.207	0.225	1014
Monday	5	1.441	0.245	1052	10	1.880	0.823	1044
Tuesday	9	1.619	0.596	1085	9	1.416	0.674	1092
Wednesday	2	1.507	0.419	1086	13	1.453	0.451	1082
Thursday	5	1.552	0.626	1025	13	1.527	0.652	1124
Friday	2	1.842	0.636	1173	6	1.137	0.125	1162
Average	**5**	**1.613**		**1076**	**9**	**1.437**		**1086**

As Table 5 illustrates for Waco, the number of phase holds for a Level 1 deployment for Phase 2 ranges from 122 to 154 for an average of 142 and for Phase 6 from 105 to 172 for an average of 154 per day. However, for the Level 2 deployment, the number of phase holds dropped significantly. For Phase 2 the range was from 2 to 9 for an average of 5 and for

Phase 6 from 5 to 13 for an average of 9 per day. It is also seen from the table that in Level 1, the duration of the phase hold for Phase 2 was a fixed value of 4.947 seconds and for Phase 6 was a fixed value of 4.667 seconds. However, in Level 2 the average duration of the phase holds are 1.613 seconds and 1.437 seconds for Phase 2 and Phase 6, respectively.

This decrease in the number of phase holds and the duration of the phase hold was expected. Level 2 AWEGS uses both advance detectors on the arterial approaches to determine the type of vehicle (car or truck). It then calculates the dilemma zone for each and every vehicle. The system is also continuously keeping track of the likely position of the vehicle as it approaches the TxDOT dilemma zone detectors. Hence, the system only provides a phase hold to vehicles that really need it and only for the duration needed to avoid getting caught in its dilemma zone. The Level 2 strategy significantly reduced the number of phase holds and their duration.

Table 5 also illustrates the daily number of phase ends for each phase in Level 1 and Level 2. In Level 1, the number of phase ends for Phase 2 range from 857 to 1057 per day; while Phase 6 ranges from 849 to 1046. It is seen that in Level 2 the number of phase ends for Phase 2 ranges from 1025 to 1173 and for Phase 6 range from 1014 to 1162. This 12 percent increase in the daily number of phase ends in Level 2 is also expected because of the similar decrease in the number and duration of phase holds from Level 1 to Level 2. This means that the Level 2 AWEGS is doing a pretty good job of predicting the operation of the full-actuated traffic signal controller, and it is having a very small influence on the controller operations (very few phase holds).

Table 6 illustrates the patterns of holds and phase ends in Brenham for Level 2. A Level 1 deployment was not deemed necessary in Brenham as the construction at the intersection was not completed until the Level 2 algorithm was developed and since Level 2 is judged to be a superior algorithm.

Table 6. Number of Phase Holds and Phase Ends in Brenham.

Day	Phase 4 (Lagging Through)				Phase 8 (Leading Through)			
	# of Holds	Mean Hold, sec	Std. Dev	Phase Ends (#)	# of Holds	Mean Hold, sec	Std. Dev	Phase Ends (#)
Sunday	15	1.819	0.627	895	6	2.618	1.359	468
Monday	16	2.005	0.898	904	5	2.238	0.83	527
Tuesday	11	2.478	1.136	907	3	2.303	0.108	551
Thursday	16	2.044	1.073	907	0	0	0	503
Friday	21	2.246	0.913	886	1	2.003	0	511
Saturday	15	2.09	0.771	922	1	2.533	0	540
Average	**16**	**2.114**		**904**	**3**	**1.949**		**517**

Table 6 shows a significant difference between the number of phase holds for Phase 4 and Phase 8. While the phase holds for Phase 4 range from 11 to 21 for an average of 16 per day, they range from 0 to 6 on Phase 8 for an average of 3 per day. Similarly, the number of phase ends ranges from 886 to 922 for Phase 4 for an average of 904, and they range from 468 to 551 for Phase 8 for an average of 917 per day. These results are expected, as there is a significant amount of traffic on Phase 3, which is the arterial left-turn movement opposing Phase 4. Hence, Phase 4 terminates more often than Phase 8 resulting in more phase holds.

Advance Warning

The data collected were also analyzed for the distribution of advance warning being provided to the motorists. Additional information about the number of times no advance warning was provided as well as the number of times the AWEGS started flashing for false calls and stopped flashing after realizing the error. For the sake of brevity, results for only one day are provided in Table 7. Table 7 illustrates the results of the data analysis for Day 1 in both Level 1 and Level 2 in Waco for Phase 2 and Phase 6 approaches.

Table 7. Advance Warning in Waco.

	Day 1					
	Phase 2 (Leading Through)			Phase 6 (Leading Through)		
	Flash at the Onset of Yellow	Flash to Start of Yellow	Flash for False Actuations	Flash at the Onset of Yellow	Flash to Start of Yellow	Flash for False Actuations
Level 1						
Count (#)	5	852	303	11	838	208
Min, sec		0.26	0.00		0.26	0.00
Max, sec		115.91	13.36		36.85	14.50
Average, sec		5.55	2.02		5.30	1.59
Std. Dev, sec		6.25	1.91		4.84	1.85
Level 2						
Count (#)	19	1012	21	5	1009	20
Min, sec		0.00	0.07		0.09	0.07
Max, sec		26.85	4.99		26.97	4.90
Average, sec		3.58	1.66		3.68	1.86
Std. Dev, sec		3.03	1.45		3.38	1.73

Table 7 provides information about three parameters regarding the advance warning for each approach. The column Flash at the Onset of Yellow illustrates the number of times AWEGS did not provide any advance warning of the end-of-green, meaning that the beacons started flashing at the onset of yellow. This operation is very efficient and does not necessarily suggest an unfavorable situation. AWEGS does not provide an advance warning when no vehicles are detected on the arterial approaches when a "hot" conflicting call is received. Providing a warning under such cases will only delay serving the vehicle on the side street and makes the intersection signal operation less efficient.

The column Flash to Start of Yellow contains the most critical information. This column states the number of times the advance warning was provided, illustrates the range of the advance warning by detailing the minimum and the maximum advance warning provided, and calculates the mean and standard deviation of the range of advance warning for the particular approach. The third column Flash for False Actuations indicates the number of times the AWEGS started flashing the beacons for an unknown false call and then had to stop flashing when the system saw the false call drop. This column indicates the number of times AWEGS corrected its actions either due to unexpected driver behavior, false calls, or wrong assumptions.

As Table 7 indicates, AWEGS provided more advance warnings in Level 2 than Level 1 for both Phases 2 and 6. This trend is consistent for the remaining days. As noted earlier, the logic of AWEGS was significantly enhanced in Level 2. As shown in Table 5, there was a 12 percent increase in the number of phase ends from Level 1 to Level 2. Hence, we see a higher count for the times advance warning was provided. Table 7 also shows a significant reduction in the number of false flashes from Level 1 to Level 2. Even this trend was expected in Level 2. The AWEGS in Level 2 has been enhanced to recognize the intricacies of the phasing sequences. While Level 1 assumed lead-lead phasing for arterial lefts, the actual phasing sequence was lag-lag in Waco. In Level 1 AWEGS started flashing the beacons a number of times only to correct it later because of the difference in left-turn phasing sequence. Level 2 deployment corrected this problem in Brenham.

Figure 20 and Figure 21 graphically show the distribution of advance warning time provided by AWEGS in Waco per day for Level 1 and Level 2 deployments, respectively. Advance warning durations of between 1 and 2 seconds seem to be predominant in the graphs. Advance warning of 1 to 2 seconds was given in about 275 cases in Level 1 and 425 cases in Level 2. On the surface this would be cause for serious concern because AWEGS's objective is to provide approximately 5 to 6 seconds of advance warning.

Upon detailed analysis of these warnings, however, it was found that all of these warnings occurred when there were no motorists on the arterial approaches when the arterial phase had terminated. Hence, a smaller warning of less than 2 seconds under those conditions is not an indication of faulty AWEGS operation. It actually means that AWEGS is correctly predicting the gap-out of the arterial phases in very light traffic conditions for a large majority of the cases. If we disregard these warnings of less than 2 seconds, it is seen that in both Level 1 and Level 2, AWEGS is providing an advance warning of 5 to 6 seconds in a majority of the phase termination and meeting the system objective. It is significant to note that almost no 0 to 1 second advance warnings were observed during the day. This implies that almost no end-of-green phase terminations were missed by AWEGS; i.e., the phase ended or was about to end with no system response previous active.

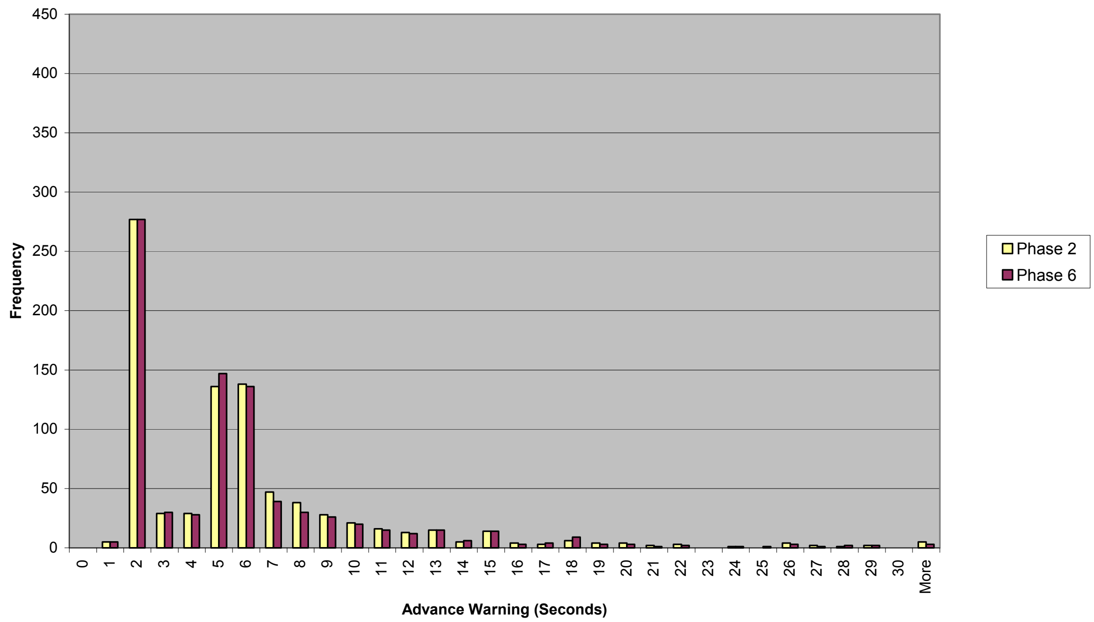


Figure 20. Advance Warning Distribution in Waco Day 1 - Level 1.

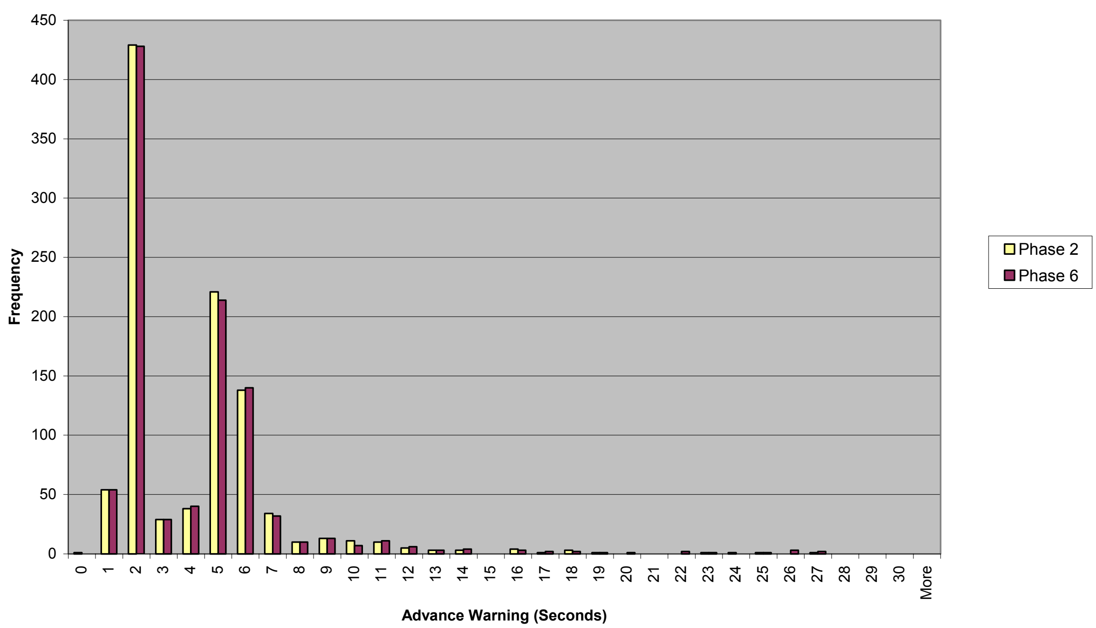


Figure 21. Advance Warning Distribution in Waco Day 1 - Level 2.

Similarly, Table 8 illustrates the flashing operations for the Level 2 deployment in Brenham. It is clearly seen from Table 8 that there is a significant difference in the operation of the beacons between Phase 4 and Phase 8. While the count of flash to start of yellow (advance warning) for Phase 4 is about 744, it is as low as 460 for Phase 8. This is clearly because of the number of phase terminations for each of the phases as seen in Table 6. However there is also a big difference in the flash at the onset of yellow parameter. While AWEGS started flashing at the onset of yellow 150 times for Phase 4 approach, it only did so 4 times for Phase 8 approach. TTI researchers analyzed these occurrences to find out the causes for this large discrepancy and found two reasons.

Table 8. Advance Warning Distribution in Brenham (Level 2).

	Day 1					
	Phase 4 (Lagging Through)			Phase 8 (Leading Through)		
	Flash at the Onset of Yellow	Flash to Start of Yellow	Flash for False Actuations	Flash at the Onset of Yellow	Flash to Start of Yellow	Flash for False Actuations
Level 2						
Count (#)	150	744	15	4	460	1
Min, sec.		0.01	0.12		0.18	0.74
Max, sec.		46.42	3.99		94.82	0.74
Average, sec.		4.73	0.80		11.31	0.74
Std. Dev, sec.		3.65	1.03		14.82	0.00

Vehicles arriving on Phase 3 (eastbound left), which is a conflicting phase for Phase 4, were often making a left turn on the red and were then waiting for a green indication in the median of the highway. These vehicles were placing a call on a detector located within the median, which was responsible for terminating Phase 4 green. However, AWEGS is only monitoring the actuations on Phase 3 and not on the detector placed in the median. And AWEGS was also making an assumption that motorists would make a left turn only after getting a protected left turn for Phase 3. However, motorists were making left turns on red, resulting in the beacons flashing numerous times at the onset of yellow. AWEGS should monitor the activity of the detector in the median of the highway in Brenham and minimize these unexpected terminations of Phase 4.

A number of eastbound through vehicles (Phase 8) were accidentally actuating (splash over) the adjacent left-turn detector (Phase 3). AWEGS monitoring the Phase 3 detector sees the call on Phase 3 but also sees the vehicle leave the detector immediately and assumes that the phase will not be served. However, the traffic signal controller had its Memory On function activated for Phase 3. The controller remembers this actuation on Phase 3 and services the phase even though no vehicle is there. TxDOT personnel have programmed Memory On to ensure that a phase is serviced with a high degree of reliability. What this means is that there will always be some unexpected terminations of Phase 4. These unexpected terminations on Phase 4 do not have any adverse impact on safety of vehicles on the approach because it will only happen when there are no vehicles at their critical locations.

Figure 22 illustrates the distribution of advance warning for Phase 4 and Phase 8 for the study day. Figure 22 shows that a majority of the advance warnings in Brenham were between 5 and 6 seconds. Some warnings were less than 1 second because no motorists were on the approach when a vehicle was detected on a conflicting phase. AWEGS is aware of the termination condition at all times. The distribution illustrates that AWEGS is providing the intended warning to the motorists in advance of the end-of-green.

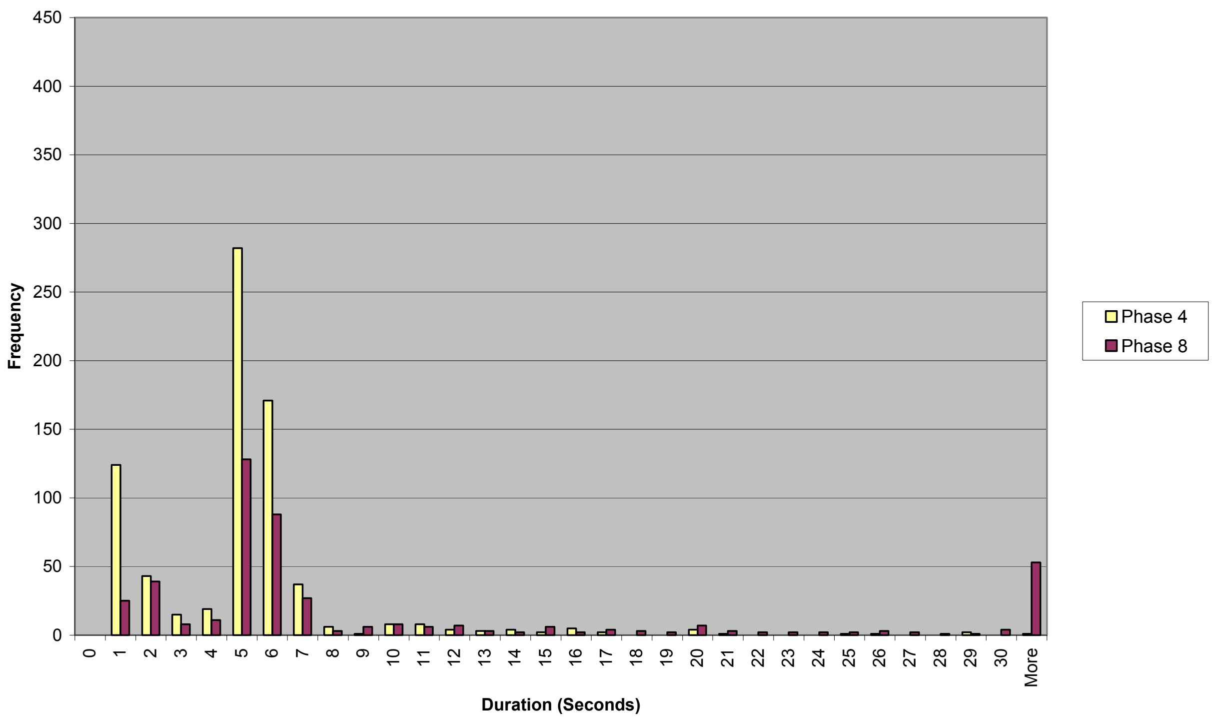


Figure 22. Advance Warning Distribution in Brenham - Day 1.

TRAFFIC PERFORMANCE

AWEGS was designed to reduce red-light-running and to improve the resulting traffic safety. The short duration of the two-year project necessitated the focus on the primary performance variable of red-light-running, which will be described in the following section for the two field sites. Methods of data collection using remote video detection will be described first, followed by a description of the criteria used to define a red-light-runner. Extensive before-after field observations will then follow. Overall, a 40 to 45 percent reduction in red-light-running was obtained at the two sites.

Method of Data Collection

The red-light-running problem before the installation of AWEGS was measured by means of surrogate methods at SH 6 and FM 185 intersection in Waco and at US 290 and FM 577 intersection in Brenham. This was done by means of a computer program that logged in actuations of detectors in the field. AWEGS collected 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 were written into two log files named as *mmddyyyy.ada* and *mmddyyyy.vda*. The *.ada* log file documents the decisions made by the system and most of the intersection and controllers events AWEGS monitors. Thus, the passage of vehicles was identifiable in such files, which were converted into Excel files. Also, the current status of the advance warning flashers and the traffic signal itself were logged into these files. The *.ada* files were utilized to monitor the system performance of the AWEGS, while the *.vda* files helped to analyze traffic performance of the system, specifically in the area of red-light-running.

Events logged into the *.vda* files (for evaluating RLR), included time stamps for actuations of the loops provided by the video imaging system installed at the site. In Waco, each main-street monitored approach had two video loops, while in Brenham each approach had one. The *.vda* file also contained time stamps for the beginning of the green, yellow, all-red, and red intervals of main-street phases. Also in this *.vda* file are counts of vehicles detected by the first loop of the video loops pair, associated with the approach, during the green, yellow, all-red, and red intervals of the main-street phases. A standard VIVDS located at the intersection was used. An example of this VIVDS system mounted on the mast arm above the luminaire in Waco is shown in Figure 23.

Development of Red-Light-Running Criteria

For two weeks prior to the installation of AWEGS, 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 vehicle 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.

Figure 23. Video Imaging Vehicle Detection System (VIVDS) at Waco.

Based on these plots, the researchers 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, are not red-light-runners. A defined period of time of 5 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 stopline (from the input side of the first through VIVDS detector) during red clearance;
- any vehicle crossing the stopline 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.

These conditions were used partly to separate true red-light-runners from other (false) events like side-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 B detector. The presence time of the A detector was utilized, however.

Before-and-After Study Results on Red-Light-Running in Waco

The before period of study was conducted from October 19, 2002, to November 2, 2002. After the deployment of Level 1 technology, three different periods of after studies were conducted during December, March, and April. These study periods were approximately four weeks, eight weeks, and three months, respectively, after installation of the Level 1 AWEGS technology. After Level 2 technology deployment, data were collected for the period between July 16, 2003, and August 9, 2003, for a total of 21 days.

Thus, for a total of 35 days after the installation of AWEGS, data were collected to analyze the impact of the Level 1 system on RLR. After the deployment of Level 2 technology, data were collected for a period of 21 days in the months of July and August 2003, which was about two weeks after the initialization of Level 2. Table 9 gives a summary of the rates for these different periods of analysis. The traffic performance results for both TX 6 directions of flow are combined in Table 9 and later also for the Brenham site.

The efficacy of various AWEGS designs to reduce RLR at the Waco site can be seen in Table 9. 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 red-light-runners per day, or nearly a 40 percent reduction. While the more traffic efficient Level 2 experienced a slight 12 percent increase in RLR per day when compared to Level 1, this small statistically insignificant increase is the same as the 12 percent increase in the number of phase ends observed between Level 1 and Level 2 in Table 5. Thus, the rate of RLR per phase end exposure is practically the same for the two systems. Further plots to identify specific nature of the reductions in RLR for the red clearance and following real red periods are given in Figure 24 and Figure 25.

Table 9. Results of Red-Light-Running in Waco.

		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	10/19/2002	11/2/2002	93	19	112	7.15	1.46	8.62
After – Level 1	35	12/4/2002	4/3/2003	135	29	164	3.86	0.83	4.69
After – Level 2	21	7/19/2003	8/8/2003	96	14	110	4.57	0.67	5.24

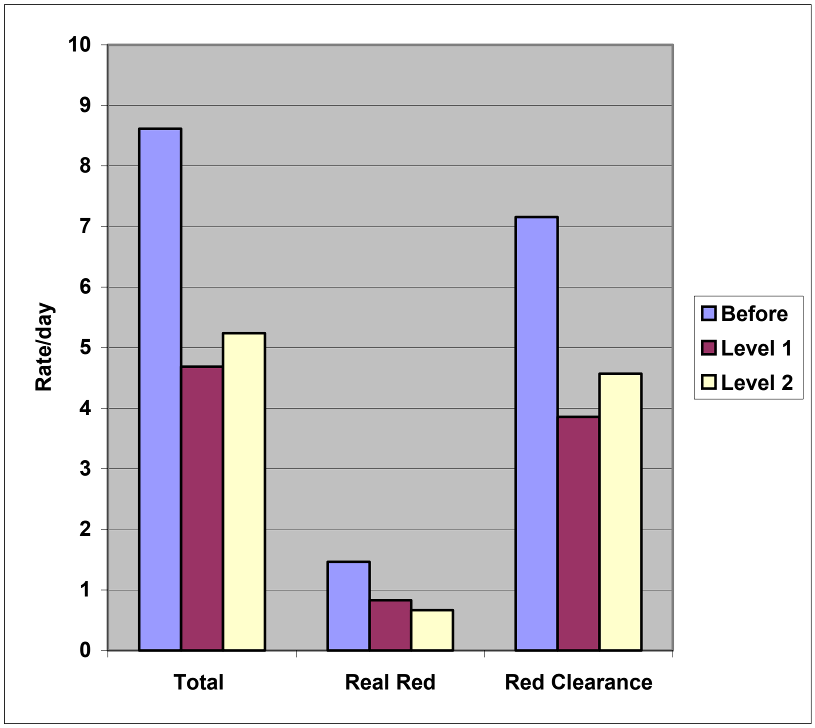


Figure 24. Red-Light-Running in Waco.

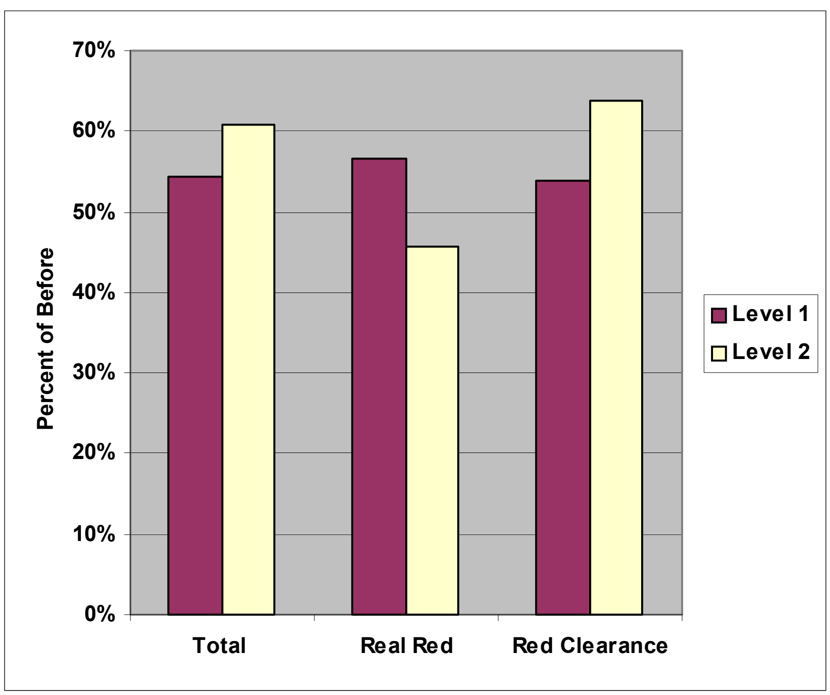


Figure 25. Reduction in Red-Light-Running in Waco.

The figures show that the Waco site experienced statistically 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 a 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.

A slight, statistically insignificant 12 percent increase in RLR was noted for Level 2 when compared to Level 1. Two reasons for this small increase are offered. One is the relatively inefficient traffic signal operation that occurred during Level 1, noted earlier in Table 5, when compared to Level 2. Level 2 had a similar 12 percent increase in the number of phase ends per day versus Level 1. This increase is strikingly the same percentage as the 12 percent increase in RLR that occurred. Thus, RLR per exposure for the two AWEGSs were the same. Another event occurred at the Waco site between Level 1 and Level 2 deployment. The high-speed road, TX 6, was repaved with a high-friction, anti-skid surface. Comparisons of handheld radar spot-speed studies conducted at the start of Level 1 and Level 2 indicate an increase in operating speed of 2-4 mph for the two directions of flow. In any case, the potential operational benefits of Level 2 over Level 1 far outweigh any RLR benefits that Level 1 might offer, except in those few cases where a speed-trap detector may fail. Here, AWEGS Level 2 will slowly transition to a still effective Level 1 system until such time as the suspect detectors are repaired.

Before-and-After Study Results on Red-Light-Running in Brenham

The 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 AWEGS (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), data were collected and analyzed for 21 days to determine the effect of AWEGS on the red-light-running events. Table 10 contains a summary of the results for both periods of data collection. It can be seen that RLR rates in Brenham were appreciably higher than in Waco, primarily due to the higher traffic volumes through the intersection at Brenham. Plots of the RLR events were done to give a clearer picture of the reduction rates observed in Brenham.

Table 10. Summary of Red-Light-Running in Brenham.

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	1879	70.24	19.24	89.48
After	21	7/17/2003	8/12/2003	859	200	1059	40.90	9.52	50.43

Figures 26 and 27 show the nature of RLR reduction observed in Brenham. Figure 26 shows a decrease from 90 to 50 red light runners per day, or nearly a 45 percent reduction in

RLR. Closer study reveals greater reduction in real-red running than in red clearance. All of these before-and-after reductions are statistically and practically significant. These results show the potential benefits to be expected in a wider deployment of AWEGS where needed.

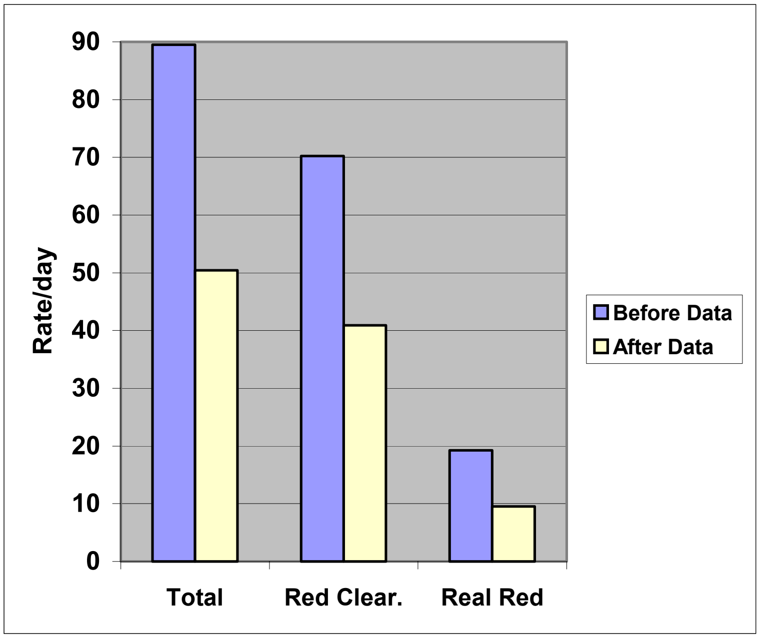


Figure 26. Red-Light-Running in Brenham.

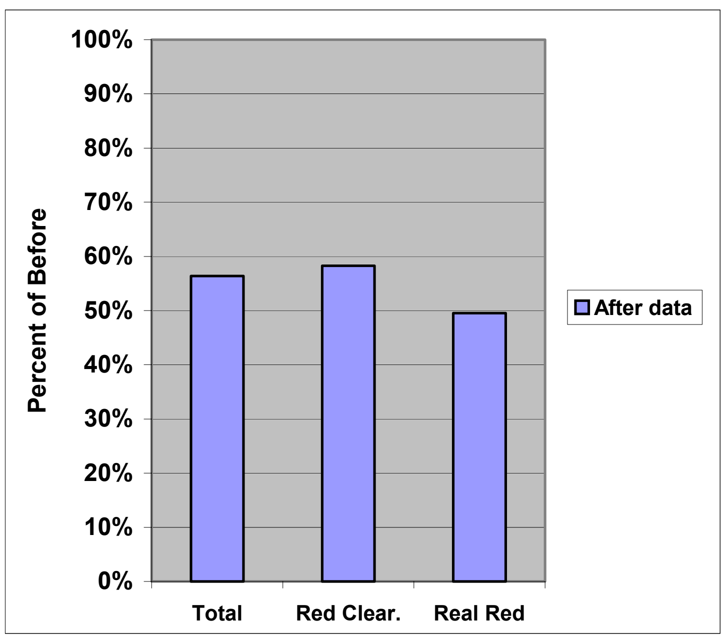


Figure 27. Reduction in Red-Light-Running in Brenham.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

This research project developed an effective system for warning approaching motorists of the forthcoming end-of-green phase at high-speed (≥ 45 mph) isolated traffic-actuated signals in Texas. The research developed a fully functional Advance Warning for End-of-Green System, known as AWEGS. AWEGS was designed by the authors from the Texas Transportation Institute for the Texas Department of Transportation. AWEGS was field tested at two sites in Waco and Brenham, Texas. The Waco site was a high-speed, two-lane rural road. The second site was a very high-speed, high-volume, four-lane divided highway located on the US 290 bypass of Brenham, Texas. Both sites had a lot of heavy trucks, but the Brenham site had many large interstate freight trucks. AWEGS reduced red-light-running, during the targeted first 5 seconds of red, by 38 to 42 percent. Level 2 features are much preferred because they also minimize any negative impact on the operation of the existing traffic-actuated controller (from phase holds). Level 2 also provides new and effective dilemma zone protection for targeted trucks and very high-speed cars.

Two companion reports were written to provide guidance on the design, installation, and operation of AWEGS (*1, 2*). More specific conclusions of this research are identified below. Based on these findings, both research and implementation recommendations are offered future AWEGS researchers and design engineers who might wish to deploy such system in Texas and elsewhere.

CONCLUSIONS

1. A series of advance warning technologies were tested over the two-year study. A base Level 1 technology was initially proposed using trailing overlaps to provide a fixed amount of advance warning of the end-of-green phase, but this method was rejected upon further investigation of its likely performance because it would give up existing dilemma zone protection routinely provided by TxDOT engineers.

2. Advance warning systems should minimize the usage of fixed trailing overlaps where full traffic-actuated systems are deployed. AWEGS Level 2 does minimize the usage of trailing overlaps to perhaps no more than 2 percent of the phase terminations per day.

3. Both Level 1 and Level 2 AWEGSs appear to provide effective advance warning for end-of-green with reductions in RLR during the first 5 seconds of red on the order of 38 to 42 percent based on the study results at the two sites in Waco and Brenham.

4. Level 2 AWEGS provides far superior overall operating features than does Level 1. It minimizes the usages of trailing overlaps, provides far fewer traffic delays due to stoppages at the signal than does Level 1, and it also provides identifiable extra dilemma zone protection only for those very high-speed vehicles and trucks needing some variable phase hold protection.

5. However, the traffic study results show that AWEGS should be designed to fall back to a Level 1 system rather than going to either a background flash or trailing overlap should either of the approach roadway's two speed-trap detectors fail.

6. Many false calls on cross-street movements are likely to be occurring at some high-speed rural signalized intersections, especially those prone to excessive red-light running. These false calls may be causing a proportionally high number of red-light-runners and related safety problems. Signalized intersections having high-speed traffic with a high percentage of left-turning traffic across unchannelized highway approaches using non-directional traffic detection of calls are candidates. Directional detection of roadway traffic, perhaps using VIVDS stopline detection would ameliorate some of this problem, where it is significant, and the addition of barrier divisional channelization would further reduce these false calls.

RECOMMENDATIONS

1. The Texas Department of Transportation should strongly consider further implementation of the above described Advance Warning for End-of-Green System at perhaps six additional sites in the various regions of the state. These systems should be operated and observed for at least three years so that reliable before-and-after traffic accident data could be collected and analyzed to verify the crash reduction capabilities of AWEGS suggested by the positive RLR studies observed in this research.

2. TxDOT should attempt to design, install, and operate such AWEGSs at known red-light-running sites using the design guidelines, software, and guidance provided by this research project. Intersection and system designs should be provided that minimize the likelihood of all types of false calls. Technical support and guidance for these implementation projects by TxDOT could be provided by the AWEGS research staff of TTI as appropriate.

3. Follow-up studies should be conducted at some of these sites where TxDOT can readily install video imaging video detection systems to monitor RLR. Summary documents could be prepared by TTI researchers in concert with TxDOT field personnel that could be used to update the two manuals being developed within this research work (*1, 2*).

4. Further research should be conducted to improve the knowledge base of AWEGS applications in general. However, two areas should be specifically considered. Human factors studies should be conducted to determine the optimal configuration and operations of the AWEGS signs as related to the various types of roadside environments expected. Off-the-shelf devices should be developed to economically and reliably drive and backup the advance flasher operation desired.

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