

**Dilemma Zone Protection on High-Speed Signalized Intersection Approaches:
Advance Detection Versus Advance Warning Flashers and Advance Detection**

by

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ABSTRACT

The performances of two methods of providing dilemma zone protection, which are used by the Nebraska Department of Roads (NDOR), were compared. One method uses advance detectors at multiple locations to extend the green and prevent the onset of yellow while approaching vehicles are in their dilemma zones. The second method has advance detection at only one location and advance warning flashers (AWF) on signs with the legend PREPARE TO STOP WHEN FLASHING, which are interconnected to the traffic signal so that the flashers are activated at a predetermine time before the onset of yellow. Field studies indicated that the two designs performed equally well with respect to drivers stopping abruptly, running the red light, and accelerating on the yellow. However, the design with the AWF had a significantly lower than expected percentage of vehicles in their dilemma zones at the onset of yellow. Also, vehicles upstream of the AWF, when they were flashing before the onset of yellow, had a greater than expected tendency to stop, suggesting that the advance warning flashers may have performed as intended. However, the advantage of the AWF design's much shorter maximum allowable headway (MAH) is compromised at low traffic volumes by the narrower speed range for which it provides dilemma zone protection.

INTRODUCTION

Dilemma Zone

On a high-speed approach to a signalized intersection, there is a length of roadway in advance of the intersection, commonly referred to as the "dilemma zone" (1), wherein drivers may be indecisive and respond differently to the onset of the yellow signal indication. When in the dilemma zone at the onset of yellow, some drivers may stop abruptly while others may decide not to stop, and perhaps even accelerate through the intersection. Such variation in driver behavior is conducive to the occurrence of collisions on the intersection approach. In some cases, drivers' decisions to proceed through the intersection at the onset of yellow may cause a collision with vehicles on conflicting phases. Thus, the safety of traffic operations on high-speed signalized intersection approaches is promoted by the provision of dilemma zone protection, which prevents the onset of yellow while approaching vehicles are in their dilemma zones.

Dilemma Zone Protection

Common methods of providing dilemma zone protection on high-speed approaches to signalized intersections are: (1) advance detection (AD) and (2) AWF. In the case of AD, detectors are placed at multiple locations on the intersection approach to extend the green and prevent the onset of yellow while approaching vehicles are in their dilemma zones. Studies in Kentucky (2), Texas (3), and California (4) have found that AD is effective in reducing crashes and traffic conflicts on high-speed approaches to signalized intersections. However, some (1,5) have noted the long allowable gaps permitted by AD increase the frequency of reaching the maximum green interval at which point the green is terminated and the yellow is displayed immediately without regard to the presence of vehicles in the dilemma zone. The termination of green in this manner is referred to as "max-out." Thus, when max-out occurs, the dilemma zone protection is lost, which becomes a greater problem as traffic volumes on the approach increase.

AWF consists of warning signs equipped with one or more yellow flashing beacons. The signs typically used are warning signs with the legend PREPARE TO STOP WHEN FLASHING. The signs are interconnected with the traffic signal at the intersection so that the

flashers are activated at a predetermined time before the end of the green interval. This lead-flash time is based on the distance from the sign to the stop line and the prevailing approach speed, or the posted speed limit. In this way, AWF is intended to reduce the indecision of drivers and the variability in their behavior by providing them with additional information about the status of the traffic signal ahead. An evaluation of the accident experience at isolated high-speed signalized intersections in California (4), indicated that AWF on high-speed signalized intersection approaches is effective in reducing total, rear-end, right-angle, and nighttime accidents. However, the results of accident studies in Minnesota (6) and Canada (7) were mixed. Some intersections experienced accident reductions and others did not, especially intersections with low minor-road traffic volumes.

Nebraska Experience

In Nebraska, as expected, the dilemma zone protection provided by AD has been limited on high-speed signalized intersection approaches with higher traffic volumes, because of frequent max-out. To overcome this shortcoming of AD, NDOR developed a new design (AWFAD), intended to provide dilemma zone protection with a shorter MAH and less frequent loss of dilemma zone protection due to max-out. Although AWFAD has received many favorable comments, especially from truck drivers, some anecdotal evidence suggests that novelty effects account for its initial success and its effectiveness may diminish over time. In addition, some studies (8,9) recommend against the use of AWFs, because they found them to encourage drivers to accelerate at the onset of yellow. In light of the anecdotal evidence and previous studies, this research was conducted to compare the dilemma zone protection provided by the designs.

OBJECTIVE

The objective of the research was to evaluate and compare the dilemma zone protection provided by the AD and AWFAD designs. The results of the evaluation were used to develop guidelines for the installation of dilemma zone protection on high-speed signalized intersections in Nebraska. The guidelines define the traffic and roadway conditions for which each design is a more cost-effective method of providing dilemma zone protection than the other. The evaluation and comparison of the designs are presented in this paper. The implementation guidelines and recommended modifications to the AWFAD design are presented elsewhere (10).

DESIGN ALTERNATIVES

AD Design

Detector Layout

The AD design includes four or five advance detectors and stop-line detection in each through lane. The advance detectors operate in the pulse mode. The stop-line detectors operate in the presence mode and are active during the extendible portion of the green interval.

The locations of the advance detectors are based on a 2.0-second passage time and the following stopping distance definition of the beginning of the dilemma zone:

$$D_{bz} = t_{PRT} V + \frac{V^2}{2a} \quad (1)$$

where, D_{bz} = beginning of dilemma zone (ft),
 t_{PRT} = perception-reaction time (s)

V = design speed (fps), and
 a = deceleration rate (fps²).

NDOR uses a 2.0-s perception-reaction time and a 10-fps² deceleration rate in Equation 1. The advance detector locations for design speeds from 45 to 65 mph are shown in Table 1.

Speed Range of Dilemma Zone Protection

The locations of the advance detectors ensure that vehicles traveling at, or below, the design speed will not be in their dilemma zones at the onset of yellow. In other words, these vehicles will either: (1) extend the green until they reach the intersection, or (2) be at least one stopping distance from the intersection at the onset of yellow. Vehicles, which are traveling faster than the design speed and have not reached the first advance detector, may be in their dilemma zones (*i.e.*, closer to the intersection than one stopping distance) at the onset of yellow. Therefore, the AD design provides dilemma zone protection for vehicles traveling at, or below, the design speed.

MAH

One of the shortcomings of the AD design is the relatively long headways it allows between vehicles to hold the green. These long headways increase the frequency with which max-out occurs, which in turn reduces the level of dilemma zone protection it provides. The MAH for the AD design is:

$$MAH = \frac{D_1}{V_{min}} + 2.0 \quad (2)$$

where, MAH = maximum allowable headway (s),
 D_1 = distance between first detector and stop line (ft),
 V_{min} = minimum approach speed required to extend green (fps), and
 2.0 = passage-time setting on controller (s).

The MAHs of the AD design for design speeds from 45 to 65 mph are shown in Table 1.

The relationship between the probability of max-out and MAH for phases serving more than one lane is:

$$P_{MO} = (1 - e^{-qMAH})^n \quad (3)$$

where, P_{MO} = probability of max-out,
 Q = total flow rate served by phase (vps),
 MAH = maximum allowable headway for phase (s),
 n = number of calls necessary to extend green to maximum.

The value of n is a function of the maximum green interval setting of the controller. The derivation of Equation 3 is presented elsewhere (11). Its solution is accomplished by an iterative procedure (1). The effects of the MAH and maximum green interval are illustrated in Figure 1.

AWFAD Design

Detector Layout

The design has one advance detector and stop-line detection in each through lane. The advance detector operates in the pulse mode. The stop-line detector operates in the presence mode, but it is not active during the extendible portion of the green interval.

In addition to the advance detector, AWF on warning signs with the legend PREPARE TO STOP WHEN FLASHING are placed on each side of the approach downstream of the

advance detector. Two yellow beacons are mounted on the top of each sign. The beacons begin to flash 5 to 7 seconds before the onset of yellow. The location of the signs is according to the guide for advance warning sign placement in the Manual on Uniform Traffic Control Devices (12). The location of the advance detector is based on a 3.0-second travel time between the detector and the advance warning sign location as follows:

$$D = 3.0V + D_M \quad (4)$$

where, D = distance between advance detector and stop line (ft), and
 D_M = distance between AWF and stop line (ft).

The locations of the advance detector and AWF for design speeds from 45 to 65 mph are shown in Table 2.

Speed Range of Dilemma Zone Protection

The 3.0-second passage time setting on the controller enables a vehicle to extend the green interval by 3.0 seconds when it passes over the advance detector. If gap-out occurs after the 3.0-second extension of the green, the yellow beacons on the advance warning sign will begin to flash. A vehicle traveling at the design speed would pass the advance warning sign at the instant the beacons begin to flash. However, the driver would not see the beacons flashing and, therefore, would not be advised to prepare to stop. A vehicle traveling below the design speed would not reach the advance warning sign before the beacons begin to flash and the driver would be advised to prepare to stop.

Once the beacons begin to flash, the green interval will continue for a period of time, which is equal to the travel time between the advance warning sign and the stop line for a vehicle traveling at the design speed. The duration of this lead flash is:

$$t = \frac{D_M}{V} \quad (5)$$

where, t = duration of lead flash (s).

After the lead flash period, the onset of yellow occurs.

Vehicles traveling at the design speed would reach the stop line before the onset of yellow and be provided dilemma zone protection. Based on the definition of the beginning of the dilemma zone in Equation 1, dilemma zone protection would also be provided for some vehicles traveling faster than the design speed; because not only would they be able to reach the stop line before the onset of yellow, but, if the onset of yellow occurs immediately before they pass over the advance detector, they would still be outside of their dilemma zones. For example, the advance detector placement of 935 feet from the stop line for the 65-mph design in Table 2 would provide adequate stopping distance, and therefore dilemma zone protection, for speeds up to 81 mph.

On the other hand, whether or not vehicles traveling below the design speed would be provided dilemma zone protection depends on their speed. If they are traveling slow enough, they would not have reached the beginning of their dilemma zone before the onset of yellow. Based on the definition of the beginning of the dilemma zone in Equation 1, the maximum speed below the design speed a vehicle could travel and not reach the beginning of its dilemma zone before the onset of yellow is:

$$V_{\max} = -(50 + 10t) + \sqrt{\frac{(100 + 20t)^2}{4} + 20D} \quad (6)$$

where, V_{\max} = maximum speed below design speed with dilemma zone protection (fps).

The speed range for which the AWFAD design provides dilemma zone protection is shown in Table 2. The range is based on the beginning of the dilemma zone defined by Equation 1 and the end of the dilemma zone at the stop line. Vehicles traveling on at speeds outside of the range are not provided dilemma zone protection.

MAH

One of the advantages of the AWFAD design is its shorter MAH. Since there is only one advance detector and the stop-line detectors are not active during the extendible portion of the green, the MAH is simply equal to the passage time of 3.0 seconds. This is much shorter than the MAH shown in Table 1 for the AD design; thus, providing a lower probability of max-out.

STUDY SITES

The evaluation and comparison of the performance of the two designs were based on data collected on six high-speed signalized intersection approaches. Three sites had the AD design with a design speed of 55 mph. The other three sites had the AWFAD design, one with a 55-mph design speed and two with a 65-mph design speed. Roadway and traffic conditions at the sites were similar. Each site was located at an isolated, full-actuated signalized intersection on a rural four-lane expressway with exclusive turning lanes at the intersections. The speed limits on the approaches were 55 mph. The average daily traffic (ADT) volumes were between 5,000 and 10,300 vpd. The approach grades were 3.0 percent or less, except at one AWFAD site, which had a 4.7 percent downgrade.

The advance detectors operated in the pulse mode. All sites had stop line detection, which operated in the presence mode. The stop line detection was active during the extendible portion of the green at the AD sites, but it was inactive during the extendible portion of the green at the AWFAD sites. The AD sites had 2.0-second passage times, minimum greens between 10 and 15 seconds, and maximum greens from 40 to 50 seconds. The AWFAD sites had passage times of 3.0 seconds, minimum greens of 15 seconds, and maximum greens of 50 seconds. The yellow plus all-red times ranged from 4.5 to 5.5 seconds.

The advance detectors in the through lanes at study sites were located according to the distances given in Tables 1 and 2. Likewise, the speed range of dilemma zone protection and MAH at each site was the same as that shown for its design type and design speed in Table 1 or 2. The dilemma-zone-protection speed range and MAH at the AD sites were 0 to 55 mph and 9.3 seconds, respectively. At the AWFAD sites, the dilemma-zone-protection speed range was 0 to 42 and 65 to 81 mph at the two 65-mph design speed sites and 0 to 35 and 55 to 68 mph at the 55-mph design speed site. The MAH at the AWFAD sites was 3.0 seconds.

DATA COLLECTION

Data collection involved video taping the traffic operations on the study approaches with the University of Nebraska's Video Data Acquisition System (VDAS), which consists of two mobile video recording trailers. Each trailer has a high-resolution video camera mounted on a 30-foot pneumatic telescoping mast, a high-grade video recorder, a time-date character generator, a video monitor, remote pan/tilt camera controller, and an AC power generator. In addition, camcorders with time-date character generators were used to supplement and integrate the fields of view provided by the VDAS cameras.

The VDAS trailers were stationed at two locations. One was placed near the intersection so that vehicles in the intersection and within about 250 feet of the intersection could be

recorded. Red-light running, abruptly stopping vehicles, and vehicle speeds at the stop line were obtained from this view. The second trailer was placed about 1,000 feet upstream of the intersection. Vehicle approach speeds were obtained from this view. Marks were painted on the edges of the pavement at each location so that reference grids could be established for data reduction.

One of the camcorders was used to record the traffic signal indications, and the other was used to record an overall view of traffic operations on the study approach. At AWFAD sites, a third camcorder was used to record the status of the flashing beacons on the advance warning sign.

In deploying the cameras, the date and time settings of all video recorders and camcorders were synchronized before each field study, and checked upon completion of the studies. This made it possible to match the video recordings taken from different cameras.

Traffic was video taped at the study sites during the month of September 1999, when the pavement was dry and the weather was clear. Useful data were obtained only during signal cycles with vehicles on the approach at the onset of yellow. Since the study sites had full-actuated signals that would only cycle when there was traffic on the conflicting phases, it was necessary to confine data collection to peak periods in order to obtain a reasonable sample size with the limits of the resources available. The goal was to obtain at least 100 cycles with vehicles on the approach at the onset of yellow at each study site.

DATA REDUCTION

The videos were processed to obtain the data needed to evaluate the dilemma zone protection provided by the design alternatives. The traffic volumes on the study approaches and the conflicting phases were determined from the videos recorded by the VDAS camera located at the stop line. Vehicle speeds, red-light running, and abrupt stops were also obtained from these videos. Vehicle speeds were also obtained from the videos recorded by the VDAS camera located 1,000 feet in advance of the stop line. The speeds at the VDAS camera locations were used to establish the speed profiles of; (1) the first vehicle in each signal cycle to stop at the onset of yellow and (2) the non-stopping vehicle immediately ahead of it. The speeds were calculated using an imaging processing system.

The stopping and non-stopping vehicles were identified by a simultaneous review of all videos recorded at the study site. The synchronized time on the videos made it possible to track each vehicle. The speeds and locations of the non-stopping vehicles at the onset of yellow were estimated from their speed profiles and their arrival times at the two reference grids. The speeds and locations of the stopping vehicles at the onset of yellow were based on their speeds and arrival times at the reference grid at 1,000 feet in advance of the stop line.

The videos of the traffic signal faces were used to determine the times of the onset of yellow and the lengths of the green times. The green times were compared to the maximum green times to determine if max-out occurred.

FINDINGS

The performances of the design alternatives were evaluated and compared on the basis of the following measures of effectiveness (MOEs):

- vehicles in dilemma zone,
- max-out green intervals,
- vehicles running red light

- vehicles stopping abruptly, and
- vehicles accelerating on yellow.

These MOEs were selected as being indicative of the degree of dilemma zone protection provided by the designs.

Vehicles in Dilemma Zone

The primary objective of the alternative designs was to provide dilemma zone protection. Ideally, there would not be any vehicles in their dilemma zones at the onset of yellow. However, if the green terminates by max-out instead of gap-out, dilemma zone protection is not provided. The percent of green intervals with vehicles in their dilemma zones at the onset of yellow when gap-out occurred at each study site is shown in Table 3. The location of a vehicle's dilemma zone was based on its speed at the onset of yellow. The beginning of its dilemma zone was one safe stopping distance upstream from the stop line, which was computed using Equation 1. The end of its dilemma zone was the stop line.

In general, a lower percent of vehicles in their dilemma zones at the onset of yellow indicates a higher degree of dilemma zone protection. However, these percentages must be viewed with respect to the percent of vehicles that were traveling within the dilemma-zone-protection speed ranges of the designs. A higher percent of vehicles in their dilemma zones would be expected when there was a lower percent of vehicles traveling within the dilemma-zone-protection speed range. For example, at Study Site 1, 69 percent of the vehicles were traveling within this speed range. Therefore, 31 percent of the vehicles were not provided dilemma zone protection and would be expected to be in their dilemma zones at the onset of yellow when gap-out occurred.

A comparison of the observed and expected percentages of vehicles in their dilemma zones at the onset of yellow when gap-out occurred is shown in Table 3. Overall, the observed percentages were much closer to their expected values for the AD design than they were for the AWFAD design. The percentages for the AWFAD design were much lower than expected. The results of the binomial proportions test indicate that the observed percentages for the new design were significantly lower ($\alpha = 0.05$) than expected; whereas, the observed percentages for the AD design were not significantly different ($\alpha = 0.05$) than the expected values. This suggests that the AWFAD design may have increased the inclination of drivers to stop when they saw the yellow beacons on the advance warning signs flashing before the onset of yellow.

The increased inclination of drivers to stop when they saw the yellow beacons of the AWFAD design flashing before the onset of yellow is supported by the information presented in Table 4. The number of vehicles observed upstream of the advance warning signs when the yellow beacons began to flash is shown for each study site with the new design. Also shown are the number and percent of them that stopped. The percent stopping ranged from 65 to 86 percent, which was significantly greater ($\alpha = 0.05$) than 50 percent, or the percentage expected if the flashing beacons had no effect on drivers' propensity to stop.

Max-Out Green Intervals

Max-out refers to the immediate termination of the green when it has been extended to the maximum green interval. When this occurs, the green is terminated without regard to the presence of vehicles in their dilemma zones and they are not provided dilemma zone protection. Therefore, a lower frequency of max-out indicates that a design provides better dilemma zone protection. The percent of green intervals that max-out at each study site is shown in Table 5.

The study sites with the AD design had much higher percentages of max-out green intervals. The results of the binomial proportions test indicate that the percentages of max-out green intervals at these sites were significantly higher ($\alpha = 0.05$) than those at the AWFAD sites. This is not surprising, because the MAH of the AD design is much longer than that of the AWFAD design.

Vehicles Running Red Light

Vehicles running the red light may indicate that they vehicles are in their dilemma zones at the onset of yellow. The percent of vehicles running the red light at each study site is shown in Table 6. These percentages of red-light runners indicate that the AD design at Study Site 3 had the highest percentage of vehicles running the red light. According to the binomial proportions test, this percentage was significantly higher ($\alpha = 0.05$) than the percentages at the other study sites. However, the overall results show that the AWFAD design was not any better or worse than the AD design. It had a lower percentage of red-light runners at some sites but not at others. The results of the binomial proportions test indicate that the performance of the AD design at Study Sites 4 and 6 was not significantly different ($\alpha = 0.05$) than that of the AD design at Study Sites 1 and 2.

Abrupt Stops

Vehicles stopping abruptly at the onset of yellow may indicate that these vehicles are in their dilemma zones at the onset of yellow. The percent of vehicles stopping abruptly at each study site is shown in Table 7. These percentages indicate that the AD design at Study Site 3 had the lowest percentage of vehicles stopping abruptly. However, the overall results show that the AWFAD design was not any better or worse than the AD design. It had a lower percentage of abrupt stops at some sites but not at others. The results of the binomial proportions test indicate that the performance of the AWFAD design at Study Sites 5 and 6 was not significantly different ($\alpha = 0.05$) than the performance of the AD design at Study Site 2; nor was its performance at Study Site 4 significantly different ($\alpha = 0.05$) than the performance of the AD design at Study Sites 1 and 3.

Vehicles Accelerating On Yellow

Vehicles accelerating at the onset of yellow could be conducive to red-light running and right-angle collisions. Therefore, designs with fewer vehicles accelerating at the onset of yellow are preferred. The results of previous research (8,9) suggest that this behavior occurs more frequently in the case of designs with AWF. The percent of first vehicles not stopping at the onset of yellow that accelerate is shown in Table 8.

The first vehicle is the leading vehicle at the onset of yellow on the approach. In some green intervals, the first vehicle at the onset of yellow stopped; and in other green intervals, the first vehicle did not stop. For example, at Study Site 1, a total of 223 green intervals were observed. The first vehicle stopped on 170 green intervals and did not stop on the other 53 green intervals. Of the 53 first vehicles that did not stop, 24 (45.3 percent) accelerated.

The AWFAD design at Study Site 5 had the highest percentage of first vehicles accelerating at the onset of yellow, which was significantly higher ($\alpha = 0.05$) than the percentages at Study Sites 3 and 6 according to the binomial proportions test. However, the overall results show that the AWFAD design was not any better or worse than the AD design. The AWFAD design had a lower percentage of vehicles accelerating at some sites, but not at

others. The results of the binomial proportions test indicate that the performance of the AWFAD design at Study Sites 4 and 6 was not significantly different ($\alpha = 0.05$) than the performance of the AD design at Study Sites 1 and 3.

CONCLUSION

The relative performance of the two designs according to the results of the field studies is summarized in Table 9. Overall, the results do not indicate that the AWFAD design was any better or worse than the AD design with respect to drivers stopping abruptly, running the red light, or accelerating on the yellow. Significant differences in terms of these MOEs among the study sites did not indicate that one design is better than the other. However, the AWFAD design did have a significantly lower than expected percentage of vehicles in their dilemma zones when the green was terminated by gap-out. In addition, vehicles upstream of the AWF when the beacons were flashing before the onset of yellow had a greater than expected tendency to stop. This suggests that the AWF may have performed as intended, with drivers heeding the warning of the impending onset of yellow and preparing earlier to stop.

Both designs were observed to provide the levels of dilemma zone protection indicated by the speed ranges for which they were designed to provide dilemma zone protection. Although the AD design experienced lower percentages of vehicles in their dilemma zones when the green was terminated by gap-out at some study sites, this could be attributed to the higher percentages of vehicles in the speed ranges for which the AD design provided dilemma zone protection. As expected, the AWFAD design provided significantly lower percentages of green intervals terminated by max-out because of its shorter MAH. At higher traffic volumes, the increase in dilemma zone protection associated with the lower max-out probability of the AWFAD design would be greater than the decrease in dilemma zone protection on gap-out resulting from the narrower speed range for which it provided dilemma zone protection.

The primary advantage of the AWFAD design is its shorter MAH, which reduces the probability of max-out and the loss of dilemma zone protection. However, the major disadvantage of the AWFAD design is the width and location of the speed range for which it provides dilemma zone protection. This speed range limits its effectiveness in providing dilemma zone protection, especially at lower traffic volumes where the probability of max-out is low for the AD design. As indicated by the relationships in Equations 4, 5, and 6, the speed range of dilemma zone protection provided by the AWFAD design is a function of its design parameters (*i.e.*, design speed, detector location, AWF location, lead flash, and passage-time setting). By adjusting the values of these design parameters, it is possible to increase the width of the speed range; but more importantly, it is possible to position the speed range to include a much higher percentage of the approach speed distribution. It should be noted that this can be done without changing the design's MAH. Thus, a modified configuration of the AWFAD design would significantly increase the probability of vehicles being within its dilemma-zone-protection speed range, while retaining the benefits of its shorter MAH. The modification of the AWFAD is reported elsewhere (10).

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FIGURE 1 Effects of MAH and maximum green on max-out probability.

TABLE 1 AD Design

Design Speed (mph)	Distance of Advance Detector from Stop Line (ft)					MAH (s)
	1 st Detector	2 nd Detector	3 rd Detector	4 th Detector	5 th Detector	
65	645	563	417	297	178	10.7
60	563	417	297	178		9.6
55	487	354	248	142		9.3
50	416	297	203	109		9.0
45	350	244	163	82		8.6

TABLE 2 AWFAD Design

Advance Detector and AWF Locations				
Design Speed (mph)	Distance From Detector to AWF ^a (ft)	Distance From AWF to Stop Line ^b (ft)	Distance From Detector to Stop Line (ft)	Lead Flash (s)
65	285	650	935	7
60	264	550	814	6
55	243	450	693	6
50	219	375	594	5
45	198	300	498	5

Speed Range of Dilemma Zone Protection				
Design Speed (mph)	Below Design Speed		Below Design Speed	
	Lower Limit (mph)	Upper Limit (mph)	Lower Limit (mph)	Upper Limit (mph)
65	0	42	65	81
60	0	40	60	74
55	0	35	55	68
50	0	33	50	62
45	0	28	45	56

^a Distance traveled in 3.0 seconds at the design speed.

^b Advance warning sign placement distance from Table II-1 on page 2C-2a in 1988 Manual on Uniform Traffic Control Devices (12). This distance provides for a 3.0-second perception-reaction time, 125-foot sign legibility distance, and braking distance according to the 1984 Green Book (13).

TABLE 3 Vehicles in Dilemma Zone

Study Site	Design	Number of Gap-Out Green Intervals	Vehicles Within Dilemma-Zone-Protection Speed Range (%)	Gap-Out Green Intervals with Vehicle in Dilemma Zone at Onset of Yellow	
				Expected (%)	Observed (%)
1	AD	143	69	31	30
2	AD	123	39	61	63
3	AD	128	55	45	38
4	AWFAD	212	20	80	56 ^a
5	AWFAD	239	11	89	69 ^a
6	AWFAD	158	29	71	61 ^a

^a Significantly lower than the expected percentage ($\alpha = 0.05$).

TABLE 4 Vehicles Stopping at AWFAD Sites When Beacons Began Flashing

Study Site	Design	Vehicles Upstream of AWF When Beacons Began Flashing		
		Total	Vehicle Stopping Number	Percent
4	AWFAD	137	117	85 ^a
5	AWFAD	158	132	84 ^a
6	AWFAD	147	96	65 ^a

^a Significantly greater than expected 50 percent ($\alpha = 0.05$).

TABLE 5 Max-Out Green Intervals

Study Site	Design	Number of Green Intervals	Max-Out Green Intervals	
			Number	Percent
1	AD	223	80	36 ^a
2	AD	193	70	36 ^a
3	AD	170	42	25 ^a
4	AWFAD	220	8	4
5	AWFAD	245	6	2
6	AWFAD	163	5	3

^a Significantly higher than the percentages at Study Sites 4, 5, and 6 ($\alpha = 0.05$).

TABLE 6 Red-Light Running

Study Site	Design	Vehicles Not Stopping ^a		
		Total	Red-Light Runners	
			Number	Percent
1	AD	53	3	5.7
2	AD	84	12	14.3
3	AD	18	10	55.6 ^b
4	AWFAD	86	9	10.5
5	AWFAD	120	8	6.7 ^c
6	AWFAD	67	11	16.4

^a Non-stopping vehicles immediately ahead of first vehicles to stop at onset of yellow.

^b Significantly different than the percentages at the other study sites ($\alpha = 0.05$).

^c Significantly different than the percentages at Study Sites 3 and 6 ($\alpha = 0.05$).

TABLE 7 Abrupt Stops

Study Site	Design	Vehicles Stopping ^a		
		Total	Abrupt Stops	
			Number	Percent
1	AD	170	7	4.1 ^b
2	AD	109	10	9.2 ^c
3	AD	152	2	1.3 ^b
4	AWFAD	134	4	3.0 ^b
5	AWFAD	125	10	8.0 ^c
6	AWFAD	96	8	8.3 ^c

^a First vehicles to stop at the onset of yellow.

^b Significantly different than the percentages at Study Sites 2, 5, and 6 ($\alpha = 0.05$).

^c Significantly different than the percentages at Study Sites 1, 3, and 4 ($\alpha = 0.05$).

TABLE 8 Accelerating on Yellow

Study Site	Design	Number of Green Intervals	First Vehicles Not Stopping		
			Total	Accelerating on Yellow	
				Number	Percent
1	AD	223	53	24	45.3
2	AD	193	84	44	52.4 ^a
3	AD	170	18	6	33.3
4	AWFAD	220	86	41	47.7
5	AWFAD	245	120	71	59.2 ^b
6	AWFAD	163	67	23	34.3

^a Significantly different than the percentages at Study Site 6 ($\alpha = 0.05$).

^b Significantly different than the percentages at Study Sites 3 and 6 ($\alpha = 0.05$).

TABLE 9 Comparison of AD and AWFAD Designs^a

Measure of Effectiveness	AD Design	AWFAD Design
Percent of Vehicles in Dilemma Zone	-	+
Percent of Max-Out Green Intervals	-	++
Percent of Vehicles Running Red Light	=	=
Percent of Vehicles Stopping Abruptly	=	=
Percent of Vehicles Accelerating on Yellow	=	=

^a = performance same as other design + performance better than other design
- performance worse than other design ++ performance much better than other design

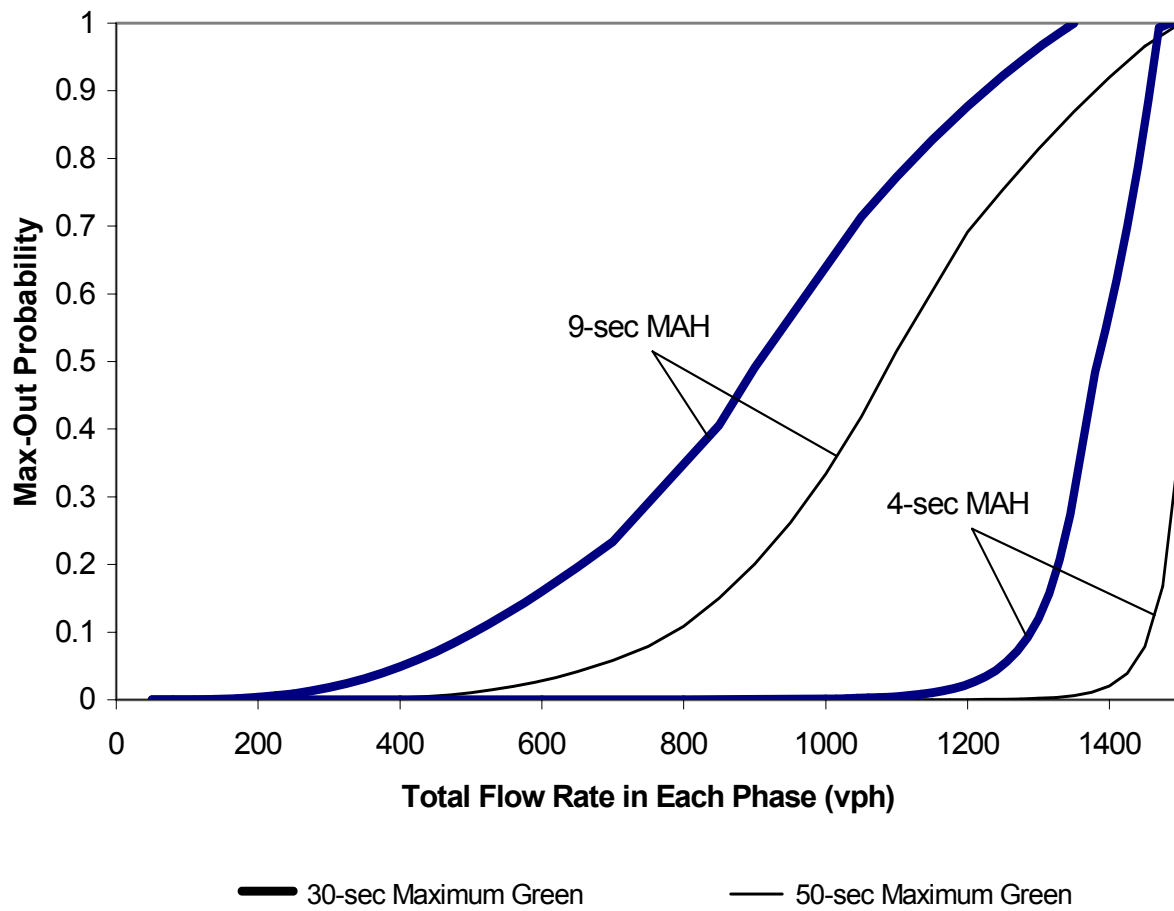


FIGURE 1 Effects of MAH and maximum green on max-out probability.