Evaluation of Advance Warning Signals on High Speed Signalized Intersections

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Disclaimer

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LIST OF ACRONYMS

DZ	Dilemma Zone
MOE	Measure of Effectiveness
AWS	Advance Warning Signal
AWF	Advance Warning Flashers
AD	Advance Detection
AWS + AD	Advance Warning Signal system + Advance Detection system
UDOT	Utah Department of Transportation
NDOT	Nevada Department of Transportation
NDOR	Nebraska Department of Roads
Mn/DOT	Minnesota Department of Transportation
UTL	Utah Traffic Lab

EXECUTIVE SUMMARY

Drivers often make incorrect judgments when faced with the sudden decision of whether to stop or go when the traffic signal changes from green to yellow. Drivers risk encroaching onto the intersection or being involved in a read-end collision when they fail to come to a safe stop. When they decide to clear the intersection, they risk running a red light or being involved in a side-on collision. The inability to perform either option successfully is attributed to the existence of dilemma zones (DZs). DZs often form at high-speed signalized intersections and occur after a long gap or when an intersection is hidden due to topography. These conditions are hazardous to driver safety, and DZ protection must be provided.

One way to avoid DZs is by providing sufficient yellow time. Other methods are to advocate stopping at the intersection through Advance Warning Signals (AWSs) and to extend the green light.

Utah Department of Transportation (UDOT) has installed AWSs at two intersections in Utah. One is in Brigham City and the other in St. George. The AWS in Brigham City is reinforced with Advance Detection (AD) technology. Effectiveness of the AWS devices in providing DZ protection to drivers was evaluated by the Utah Traffic Lab.

UTL compared the intersections with AWS to an intersection without AWS. They found that the AWS in St. George was not effective in reducing the number of drivers in DZs. Although 90 percent of drivers responded positively by reducing their speed when the signal was flashing, most of them reserved their decision to stop or proceed until they were close to the intersection. Speeds were reduced by an average of five to 10 mph. They were reduced less if drivers could see that the traffic light at the intersection was still green. St. George had 1.15 percent more vehicles in the DZ than the control intersection. The AWS setup at Brigham City was effective in reducing vehicles in the DZ. It had 1.4 percent fewer vehicles in the DZ than the Logan intersection. The effectiveness of AWS in Brigham City may be attributed to its combined AWS+AD setup. Because the research results did not yield conclusive results on the effectiveness of AWS systems, UTL recommends an intensive study at potential AWS locations before any future installations. UTL also recommends modifying the AWS system at St. George to improve its effectiveness.

1. INTRODUCTION

This chapter presents the safety risks near high-speed signalized rural intersections. It also summarizes the need for this study and reviews its scope, goals, and tasks.

1.1 Background

Roadway accidents are one of the major causes of transportation-related casualties. Thousands of lives are lost each year in collisions caused by lack of proper judgment and disrespect for traffic rules. There were more than 37,000 road fatalities in 2001 (9). Fatalities are particularly high along high-speed rural roads, therefore, transportation agencies give high priority to these roads.

Traffic signs and warning devices inform drivers of changes in route, road geometry, alignment, grade, and of approaching school zones, animal crossing zones, and intersections.

Planners and engineers pay special attention to road geometry and alignment when two or more high-speed roads meet at a junction. An intersection that occurs after a considerable gap from the previous one is particularly dangerous.

DZ is the area near an intersection where drivers going the legal speed limit can neither stop nor clear the intersection successfully. The problem of DZs becomes more pronounced at isolated high-speed intersections when drivers have no prior knowledge of the state of the traffic signal. If drivers proceed on yellow, they risk violating the law if the light turns red before they clear the intersection. Some drivers, in an attempt to cross the intersection on yellow, speed through the intersection and end up clearing it on red. This is known as "red-light running." It is illegal in many states and can lead to side-sweeps, side-on, and right angle collisions. Drivers that come to a sudden stop at the intersection run the risk of being involved in a rear-end collision.

DZ protection prevents drivers from being caught in dangerous situations. The need for DZ protection is determined by the number of vehicles in the DZ at the onset of yellow. As the number of vehicles in the DZ increases, protection to drivers decreases.

Prior information about the change in signal generally provides DZ protection. The information prepares drivers to slow down and come to a safe stop. Technologies currently used for DZ protection are Advance Warning Signals (AWS) and Advance Detectors (AD).

1.1.1 Problem Statement

The problem statement of this research is to find whether the performance of AWS systems at Brigham City and St. George are effective.

1.1.2 Need for Research

UDOT has installed AWS at two high-speed intersections in Utah. One is situated outside St. George and the other is on the outskirts of Brigham City. These AWS are activated a few seconds before the start of the yellow signal to inform drivers that they are approaching an intersection. UDOT wants to know the effectiveness of the AWS for the following reasons:

- Installation entails huge expenditures that place a financial burden on the agency and on the community.

- Effectiveness must be justified to obtain public and political support.

UDOT presently does not have any standard guidelines for installation; therefore, a set of guidelines is needed. Also the AWS systems are a relatively new concept in traffic. UDOT wants to study them to determine their tangible benefits to the driver community.

1.2 Scope of Research

The scope of this research compares the effectiveness of DZ protection provided to drivers at Brigham City and St. George with an intersection without DZ protection. To study the DZ activity during "without AWS" conditions at Brigham City and St. George requires removal of the existing AWSs and their reinstallation. However, such a measure would have been impractical and beyond the scope of the study. Therefore, a control site was used to represent the conditions at an intersection without AWS. An intersection in Logan was selected as the control site. This intersection is located on US 89/91 at SR 101 and has vehicle approach speeds and a yellow length interval similar to the test sites. The study also will provide recommendations based on past evaluations of AWS and also from the research outcome.

1.3 Project Goals and Objectives

The goal of the project is to determine whether AWS are beneficial and whether they should be installed in other locations with similar topography, terrain, and intersection characteristics; in addition, to find whether the novelty effect of the newly installed AWS retains its influence on drivers with the passage of time.

The following is a summary of the project objectives:

1. Review the latest technology for DZ protection.
2. Evaluate the effectiveness of UDOT's AWS.
3. Recommendations for future installations.

1.3.1 Research Tasks

The following major tasks were performed to satisfy the research objectives:

- literature review of the rules and guidelines for installing AWS
- identification of study method and sites
- data collection method and research methodology
- data analysis
- results and conclusions
- recommendations for existing AWS and future installations

1.4 Report Organization

This report is organized into 10 chapters. Chapter two explains the concept of DZs, describes how they are formed, and presents a procedure to find the range of speeds that exist in the DZ for an intersection. Chapter three discusses the latest technologies for DZ protection used by transportation agencies throughout the world. Chapter four contains a comprehensive review of available literature on AWS and evaluation case studies of DZ warning signs and other technologies. Chapter five gives a detailed explanation of research methodology, MOEs, and statistical tests. Chapter six describes how to model the number of vehicles in the DZ, the purpose of the model and its underlying assumptions, modeling procedure, and calibration parameters. Chapter seven presents the data collection for the study, its procedure, and a description of the study intersections. Chapter eight contains findings on field data collection and a model for each study intersection. Chapter nine interprets and provides a detailed explanation of the results. In chapter 10 conclusions are drawn from the results. Also, recommendations and suggestions are given for future research. The limitations of the research study also are included in this chapter.

2. THEORY OF DILEMMA ZONE

This chapter describes the formation of DZs. It also addresses how drivers respond to traffic signals. The first section introduces the theory of DZs. The other sections show how DZs can be computed mathematically.

2.1 Driver's Dilemma

Approach speed and location of the driver from the intersection generally influence his decision of whether to stop or proceed. Drivers can come to a safe stop if they are far enough away from the intersection. They can clear the intersection if they are close enough to it.

2.1.1 Factors Influencing Driver's Decision

Some factors influencing the driver's decision of whether to stop or clear the intersection are:

- vehicle approach speed
- color of the traffic signal when noticed by the driver
- vehicle location from the stop line
- length of phase change interval or yellow time
- driver's perception-reaction time
- sight distance
- rate of deceleration
- intersection clearing time
- road surface conditions
- adverse weather conditions such as snow, fog, rain, etc.

Drivers caught in a DZ have a strong natural tendency to proceed through the intersection. This behavior increases the risk of collisions with side-street traffic.

A study conducted by Gazis, Herman, and Maradudin found that when drivers were located in a particular segment of the road they were confused about what action to take when the signal changed from green to yellow [1]. The authors attributed this confusion to the formation of DZs, which they believe are caused by poorly designed yellow signal timings. They also concluded that an improperly designed signal phasing results in a greater number of collisions than a properly designed phase.

2.2 Dilemma Zone

2.2.1 Stopping Distance (d_0)

A driver can stop at the intersection if he has enough stopping distance (d_0) in front of him at the onset of the yellow signal. The driver should decide to come to a stop when he is at a critical distance from the stop line. The critical distance required to stop depends on speed of the vehicle, driver's reaction time, and his deceleration rate.

Critical distance is computed using the following equation:

$$d_0 = vd + \frac{v^2}{2a}$$

Where:

v = speed of the approaching vehicle
d = perception-reaction of the driver
a = maximum comfortable deceleration rate of the vehicle

2.2.2 Clearing Distance (d_c)

A driver can clear the intersection if he has enough clearing distance in front of him when he perceives the change in signal. If d_0 is the distance from the stop line where a driver traveling the speed limit will not be able to clear the intersection safely or legally on yellow, then

$$d_c = vt - (w + L).$$

A successful clearing maneuver can be represented as:

$$d + w + L - v_0 d \le v_0(t - d) + \frac{1}{2}a_1(t - d_1)^2$$

Where:

L = length of the vehicle
d = vehicle position from the intersection stop line
w = width of the intersection
a_1 = rate of deceleration of the car

The right hand side of the equation represents the distance traveled from an initial speed (v_0) at a constant acceleration (a_1) during the time interval $(t - d_1)$ subsequent to perception-reaction time and before the onset of the red signal.

2.2.3 d0 vs. dc

The distance from the stop line required for the driver to come to a smooth and comfortable stop is defined as d_0. A DZ exists when $d_0 > d_c$, i.e., a vehicle approaching an intersection at the legal speed limit can not execute either maneuver safely, legally, and comfortably. The DZ is represented by $d_0 - d_c$. This is shown in Figure 2-1.

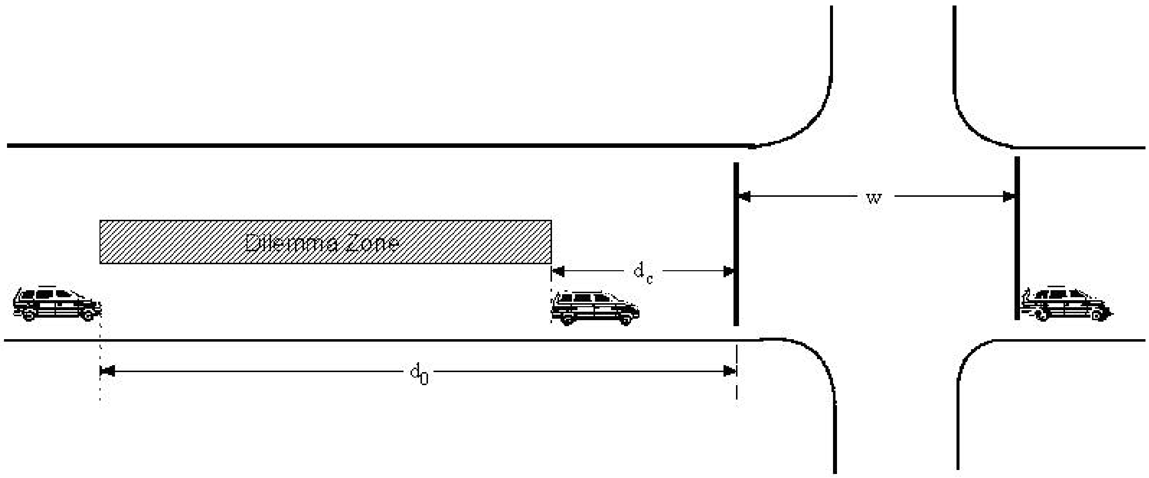


Figure 2-1 Dilemma Zone Near Intersection

When $d_c > d_0$, the driver can either stop or proceed. This is known as the option zone.

2.2.4 d_0 and d_c Plot

Papacostas and Kasamoto recommend drawing d_0 and d_c plots on a single sheet to understand the problem of DZ. The curves d_c and d_0 are drawn for the study intersection for various speeds. The single plot of the two curves tells whether or not the yellow time for the intersection has been designed properly. It also reveals the range of speeds near the intersection.

The curves may or may not intersect. When the two curves intersect at two points, as shown in the figure below, drivers in a certain speed range can either stop or proceed. As shown in Figure 2-2, drivers between the speeds of V_1 and V_2 are in this option zone. Drivers in Region A cannot clear the intersection, but have enough time to stop at the intersection. Drivers in Region B can clear the intersection, but can not stop. Drivers in Region C can execute either maneuver. Drivers in Region D are located in the DZ and can not execute either maneuver successfully.

For other speeds, it can be determined whether a driver is in a DZ if his speed and location are known. If the curves barely touch each other, drivers are in the option zone for that speed. If they do not intersect and if the d_0 curve is always higher than the d_c curve, drivers are in a DZ, regardless of speed.

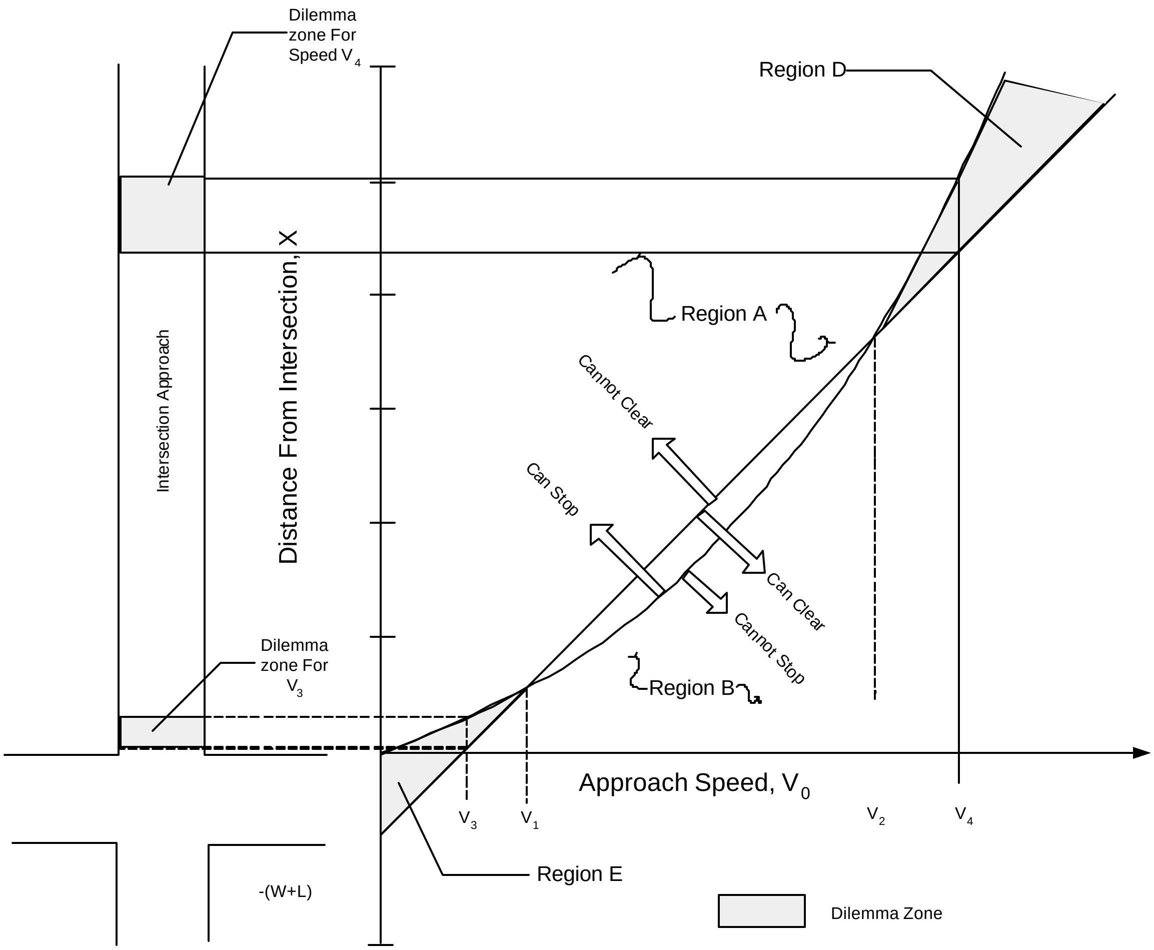


Figure 2-2 d_0 and d_c Plots
(*Source: Papacostas and Kasamato)*

The yellow phase interval is given in seconds by $t_{\min} = d + \frac{v_0}{2a + 2Gg} + (W + L)/v$

Where:

$t_{\min}$	=	yellow length interval
d	=	perception-reaction time of the driver
v_0	=	approach speed of the vehicle
a	=	comfortable deceleration rate for stopping taken as 3.41 m/s^2 (11.2 ft/s^2)
W	=	width of the intersection
L	=	length of vehicle
g	=	acceleration due to gravity taken as 9.8 m/s^2 (32.2 ft/sec^2)
G	=	grade of the road

The following table uses equation 3 to show the computed yellow times for the approach to an intersection with a particular width and speed limit. Yellow time increases as speed stays the same and the width of the intersection increases. When width stays the same and speed increases, yellow time first decreases and then increases. Accommodating long yellow phases is not feasible because it requires huge cycle lengths and increased delays at the intersection. Therefore, transportation agencies limit the length of the yellow phase and increase red times.

Table 2.1 Computed Yellow Times for Different Speeds and Intersection Widths

Width, feet / Speed, mph	Intersection Width →						
	80	90	100	110	120	130	140
30	5.83	6.17	6.50	6.83	7.17	7.50	7.83
35	5.61	5.89	6.18	6.46	6.75	7.04	7.32
40	5.50	5.75	6.00	6.25	6.50	6.75	7.00
45	5.47	5.69	5.92	6.14	6.36	6.58	6.81
50	5.50	5.70	5.90	6.14	6.58	6.81	5.50
55	5.57	5.75	5.93	6.11	6.30	6.48	6.66
60	5.67	5.83	6.00	6.17	6.33	6.50	6.67
65	5.79	5.94	6.10	6.25	6.40	6.56	6.71

Speed ↓

The yellow phase interval provided by UDOT for a typical urban arterial intersection is four seconds with one to two seconds of all red time depending on the width of the intersection. UDOT uses the MUTCD equation for roads with posted speed limits greater than 40 mph, but limits the yellow time to a maximum of 5.5 seconds and provides an all red time of 2.5 seconds. The yellow phase lengths are designed to help drivers perceive the change in right-of-way to the other direction and come to a stop near the intersection. Vehicles approaching the intersection at speeds higher than the posted speed limit may experience a DZ problem.

Drivers approaching signalized intersections at high speeds find it difficult to stop when the light turns yellow. This can cause serious accidents near the intersection with opposing right-of-way traffic. Adequate knowledge of the signal change must be provided to the driver beforehand to assist him in coming to a stop before the stop line. The problem of DZs increases dramatically if the intersection is at the junction of two highways. DZ protection must be provided to minimize red light running and help drivers make an advance decision to stop or go.

3. DILEMMA ZONE REMEDIES

This chapter describes ways to reduce and avoid DZs. It discusses the methods currently used for DZ protection at high-speed signalized intersections: redesign the yellow phase, advocate stopping, and extend the green phase.

3.1 Redesign the Yellow Signal

Adequate yellow time can reduce the number of vehicles in the DZ. Increased yellow time is particularly useful at intersections with sight limitations. However, increased yellow time can increase cycle lengths, delays, and queue lengths. Also, drivers may use the signal's timings as an aid to clear the intersection. Although extended yellow time decreases the number of vehicles in the DZ, it also can increase red-light running.

Retting and Greene studied 10 signalized intersections in New York to learn how signal timings influence red-light running [5]. They performed an onsite field observation of vehicles that entered the intersection after the onset of the yellow signal. They then assessed performance of the improved signal timing by comparing the number of red-light violations to old timings. The study found that red-light violations were reduced drastically when the length of the yellow signal was increased according to ITE's recommendations. Sufficient yellow times, combined with severe penalties for red-light violators, reduce the number of accidents.

The yellow signal also can be shortened and replaced with an "all red time." A shorter signal can discourage drivers from accelerating through the yellow light. Severely enforced red-light violations also can reduce high approach speeds and the number of drivers in the DZ.

Datta, Schattler, and Sue conducted a study in Detroit, Mich., comparing the number of red-light violations at an intersection with all red time and an intersection without all red time [4]. The analysis was based on before and after crash study analyses at the intersections. The "before" case was conducted without all red time. The "after" case was conducted with all red time. The study found a significantly lower number of red-light runners at the intersection with all red time.

3.2 Advocate Stopping

3.2.1 Passive Warning

Traffic signs warn drivers of changes in geometry, such as direction and slope. They also advise them of an approaching intersection. If drivers miss the traffic sign, however, they may end up in a collision. Additional DZ protection must be provided.

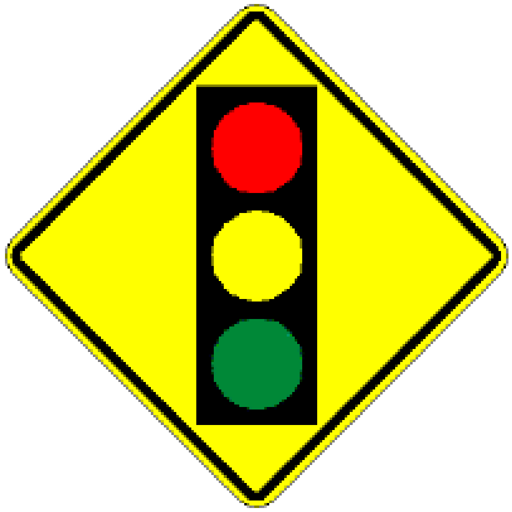


Figure 3-1 Passive Warning Sign

3.2.2 Active Warning

The techniques commonly used for DZ protection are: Advanced Detection (AD), AWS, and a combination of AD and AWS. AD devices include long distance detectors and double long distance detectors. Long distance detectors currently are used in the United States, Australia, and Canada. Double long distance detectors are used in Ontario, Canada. These detectors are placed downstream from the intersection on downhill grade. Active advance warning and true active advance warning techniques presently are being used in the United States.

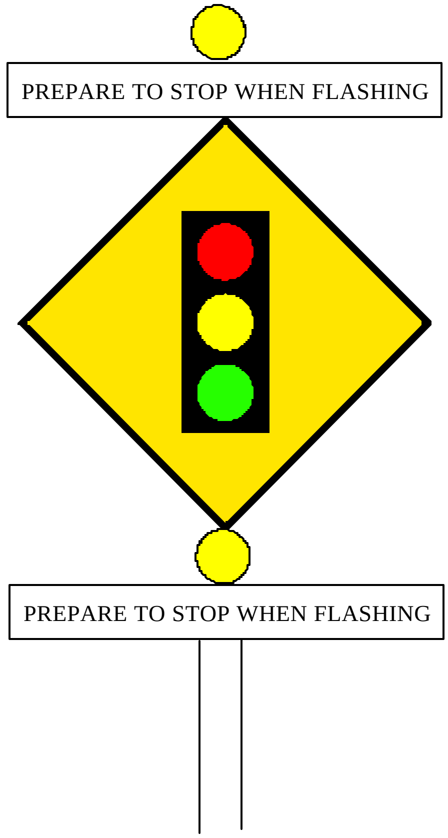


Figure 3-2 Advance Warning Signal System

Figure 3-3 AWS Design Adopted by MnDOT

3.3 Extend Green Light

This section describes technologies based on the concept of extending the green phase for a direction, when drivers approach intersection during the transition of right-of-way.

3.3.1 Advance Detection

The AD technique employs a pair of loop detectors that detect approaching vehicles and extend green time accordingly. The AD technique includes four or five detectors close to the stop line and upstream from the intersection. Distance between the detectors depends on location of the DZ. The detectors are placed just outside the DZ so they can detect approaching vehicles and give them sufficient time to clear the intersection. Location of the ADs is based on a two-second-passage time. The beginning of the DZ is determined by the following equation [10]:

$$D_{bz} = t_{PRT} + \frac{V^2}{2a}$$

Where:

D_{bz}	=	beginning of DZ (ft)
t_{PRT}	=	perception-reaction time (secs)
V	=	design speed of the vehicle (mph)
a	=	deceleration rate (ft/sec^2)

A vehicle's presence is detected and sent to the signal controller. Green time is then extended for a few seconds so vehicles have time to clear the intersection before the light changes to red.

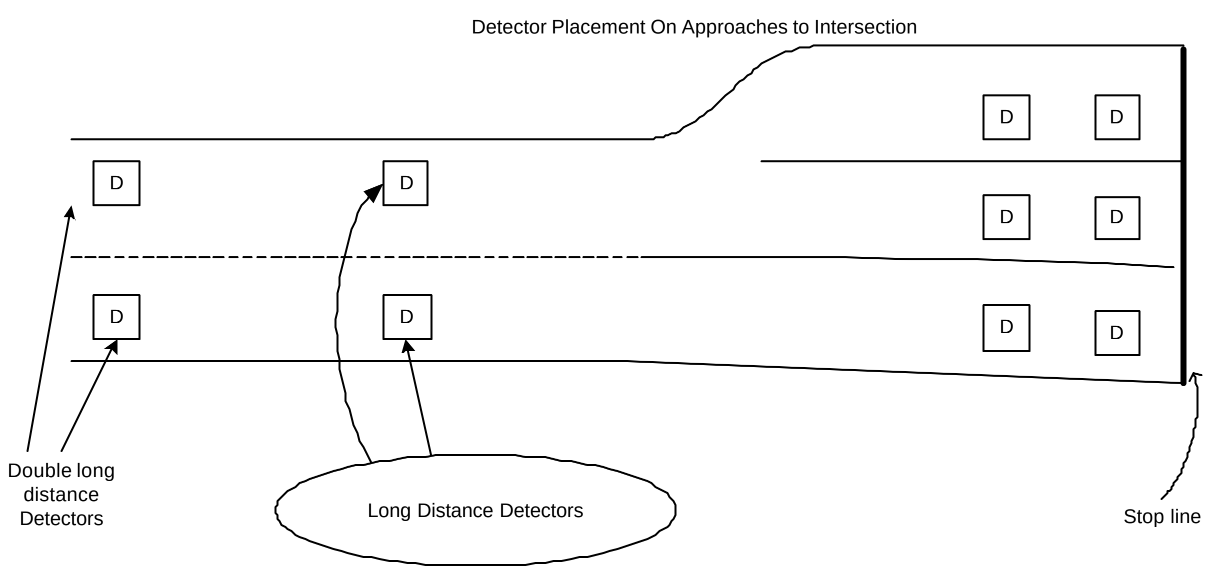


Figure 3-4 Detector Placement on Intersection Approach

When the green timer and extension timer slow down, the controller estimates that there are no vehicles in the DZ or that approaching vehicles are far enough away to come to a stop. However, the controller automatically shifts the signal when the maximum green time is reached. This shift generally is abrupt and does not give adequate warning to drivers in the DZ. This usually occurs when the gap, i.e. the headway between vehicles, is large. This is known as max out. Shifting right of way to the minor road, when there are no vehicles on the major road is known as gap-out. Gap-outs are favored to max-outs. In areas with frequent max-outs due to heavy traffic volumes, AWS systems are used for DZ protection.

A major disadvantage of AD is that it extends the green signal for vehicles between long headways. These long headways increase the probability of max-outs and reduce the level of DZ protection. This problem becomes more pronounced during high flow rates. The maximum allowable headway for AD design is:

$$MAH = \frac{D_1}{V_{\min}} + 2.0$$

Where:

MAH	=	maximum allowable headway (s)
D1	=	distance between first detector and stop line (ft)
V_{min}	=	minimum approach speed required to extend green (ft/sec)
2.0	=	passage time setting on the controller (sec)

Heavy vehicles pose a threat to the safety of other vehicles because they often experience difficulties in coming to a complete stop when the light turns yellow. To remedy this problem, additional detectors are placed 100 m upstream from the existing detectors. These additional detectors are known as double long distance detectors.

The study found that long distance and double long distance detection significantly reduce crashes and seem to be effective in reducing vehicles in the DZ. A benefit cost analysis found that long distance and double long distance detectors yielded a benefit cost ratio of 2.0.

3.3.2 AWS + AD

This technology uses advance detectors and AWS for providing DZ protection. ADs detect vehicles and the controller extends the green light at the intersection. When the green time reaches a maximum, the controller starts a count down to the yellow signal. AWS is activated simultaneously to warn drivers to slow down and stop at the intersection. This combination of AD and AWS provides better DZ protection than when each method is used separately.

4. LITERATURE REVIEW

This chapter examines the literature published on various DZ protection methods.

Pant and Yuhong Xie [1] compared the way drivers respond to various types of warning signals. The study was based on a speed and intersection conflict analysis. They studied the effect of Continuously Flashing Symbolic Signal Ahead (CFSSA), Prepare To Stop When Flashing Sign (PTSWFS), Flashing Symbolic Signal Ahead (FSSA) and the Passive Symbolic Signal Ahead (PSSA) sign on drivers' approach speeds to intersections. They found that CFSSA had the same effect as PSSA in reducing speeds. However, PTSWFS and FSSA increased vehicular speeds because drivers attempted to sneak through yellow signal phases. The continuous flasher does not inform the driver of changes in signal state. However, it does help reduce approach speeds. The benefits of these signs also depend on road geometry. The study recommends installation of CFSSA before PTSWFS.

The Ministry of Transportation in Ontario conducted a before and after study to evaluate effectiveness of true active, active advance warning, and other detection techniques [3]. The study compared accident occurrences, collision frequency, red light violations, speed profiles, and the number of vehicles in DZ per cycle. The Ministry found that AWS and AD were ineffective in reducing vehicles speeds at high-speed intersections. However, they reduced the overall accident rates. The study also found that long and double distance detectors reduced the number of vehicles in DZ.

Gibby, Washington, and Ferrarra [2] studied high-speed isolated signalized intersections (HSISI). They found that HSISI with AWSs functioned better than those without AWSs. Intersections with AWS had significantly lower rear end, left turn, right angle, and rear end approach accident rates. They recommend placing flashing beacons on AWS systems that are more than 2,000 feet from an intersection. This alerts drivers and gives them sufficient time to make decisions when approaching an intersection. The study focused on accident rates and vehicle approach speeds. Benjamin, Jr. evaluated strobe lights. Strobe lights are horizontal bars positioned across the middle of the red lens with about 60 flashes of white light. The Virginia Department of Transportation equipped several intersections with strobe light technology. The study evaluated intersections with strobe lights to determine their effectiveness in reducing red light violations. It considered accident rates and the number of red-light runners.

McCoy and Pesti compared the performance of AD and AWS at high-speed signalized intersections in Nebraska. They found that AD and AWS performed similarly during field studies. A combination of AD and AWS significantly lowered the expected percentage of vehicles in DZ at the onset of the yellow signal. They allowed drivers traveling at design speeds and just below design speeds to decide in advance whether to stop or proceed through an intersection. They also reduced the problems of "max-out" and maximum allowable headway that occur when AD and AWS are used separately. McCoy and Pesti compared systems using the following performance measures: number of vehicles in DZ, number of red-light runners, frequency of max-outs, number of abruptly stopping vehicles, and number of drivers that accelerated upon seeing the yellow signal.

Denise describes the installation of AWS as an improvement and alternative to the DZ protection provided by traffic signals. He is in favor of AWS systems. The AWSs are used at intersections with at least one of the following:

- a posted speed of 70 km/hr (45 mph) or greater
- an obstructed view of the traffic signals due to vertical or horizontal alignment
- a grade on the road, which requires an above-average braking effort
- intersections occurring after long stretches on a high-speed road

4.1 Summary of Literature Review

The literature show that AD and AWS perform similarly and do not provide a high degree of DZ protection. AWS effectively informed drivers of changes in the downstream intersection signals, however, they could not prevent drivers from being caught in DZ. The AD technique did not produce a significant change in driver speed, but did not reduce the number of vehicles in DZ. AWS will be less effective over time as drivers become accustomed to the signal mechanism.

The following observations can be made from the literature reviewed so far:

- AD is a widely used technique for reducing the number of vehicles in DZs. This method has some limitations.
- AWS are more effective when they are placed at intersections occurring after a long gap or when there are sight limitations due to road alignment and geometry.
- The initial success and response toward AWS attributed to its novelty and its effectiveness is reduced over time, therefore, AWS must be used sparingly.
- Few studies have completely evaluated the AWSs and considered the complete list of relevant MOEs.

5. RESEARCH METHODOLOGY

The chapter describes methodology used for studying the effectiveness of AWS systems at Brigham City and St. George. This research will determine whether the current AWS systems are effective in reducing the number of drivers in the DZ. This can be achieved by evaluating whether the benefits to drivers compensate for installation costs. The AWSs can be evaluated by performing a "before and after" study. The "after" case can be easily performed, since AWS has already been installed. However, for the "before" case, the intersection must not have AWS. Since the removal and installation is expensive and not economically feasible, the "before and after" study is modified and another intersection without AWS is selected. This intersection is designated as the control intersection. The control intersection is compared with the two study locations equipped with AWS.

Study locations:
Brigham City: located at the junction of US 89/91 and Main Street
St. George: located at the junction of Snow Canyon Parkway and SR 18

Control location:
Logan: located at the junction of US 89/91 and SR 101

The Brigham City and St. George AWS systems are perfect candidates for the "after" case because drivers are becoming familiar with them.

The method for the research is: obtain field data, build a model to adequately represent field conditions, find the number of vehicles in DZ, and validate it by comparing it with the real world data. The study's MOEs are compared using a chi-square test. A model is constructed to find the number of vehicles in DZ for each intersection. The model will account for differences between the control intersection and the study intersections such as geometry, topography, AADT, and signal timing. The model is described in the next chapter.

5.1 Evaluation Parameters

The study considers these measures:

- number of vehicles in DZ
- number of vehicles running red lights at the intersection
- number of vehicles coming to an abrupt stop
- vehicle speeds before and after AWS

The above measures are used to compare the performance of the Brigham City and St. George AWSs. The following table lists the various MOEs and the variables used to compute them.

5.2 Estimating Sample Size

Sample size is computed using the formula $n = \dfrac{Z_{\frac{a}{2}}^{2} p^{*}(1-p^{*})}{E^{2}}$

Where:

$Z_{\frac{a}{2}}$ = number of standard deviations corresponding to the confidence level α
p^{*} = estimate of the proportion
E^{2} = allowable error in the estimated proportion

A test sample can be obtained using a confidence interval, such as 90 percent or 95 percent.

A modified form of the above equation is $n = \dfrac{\left[Z_{1-(1/2)a}\right]^{2}(1-p)}{r^{2}p}$

Where:

r = allowable error
p = proportion of vehicles in DZ

If 10 percent of 1990 vehicles sampled are in DZ, then for a 90 percent confidence interval, the number of vehicles that should be sampled is 2,450. If only 6 percent are in DZ the sample size is 4,265.

5.3 Chi-square Test

A chi-square test determines whether the computed chi-square value is significantly different from the theoretical chi-square value.

5.3.1 Why the Chi-square Test

The chi-square test is used for the following reasons:

- to compare frequency of occurrence in each group for each level
- to test if the differences in proportion of vehicles in DZ at the two locations are due to chance.
- to compare two different populations
- to make no random assignment of treatment as in ANOVA

5.3.2 Description

The chi-square (c^{2}) test can be used to compare the proportion of vehicles in DZ for any two scenarios.

When two categorical variables are studied, a two-way table, also known as a contingency table, can be developed. The contingency table follows.

CONTINGENCY TABLE			
	Column Variable (Group)		
Row Variable	1	2	Totals
Successes	X_1	X_2	X
Failures	$n_1 – X_1$	$n_2 – X_2$	n – X
Totals	n_1	n_2	n

Where:

X_1 = number of successes in group 1
X_2 = number of successes in group 2
$n_1 - X_1$ = number of failures in group 1
$n_2 – X_2$ = number of failures in group 2
$X = X_1 + X_2$ = total number of successes
$n - X = (n_1 - X_1) + (n_2 - X_2)$ = total number of failures
n_1 = sample size in group 1
n_2 = sample size in group 2
$n = n_1 + n_2$ = total sample size

The overall proportion of successes is obtained by dividing the total number of successes by the total sample size. When the proportions are different, the category an observation falls in depends on one variable, or is related to the category into which an observation falls for the other variable. If the proportions are not different, the likelihood of falling into a given category on one variable is independent of or not related to the category into which the observation falls on the other variable. Therefore the test is considered a test of the independence of the two variables that define the rows and columns of the table.

To test the null hypothesis between the two population proportions, $H_0 : p_1 = p_2$ is tested against the alternative that the two populations are different, $H_1 : p_1 \neq p_2$.

The chi-square value is obtained from the observed and expected frequencies,

$$c^2 = \sum_{allcells} \frac{(f_0 - f_e)^2}{f_e}.$$

The computed chi square value is compared to the test $c^2_{test\_statistic}$ value for a 0.05 level of statistical significance.

6. MODEL DEVELOPMENT

This chapter describes the mathematical model to estimate the number of vehicles in DZ, when there is available dilemma zone protection near an intersection.

6.1 Model Purpose

The purpose of modeling is to help engineers estimate the number of vehicles in DZ when there is no dilemma zone protection such as AWS to the drivers. Base conditions are used to model the "before AWS" scenario.

6.2 Model Description

The position and distance of approaching vehicles from the stop line is modeled to determine if a vehicle is in DZ at the onset of the yellow signal. Vehicle speeds are modeled at a point upstream from the intersection using normal distribution. Vehicle class also follows normal distribution. Headway between each vehicle is modeled using exponential distribution. Signal timing of the study approach is obtained from the field data. The yellow signal's cycle times are used to determine the distance traveled by approaching vehicles in that cycle. If the distance traveled is greater than the distance at the reference point, it is assumed that the vehicle has already crossed the intersection. Vehicles that have already crossed the intersection when the light changes to yellow are ignored.

6.3 Model Assumptions

The assumptions of the model are:

- drivers maintain speed until they perceive a signal change
- perception reaction time
- average value is 1.0 second
- maximum value is 2.5 seconds
- deceleration rate
- comfortable rate is 10 ft/sec^2
- maximum rate is 20 ft/sec^2
- vehicle length
- minimum value is 20 ft
- maximum value is 118 ft

6.4 Model Parameters

The parameters required for the model are:

- average and standard deviation of vehicle speed
- average vehicle headway
- vehicle classification
- yellow signal timing for each cycle

7. DATA COLLECTION

This chapter delves into the field data collection part of the study. The three study sites are discussed in the sections that follow. The study sites are described with respect to their different geometric and traffic characteristics.

A preliminary study a reconnaissance visit to the study locations. During this visit, the location is surveyed to decide an appropriate data collection procedure that takes the junction's topography and the positioning of the equipment into account.

7.1 Logan

7.1.1 Description

The northbound approach of US 89/91 is used for the study. The approach road consists of two lanes. It is straight and has no grade. Drivers can view the traffic lights from a distance.

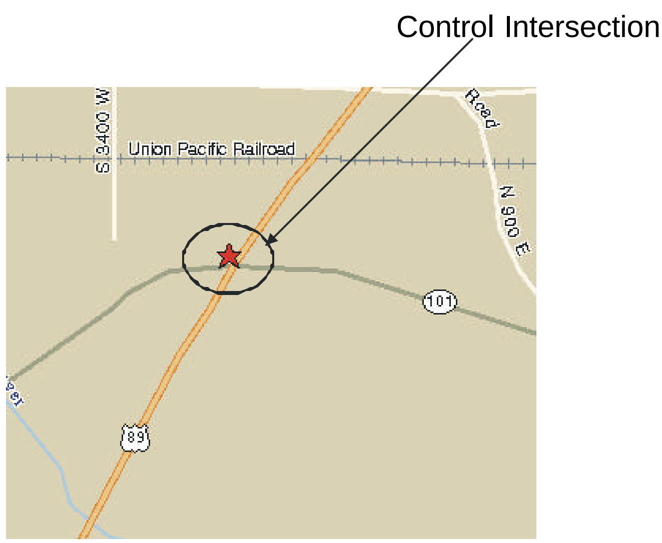


Figure 7-1 US 89/91 and SR 101

DZ detectors are placed 500 ft from the stop line.

7.1.2 Intersection Characteristics

The posted speed limit on US 89/91 northbound is 50 mph, but is reduced to 45 mph near the intersection. The geometric characteristics of the intersection are:

Width (w) = 108 ft
Yellow length interval (t) = 4.5 seconds

7.1.3 Data Collection Method

Automatic tube counters were used to obtain approach speeds, headways, and vehicle classification. Placement of the counters varied from 700 to 1,000 ft from the stop line.

An observer was assigned to video record the intersection during the field data collection period. The video later was used to verify data collected by the tube counter. Two observers performed a speed study to find if drivers were reacting to the AWS when it was in flashing mode. A fourth observer recorded the signal timing at the intersection and a fifth recorded red-light runners and abruptly stopping vehicles. Figure 7.3 shows the observers' positions on field at the Logan intersection.

The location of the tube counters was based on the following graph, which is a combination of d_c and d_0 plots. The speed range near the intersection was 40 to 73 mph. The tube counters were 730 and 250 ft from the stop line.

The following assumptions were used:

- The reaction time of drivers is 1.25 seconds
- The deceleration rate is 10 ft/sec^2
- Drivers do not change speed before they perceive a signal change.

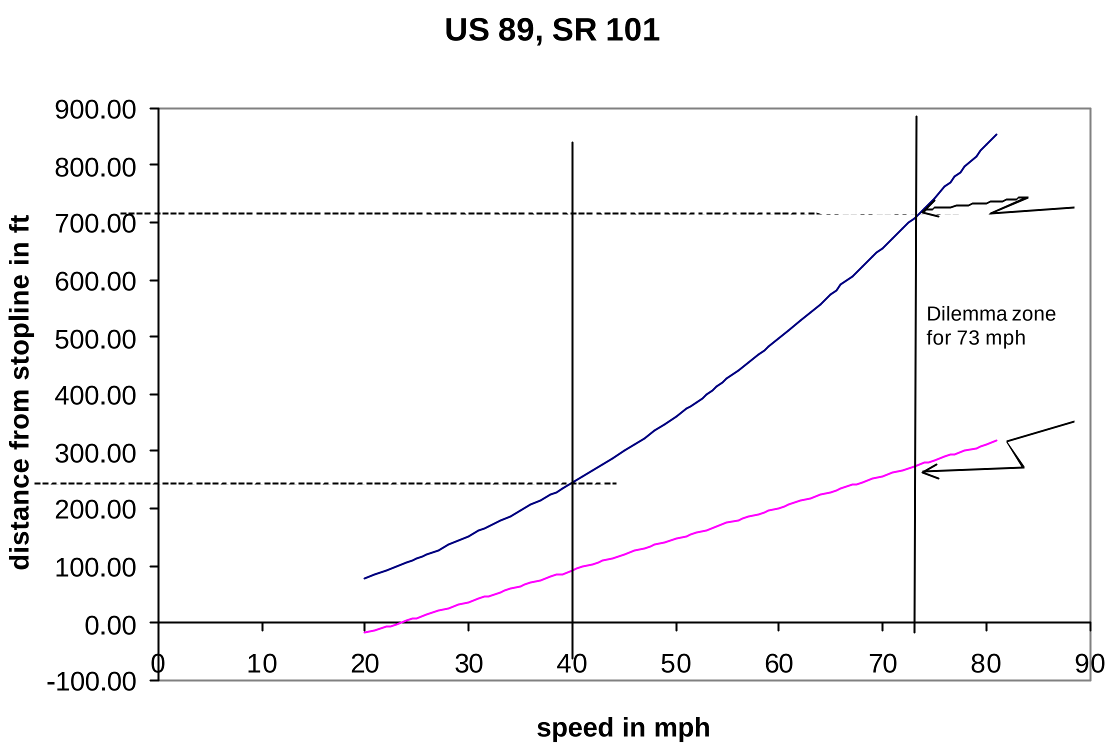


Figure 7-2 Tube Counter Location in Logan

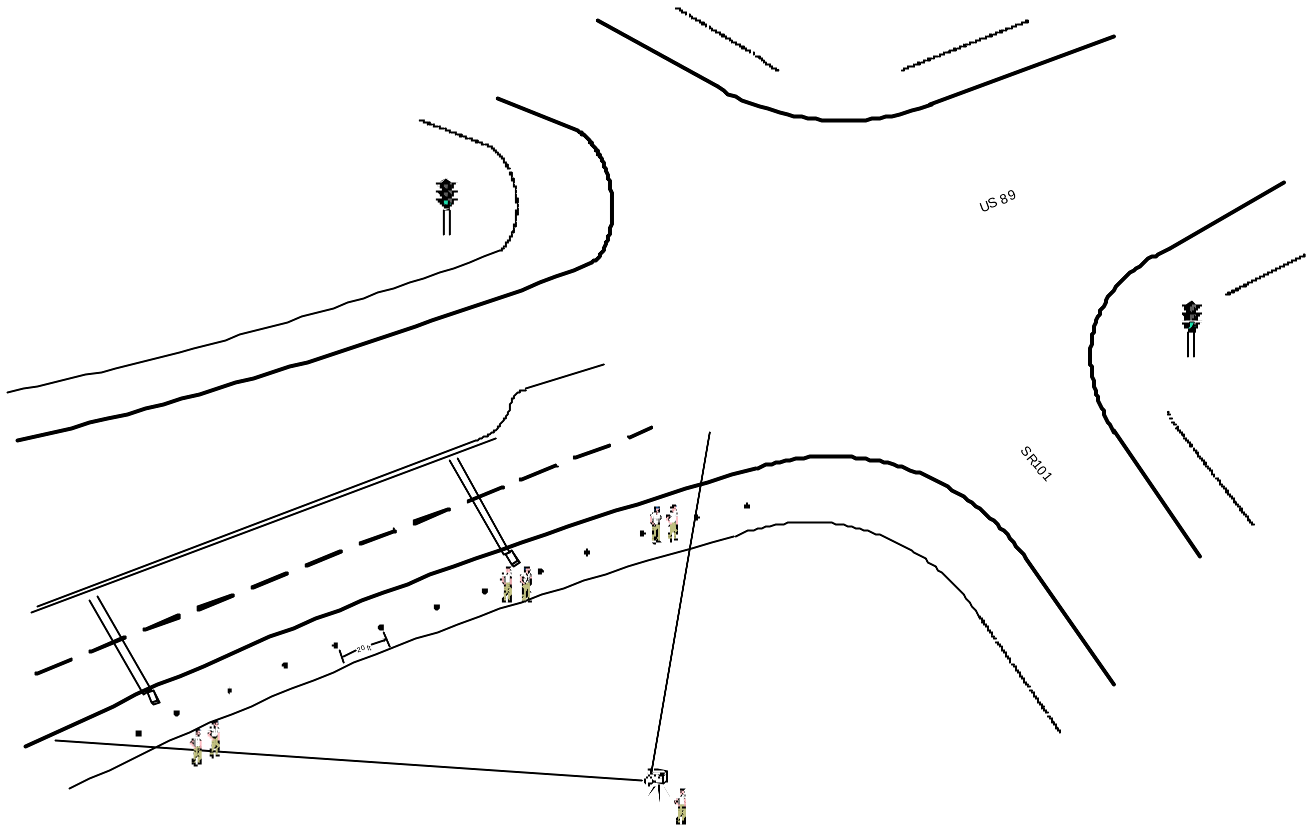
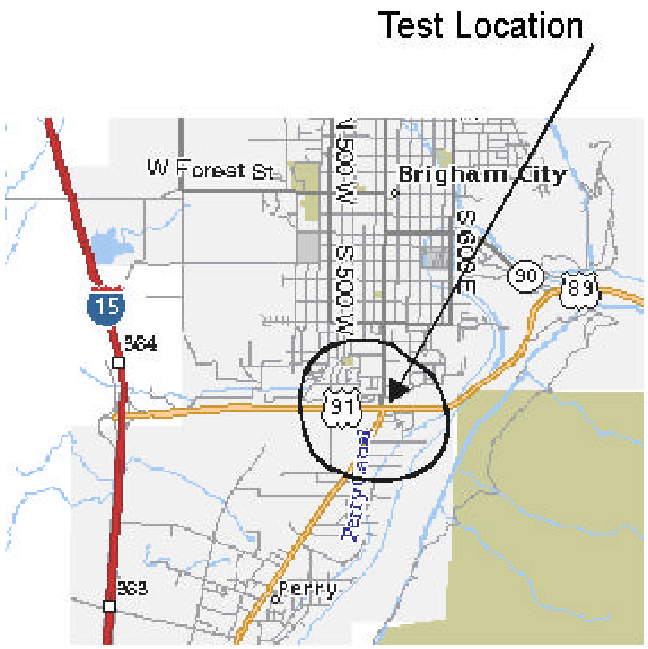


Figure 7-3 Data Collection Procedure at US 89/91 and SR 10

7.2 Brigham City

7.2.1 Description

The AWS is placed upstream from the intersection along the westbound route of US 89/91. A "PREPARE TO STOP WHEN FLASHING" sign is placed on the AWS. The signal starts flashing six seconds before the signal turns yellow. AWS is placed on the downgrade, so drivers can see the AWS and the traffic signal at the same time.



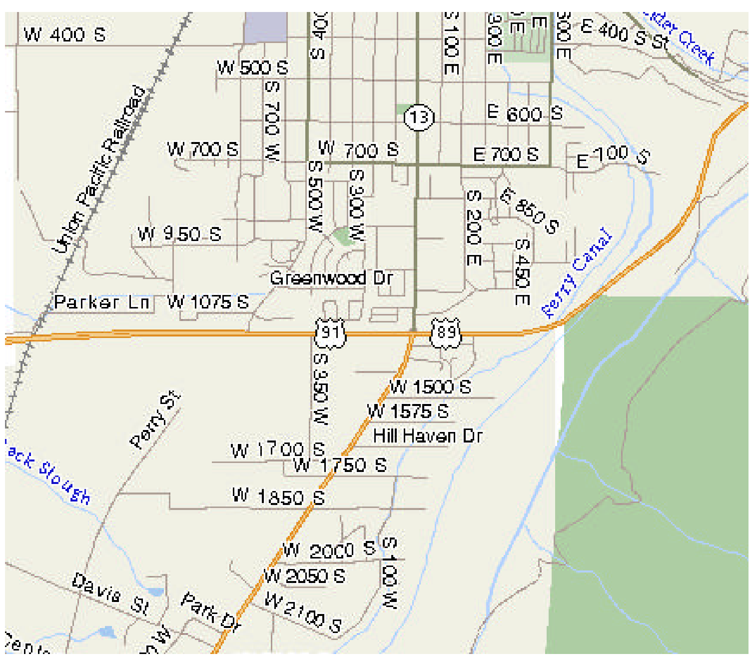


Figure 7-4 Junction of US 89/91 and Main Street, Brigham City

7.2.2 Intersection Characteristics

The characteristics of the Brigham City junction are:

- Intersection width = 95 ft
- Grade = 6 percent down grade
- Number of lanes = two
- Yellow time interval = 4.5 seconds
- All red time = 2.0 seconds
- Location of AWS from stop line = 500 ft.
- AWS lead flash time = 6.0 seconds

7.2.3 Data Collection Method

Day I: April 11, 2003
Five observers were employed to collect data at the intersection. Two observers collected vehicle speeds, two observers counted the number of red-light runners and abruptly stopping vehicles and a fifth observer recorded the signal timing at the intersection using a manual count board. The data was collected for five hours. The video recording of the approach was used to complement the data recorded by the tube counter. A tube counter was placed 750 ft from the intersection stop line.

Day II: July 7, 2003
A second field study was conducted at Brigham City to supplement data collected during the first field study. Two observers were employed to collect data for the study. Six hours of data was collected on the same day during two sessions. One observer recorded the vehicles abruptly

stopping at the intersection and those that were running the red light. The second observer recorded the total number of vehicles passing through the intersection. Table 7.1 shows the field data collected at Brigham City.

Table 7.1 Brigham City Field Data

Item	Day I	Day II	Total
Abruptly stopping vehicles	20	19	39
Red light running vehicles	7	6	13
Number of vehicles in DZ	27	25	52
Total number of vehicles sampled	1545	2446	3990
Proportion of vehicles in DZ	0.0175	0.01022	0.013
Number of signal cycles	194	166	460

7.2.4 Observations

The following observations were made during the field study at the Brigham City intersection.

- Drivers decided to stop or clear the intersection based on the traffic lights at the intersection rather than on the flashing AWS.
- Drivers increased their speeds to clear the intersection when AWS was flashing.
- Drivers usually stopped if they were more than 300 ft away from the intersection; if they were closer than 300 ft, drivers usually cleared the intersection.

7.3 St. George

7.3.1 Description

The AWS in St. George is located upstream on the northbound route of SR 18 at Snow Canyon Parkway about 850 ft from the stop line. The AWS begins flashing seven seconds before the start of the yellow signal. It continues flashing until the end of the red signal. The approach is on a curve and the intersection is hidden due to topography. At times the AWS continues flashing six seconds into the green signal. This is caused when the controller activates a dummy left turn phase. This confuses drivers because the flashing AWS is not followed by a red or yellow light. Drivers that become familiar with the flashing AWS likely would ignore it rather than slow down.

Figure 7-5 AWS at Junction of SR 18 and Snow Canyon Pkwy

7.3.2 Intersection Characteristics

The following are the intersection characte ristics at St. George.

- Intersection width = 95
- Number of lanes = two
- Location of AWS from stop line = 850 ft.
- Yellow time interval = 4.5 seconds
- Lead flash time of AWS = 7.0 seconds
- Lag flash time of AWS = 6.0 seconds

Figure 7-6 Approach Lane to Junction of SR 18 and Snow Canyon Pkwy

7.3.3 Data Collection Procedure

Two observers collected data in St. George. The first observer collected MOEs, such as the number of red-light runners and the number of abruptly stopping vehicles. The other observer performed a speed study. He compared vehicle speeds before and after passing the AWS.

7.3.4 Observations

The following observations were made during field data collection at Brigham City.

- Drivers approached the intersection at high speeds.
- Drivers only reduced their speed near the stop line if they were turning left.

8. RESULTS

This chapter analyzes data collected from the three study sites and the model. The results are discussed in the next chapter.

8.1 Field Data

The following table shows the field data collected in three sessions at Brigham City.

Table 8.1 Field Results by Site

Site	#Abruptly stopping vehicles	# Vehicles Running RED	# Vehicles in DZ	# Signal cycles	Total # vehicles	Proportion of vehicles in DZ	% Of vehicles in DZ	%(Test Site) – %(Logan)
Logan	28	26	54	194	1987	0.0271	2.72	-
Brigham City	39	13	52	278	3990	0.0130	1.3	-1.42
St. George	11	10	21	196	543	0.0386	3.87	1.15

8.1.1 Brigham City

From the chi-square test, computed $c^{2}_{computed}$ value is 15.23 and the chi-square $c^{2}_{teststatistic}$ test statistic is 3.81. Since $c^{2}_{computed} > c^{2}_{teststatistic}$, the null hypothesis is rejected. DZ activity in Logan and Brigham City, therefore, is significantly different. Impact of the AWS in Brigham City is significant enough to reduce the number of vehicles in DZ at the intersection.

It was found from the chi-square test for Logan and St. George, that computed chi-square value is 4.65 and the chi square test statistic is 3.81. Since the computed chi-square is greater than the test statistic, there is a significant difference in the proportion of vehicles in DZ between Logan and St. George. St. George, in fact, had a higher number of vehicles in the DZ than the control intersection. The St. George AWS also did not reduce vehicle speeds.

8.2 Model Results

This section shows results from the model using the data collected from three intersections.

Table 8.2 Model Results

Model	No. Of Vehicles in Dilemma Zone	Number of vehicles sampled	Proportion of vehicles in DZ	Percentage of Vehicles in DZ
Logan	54	1918	0.028	2.8
Brigham City	33	1431	0.023	2.3
St. George	22	535	0.041	4.1

Table 8.3 Chi-square Test Results

Site	$c^{2}_{computed}$	$c^{2}_{test\_statistic}$	Null Hypothesis: $p_1 = p_2$
Model_Logan	0.051	3.841	Not Rejected
Model_Brigham City	6.8	3.841	Rejected
Model_St.George	0.042	3.841	Not Rejected

9. DISCUSSION

This chapter interprets results obtained from the model and field data.

9.1 Brigham City

The field data shows that Brigham City has 1.4 percent fewer vehicles in DZ than the control intersection at Logan. The difference is not significant enough to show high benefits for AWS. The study of vehicle speeds near AWS shows, however, that most drivers respond positively to the flashing AWS and reduce their speeds. This anomaly between the chi-square test results and the speed study is due to the following reasons:

1. Familiarity with AWS: Most traffic on this road is local. After passing the flashing AWS a number of times drivers become familiar with the way it works. This familiarity with the signal helps them to pre-calculate the time left before the yellow phase and accelerate accordingly to clear the intersection. This familiarity defeats the purpose of AWS and is the main cause for the signal's ineffectiveness.
2. Topography: The approach to the Brigham City intersection along US 89/91 Southbound has a 6 percent downgrade. This allows drivers to see the flashing AWS and the traffic lights at the intersection simultaneously. Drivers initially decelerate upon seeing the AWS flashing and then accelerate when they see that the traffic signal is still green. Intending to beat the traffic lights at the intersection makes drivers vulnerable to DZs.
3. Downgrade: Since the road is on a downhill grade, drivers are more inclined to clear the intersection than to stop.

9.2 St. George

The chi-square test for St. George and Logan shows that the AWS in St. George is ineffective due to lag flashing. The AWS at St. George continues flashing for a few seconds even after the signal turns green. The lag flash time confuses the driver because, although the AWS is still flashing, he can see that the traffic signal has changed from red to green. As drivers become familiar with the lag flash time, the effectiveness of AWS is reduced.

10. Conclusions

This chapter provides conclusions drawn from the study and some recommendations for improving the effectiveness of AWS systems.

The study considered the two AWS systems presently used in Utah. It found that the setup and performance of the two systems vary. Therefore, conclusive evidence of the systems' effectiveness cannot be provided. The following conclusions are specific to the study sites.

- The AWS in Brigham City is effective in providing DZ protection.
- When the AWS is active in Brigham City, drivers reduce their speeds near the signal.
- The AWS in St. George is not effective in providing DZ protection.

10.1 Recommendations

UDOT can implement the following recommendations for maintaining the existing AWSs and for installing new ones:

1. Install AWS such as at Brigham City.
2. Make future investigative studies must be location and intersection specific.
3. Modify existing AWS at St. George by removing lag flash time.

10.2 Limitations of the Study

The limitations of this research are:

- collection of real world data for the "before AWS" scenario
- duration of study and confidence interval of the sampled data
- unavailability of suitable equipment to measure drivers' reaction time and deceleration rates

10.3 Recommendations for Future Research

Recommendations for future research are:

1. Conduct an extensive study of AWS by selecting a suitable intersection. The intersection should be a junction of two high-speed roads with constrained sight distances and/or on a grade. The study can use a portable form of AWS that can be moved easily along the approach to the intersection.
2. Consider many AWS sites, if possible.

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Appendix A-1.

MN/Dot guidelines for advance warning flashers

The following is taken from Chapter 9 of the Traffic Engineering Manual, MN/DOT.
9-4.02.03 Advance Warning Flashers Consideration

An Advance Warning Flasher (AWF) is a device which MN/DOT uses to convey to the motorist information about the operation of a traffic signal. An AWF typically is found at certain high speed locations where it may be necessary to get motorist attention through a visual indication about a pending change in the indication of a traffic signal. The AWF assists the motorists in making safer and more efficient driving decisions by informing them that they must prepare to stop. The AWF configuration, placement, and timing details can be found in Chapter 4M of the MN MUTCD.

The following guidelines indicate when the installation of advance warning flashers (AWF) for signal change interval should be considered. Due to the complex nature of traffic flow characteristics, these guidelines should be applied with engineering judgment. Guidelines should be reviewed for each prospective installation.

An AWF should be installed only 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 action should be considered.

The following guidelines generally apply only where the posted speed is 55 mph or higher:

1. An isolated or an unexpected signalized intersection

   This situation can occur where there is long distance from the last intersection at which the mainline is controlled, or the intersection is otherwise unexpected. This guideline may be applicable where the distance from the last intersection is greater than 15 km (10 miles), a freeway terminus, or at other locations where the intersection is unexpected.

2. A limited sight distance

   This can occur where the distance to the stop bar, D with two signal heads visible is insufficient. See Graphs of Limited Sight Distance, Table 9.1A & Table 9-1B. A sight distance falling below the lines for the given speed and grade indicates the possible need for an AWF.

$$D \leq 0.45vt + \frac{v^2}{10(a + 9.8s)} \qquad \text{(metric)}$$

$$D \leq 1.467vt + \frac{v^2}{0.93(a + 32.2s)} \qquad \text{(English)}$$

Where:

D = distance to stop bar in meters or feet
v = posted speed limit in mph
t = reaction time, 2.5 seconds
a = acceleration rate

for trucks use	$2.4\ m/s^2$	(metric)
	$8\ ft/s^2$	(English)
for all traffic use	$3.0\ m/s^2$	(metric)
	$10\ ft/s^2$	(English)

s = positive or negative decimal gradient

3. Dilemma zone

   This situation exists when a dilemma zone exists for all traffic or for heavy vehicles. A dilemma zone exists if the yellow interval time can not practically be set to at least the yellow interval time indicated in Signal Timing Manual. An AWF may be considered, but longer yellow should be considered first.

4. Crashes

   If an approach has crash problem, the intersection should be examined for existence of dilemma zone or sight distance restriction. If no sight distance or dilemma zone problems exist, an AWF may not be an appropriate countermeasure for accident problems.

5. Heavy truck volume

   Where the roadway has a grade of 3 percent or greater and truck volume exceeds 15 percent.

6. Engineering judgment

   Combinations of the above guidelines or other considerations may justify installation of an AWF. Engineering judgment should be based on additional data, such as complaints, violations, conformity of practice, and traffic conflicts. Prior to installing an AWF, consideration should be given to countermeasures including but not limited to: adjustment of timing parameters which may include increasing yellow and/or all red intervals, improving detection, modification of the signal system as by adding signal heads, adjusting speed limits, and installing continuously operating flashers with standard "signal ahead" warning signs.

July 1, 2000

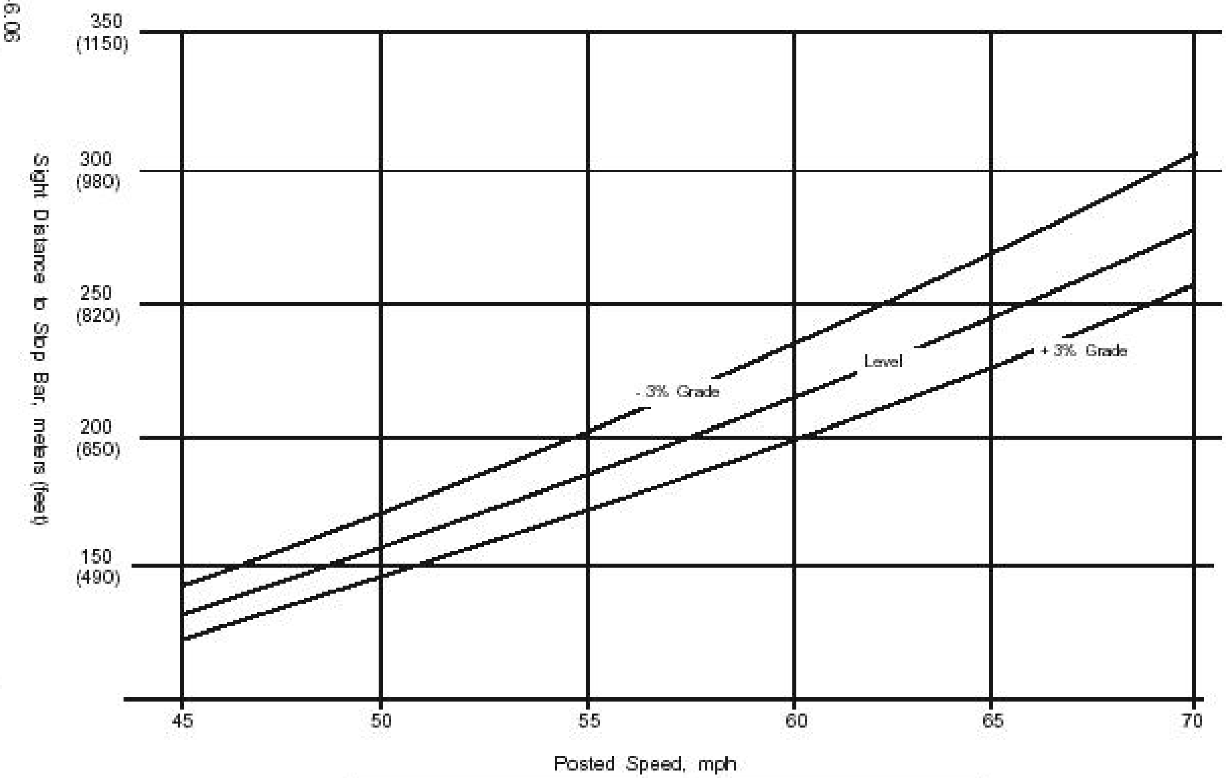
LIMITED SIGHT DISTANCE GRAPH

TABLE 9.1A

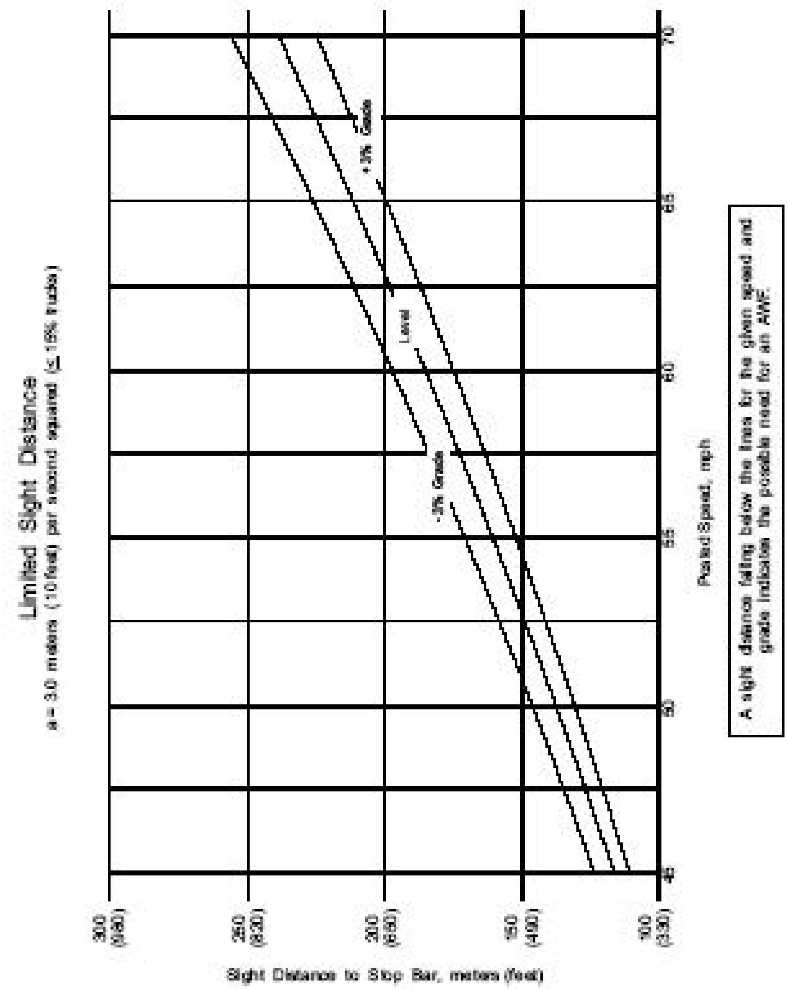
Text Ref.: 9-6.06

Limited Sight Distance

a = 2.4 meters (8 feet) per second squared (> 15% trucks)



A sight distance falling below the lines for the given speed and grade indicates the possible need for an AWF.



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July 1, 2000	LIMITED SIGHT DISTANCE GRAPH	TABLE 9.1B

Appendix A-2.

MN/DOT MUTCD

PART 4. HIGHWAY TRAFFIC SIGNALS

Chapter 4M. Advance Warning Flashers

4M.1 Description

SUPPORT:

The Advanced Warning Flasher (AWF) is a device which, at certain high speed locations, has been found to provide additional information to the motorist describing the operation of the traffic signal. It has been found that and Advance Warning Flasher can assist the driver in making safer and more efficient driving decisions. The additional information includes a visual indication to get the driver's attention and a specific notice that the driver must prepare to stop.

The Minnesota Advance Warning Flasher system consists of a flasher and a sign located on main street approaches to a high speed signalized intersection. The AWF is connected to the traffic signal in such a way that when the main street green is about to change to yellow, the flasher is turned on to warn the approaching drivers of the impending change. Basically, the purpose of an optimally designed combination of traffic signal and Advance Warning Flasher system is twofold: 1) to inform the driver in advance of a required drive decision (prepare to stop) and 2) to minimize the number of drivers that will be required to make that decision.

4M.2 General Design and Operation

GUIDANCE:

If used, then the guidelines for installation should be the following:

1. Advance Warning Flasher - The Advanced Warning Flasher assembly is shown in Figure 4M-1. The flasher shall flash yellow in a wig-wag manner prior to the termination of the green (See number 3, below), and during the yellow and red periods of the signal. The flasher will also flash if the signal goes into flashing operation. Power shall be supplied to the Advance Warning Flasher from the signal control cabinet.

Posted Speeds (mph)	AWF Placement meters	AWF Placement feet	Leading Flash (seconds)
40	170	560	8.0
45	170	560	7.0
50	215	700	8.0
55	215	700	7.0
60	260	850	8.0
65	260	850	7.5

Table 4M-1. Advance Warning Sign Placement

2. Advance Warning Flasher Sign Placement - The Advance Warning Flasher should be set back from the intersection in accordance with the Table 4M-1. Where this is not possible, the leading flash must be adjusted for the actual distance by using the formula below. At locations on four lane divided roadway, it shall be placed on both sides of the approach.

3. Leading Flash - The Leading Flash is the amount of time, prior to the signal turning yellow, that the Advance Warning Flasher flashes. It shall flash during the Leading Flash Period and continue flashing through the signal's yellow clearance interval and the red. The Leading Flash time is shown in Table 4M-1.

For existing systems where the placement is other than what is listed in Table 4M-1, the Leading Flash Time can be computed by the following formula:

Metric: $$F = \frac{2.24D}{v} - 1.5$$

English: $$F = \frac{0.68D}{v} - 1.5$$

Where:
F = Leading Flash Time (seconds)
D = AWF Placement (meters or feet)
v = Posted Speeds (mph)

4. Detector Placement - The detection of the intersection shall be determined without regard to the Advance Warning Flasher.

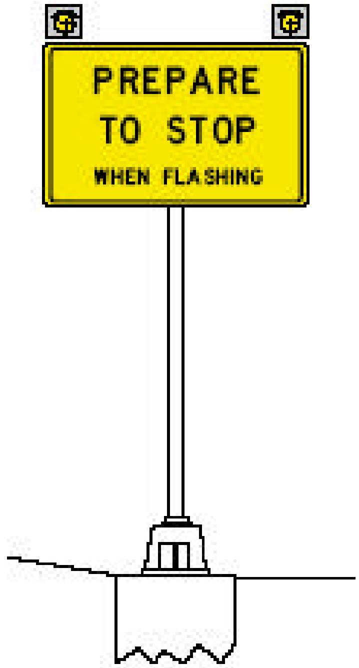

Figure 4M-1. Advance Warning Assembly