OPERATIONAL ANALYSIS OF ADVANCE WARNING FLASHERS

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Review paper

Abstract: *Advance Warning Flashers have been used across United States and Canada for warning the motorists approaching a high-speed signalized intersection to either slow down or prepare to stop. These systems are in close correlation to geometry of the intersection and dilemma zone protection. Conventional warning systems usually work in fixed-time or with a trailing overlap at the end of green, leading to increased red light running as users adapt to the system. Recently developed systems tried to integrate separate computer devices to add the ability to predict the end of green phase. Those systems faced issues with false activations and lengthy lead flash times. This paper provides a comprehensive review of the current agency's practices and newly developed advance warning systems. Furthermore, paper elaborates on the drawbacks that these systems face and proposes an advance warning system integrated in the controller logic.*

Keywords: *Advance warning flashing, dilemma zone protection, human factors, traffic signal controller*

OPERATIVNA ANALIZA UPOZORAVAJUĆIH SIGNALNIH TREPTAČA

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Pregledni rad

Rezime: *Upozoravajući signalni treptači pre raskrsnica sa visokom vrednosti ograničene brzine se koriste u Sjedinjenim Američkim Državama i Kanadi da upozore vozače na potrebu za smanjenjem brzine ili zaustavljanjem. Ovi sistemi su u direktnoj vezi sa geometrijskim karakteristikama raskrsnice i potrebom za zaštitom zone dileme. Konvencionalni sistemi upozorenja obično koriste predodređeno ili preklapajuće vreme na kraju zelenog vremena, što dovodi do povećanog broja prolaska kroz crvenu signalnu indikaciju, s obzirom da se korisnici navikavaju na sistem. Sistemi koji su razvijeni u skorije vreme se baziraju na dodatnom kompjuteru, koji pored kontolera saobraćaja pokušava da predvidi kraj zelenog signalnog vremena. Ovi sistemi se suočavaju sa problemima lažne aktivacije i dugih vremena preklapanja rada treptača i svetlosnog signala. Ovaj rad predstavlja sveobuhvatni pregled trenutne prakse i novih sistema među saobraćajnim organizacijama. Dalje, ovaj rad ukazuje na konkretne problem postojećih sistema, i predlaže integraciju sistema treptajućeg upozorenja i indikacije svetlosnog signala unutar logike rada kontrolera za upravljanje radom svetlosnog signala.*

Ključne reči: *Upozoravajući signalni treptači pre raskrsnica, zaštita zone dileme, faktori vozača, kontroler za upravljanje radom svetlosnog signala*

1. BACKGROUND

The introduction of traffic signals usually tries to resolve two conflicting interests of the intersection operation: the interest for safety and the interest for efficiency. In the case when signalized intersection is located on a high-speed road where speed is greater than 45 mph, the emphasis on intersection safety is of greater importance. The emphasis on safety is mainly due to the larger collisions consequences. Although traffic signal on a high-speed road can serve its primary safety function of separating conflicting flows of vehicles, additional safety issues might appear. The issues are usually with sight or stopping distance and can relate to unawareness of intersection, dilemma zone, or other issues [1].

Limited sight distance issues can result in unawareness of intersection and are mainly due to the geometric constraints. The issues usually originate from vertical or horizontal curvature, or sight obstruction objects. Stopping distance issues are under significant influence of dilemma in the diver decision process. This dilemma appears in the case of onset of yellow change interval. This is in the area at a definite distance from the intersection where driver is in the dilemma zone, i.e., a driver is unsure whether the distance from the stop bar is short enough to proceed through intersection or it is too long and he has to slow down and stop [2]. In the cases of wrong driver decision in dilemma zone, an abrupt stop may lead to rear-end collision, while proceeding and running on red may lead to right-angle crashes. Factors such as vehicle type or downhill grade contribute to increasing the size of dilemma zone [3, 4]. Figure 1 summarizes the factors affecting driver behavior approaching an intersection.

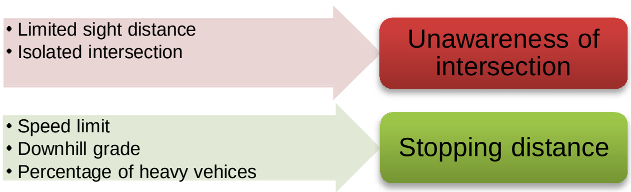

Figure 1. Factors that affect the driver behavior approaching a signalized intersection

There are many conventional solutions in response to these issues at high-speed intersections. Some of the solutions are installation of advance guide signs, advance warning signs, overhead street signs, or using pavement markings. In addition to these, there are solutions related to signal timing, including special clearance intervals, special detector layout and traffic signal controller settings. Advanced Warning Flasher (AWF) is one of the systems related to signal timing. AWF has gained importance in US in recent years [5]. AWF is intended to provide traffic signal status information to upstream traffic and help motorists in deciding to proceed or slow down.

2. THEORETICAL BASIS FOR ADVANCE WARNING FLASHERS (AWF) DEPLOYMENT

The first AWF installation can be traced back to 1968, in Alberta, Canada [6]. AWF consists of warning beacons operating in flashing mode, approximately once per second. AWF is a device that provides a supplemental emphasis to a warning sign. The types of flashing beacons or warning signs vary greatly across and even within states [7]. There have been several generations of AWFs. Some AWF installations are only attracting attention to the "Signal Ahead" signs, with constant flashing. The flashing period of second generations AWFs is initiated/interrupted in relation to signal timing, but it has fixed time values. Latest generation of AWFs operate in a mode dependent on the dynamics of traffic signal controller operation.

The location and timing of the signs are usually affected by the following factors:

1. Vehicle speed
2. Perception reaction time
3. Deceleration rate
4. Approach grade, and
5. Friction factor

Not all agencies consider all the factors for determining the location of the flashers. The 85th percentile speed is considered most commonly for calculation of distance of flashers from stop bar [6]. The perception reaction time varies from 1.0 sec used in British Columbia [8], to 2.5 seconds recommended by MUTCD [9]. The deceleration rates used in Canada is 8.5ft/sec^2, 10.0ft/sec^2 in Minnesota, 5.2ft/sec^2 in Calgary and the AASHTO's "Greenbook" recommends a value of 11.2ft/sec^2 [10]. Friction factor is a variable that can either be computed dividing the deceleration rate by acceleration due to gravity (AASHTO's "Green book") or a fixed value like that shown in
T.

Table 1. Friction factors for wet pavement used in British Columbia

Posted Speed (mph)	Friction Factor
25	0.38
31	0.36
37	0.34
43	0.32
50	0.31
56	0.3
62	0.3

The equations used for calculation of distance of flashers from stop bar are listed below:

$$D = 1.47Vt_{pr} + \frac{V^2}{30\left(\left(\frac{a}{32.2}\right) \pm G\right)} \qquad (1)$$

Where:
D = AWS placement from the stop bar (ft),
V = design speed (mph),
t_{pr} = perception reaction time (sec),
a = deceleration rate (ft/s^2)
G = grade (ft/100ft)

$$D = \frac{V^2}{30(f)} \qquad (2)$$

Where,
f= friction factor (0.16 recommended value)

$$D = 1.47Vt_{pr} + \frac{V^2}{30(f \pm G)} \qquad (3)$$

In Nebraska, sign legibility distance was also considered into account changing the equation to,

$$D = 1.47Vt_{pr} + \frac{V^2}{0.93a} - d_L \qquad (4)$$

Where,
d_L= sign legibility distance (ft)

Lead flash time of the flashers is sometimes computed, while sometimes it is a fixed length of time. Some of them are even set to come on at the onset of yellow phase.

The basic form of the equation to compute the lead flash time is:

$$T = \frac{D}{1.47V} \qquad (5)$$

Where,
T = lead flash time (sec)
D= Distance of flashers from stop bar (ft)
V= Posted speed (mph)

Variations of this equation include perception time, legibility distance or dilemma zone distance. The Type II dilemma zone, which relates primarily to driver's reactions, is considered in this case with time boundaries of 2.5s-5.5s to the stop bar [11].

Some recently developed systems have a variable lead flash time. They are programmed to come on when a gap is detected in traffic. The system predicts that the controller will end the green and therefore starts flashing to proving warning about the end of green. Summary of agencies' design criteria guidelines is presented in Table 2. The fields with a check mark represent that criteria is considered, while empty fields represent criteria not considered.

Table 1. Summary of Agencies' design criteria guidelines

Criteria		Minnesota	Nevada	Calgary	British Columbia	Ontario	Kentucky	Washington	California	Alaska	Virginia
Distance from Stop line	Vehicle speed	√	√	√	√	√	√	√	√	√	√
	Perception reaction time	√	√		√	√	√	√	√	√	√
	Deceleration rate	√	√	√		√		√	√	√	
	Grade	√			√	√	√				
	Gravity						√				
	Friction			√		√	√				√
Lead Flash	Before Yellow	√	√	√	√		√	√		√	
	Onset of Yellow					√			√		√

3. AWF GENERATIONS

Throughout the last several decades, there have been several generations of state-of-the-practice AWF systems.

1st generation

First generation of AWF are static flashers that are operational constantly throughout the day and do not contain any additional intelligence. They are merely emphasizing the existing "Signal Ahead" signs. Their operation is independent of the signal status at the intersection ahead.

2nd generation

Among the existing state practices, the most common are second generation AWFs. In the second generation, flashing starts at the onset of yellow or with a fixed time before the yellow by using the trailing overlap method typically 7 to 8 seconds long [11, 12].

3rd generation

Some of the recently developed systems, such as Blank Out Dynamic Advance Warning System (BODAWS) [6] in Utah, use advance detectors along with the dilemma zone detectors. The usage of advance detector in these warning systems is to provide warning prior to the end of green without replacing the dilemma zone protection at the intersection.

The AD component of the BODAWS system was installed to reduce the percentage of vehicles in the DCZ at the onset of the yellow change interval. The AD component was a single optical detection zone using a video camera. The BODAWS detector was located based on 85th percentile speed. Stop bar detectors were used; they remained on until the extendable portion of the green, when they were turned off.

Four events occur in the following sequence

- At the beginning of the extendable portion of green, BODAWS detectors are active and stop bar detectors are inactive. The signal controller ends green when a gap is seen. A 3sec extension of green is provided if speed of vehicle exceeds 55mph.
- Activation of flashers (6.5secs before onset of yellow if 85th percentile speed is 65mph)

$$t_F = \frac{D_M + D_P}{v_0} \qquad (6)$$

Where,
tF = lead flash time (sec),
DM = distance from the BODAWS sign to the stop bar (ft),
DP = minimum perception distance of the BODAWS sign (ft), and
vo = design speed (ft/sec).

Once the BODAWS signs and flashers are activated they remain active through the yellow change interval, the all-red clearance interval, and the red interval and return to inactivity at the beginning of the following green interval

- All of the vehicles that approach the intersection after gap-out will receive the warning from the BODAWS sign and flashers and have sufficient distance and time to safely stop
- The BODAWS signs and flashers remain active and warn approaching motorists that the signal is red. 2sec all-red clearance interval is provided.

4th generation

The latest generation of AWF includes Advance Warning for the End of Green Signal (AWEGS) [12] developed in Texas. This system has a variable lead flash time. AWEGS uses external control logic installed on industrial computer that tries to predict when the controller will end the phase green (gap out or max out). This system makes use of an additional pair of detectors located upstream of the flashers to obtain speed of the vehicles and project the values and see if they are going to extend the green, before turning on the flashers.

Traffic signal controllers typically deployed at high-speed rural intersections in Texas operate in the full traffic-actuated mode. The green for a cross-street approach is called only on detected traffic demand, and the signal green can terminate either because large gaps in the traffic stream are detected (i.e., gap-out) or because of the green reaching its maximum allotted time under heavy traffic demand (i.e., max-out). An active advance warning system that warns the motorist about the termination of green should do so safely and consistently. This means that advance warning should be provided in a either consistent manner when the controller gaps-out or maxes-out. It is essential to provide a consistent warning to the drivers to ensure driver respect for the AWEGS [12, 13].

These systems use an additional pair of detectors located upstream of the flashers to obtain speed and type of the vehicles to compute the vehicle trajectories and ensure that they are not in the dilemma zone and extending the green while the AWEGS system prepares to activate the flashers. The AWEGS logic can be summarized as shown in the flowchart in Figure 2.

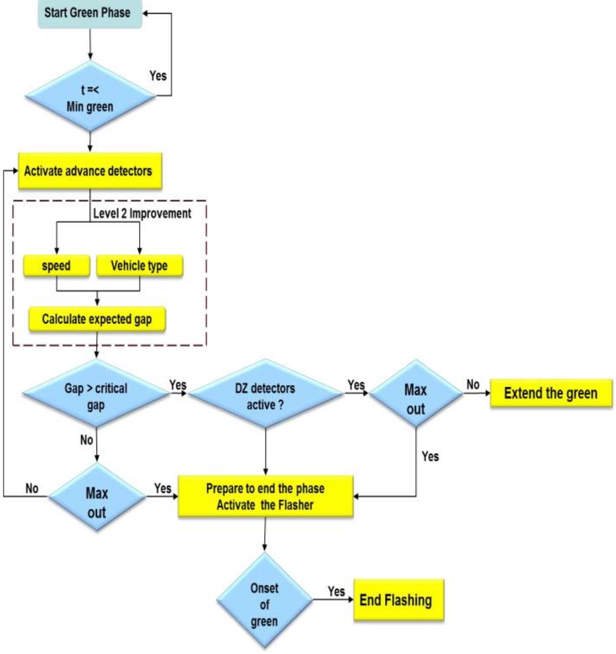

Figure 2. AWEGS Level-2 Operation Logic Flowchart

5th generation

The fifth generation of AWF, developed in Minnesota, includes the combination of AWEGS and Integrated Platoon Priority System [14]. Conventional AWFs use the method of trailing overlap of green (hold green by fixed time 7-8secs at the end of phase – beacons flash with the trailing overlap). The fixed length hold replaces the DZ protection because there are no more extensions allowed after the hold time, which increases delay on minor approaches. Since hardware requirements and operation of platoon priority and AWEGS are similar as they both use Advance detectors and when necessary override the signal controller, they are integrated to develop the Integrated System. The system is designed to estimate travel time (assuming constant speed after detectors are crossed, no lane changes or passing), override controller to provide platoon priority to detected platoons and predict gap-outs and provides advance warning using AWEGS technology developed by TTI for TxDOT [14].

4. RESULTS OF PREVIOUS AWF DEVELOPMENTS

4.1. Field Evaluation Results

Several research studies have been conducted on the effectiveness of AWF systems. The accident studies were conducted on isolated high-speed signalized intersections in California (Klugman et al., 1992) and Ohio (Pant and Xie, 1995) indicated that the advance warning signs are effective in reducing accidents. An accident study in Minnesota (Hughes, 2000) provided mixed results, the advance warning beacons were recommended for 55mph or higher speed intersections. Another safety study in British Columbia [15] showed a reduction in total number of accidents, but the reduction was statistically insignificant. Mc Coy and Pesti (2002) [5] combined advance detection and active advance warning signs to provide dilemma zone protection. It reduced the frequency of max-outs, thus improving the dilemma-zone protection, especially at higher volume locations.

Gibby, Washington, and Ferrarra [16] studied high-speed isolated signalized intersections (HSISI). They found that HSISI with AWSs functioned better than intersections without AWSs. Intersections with AWS had significantly lower left turn, right angle, and rear end approach collision rates. They recommended placing flashing beacons on AWS systems that are more than 2,000 feet from an intersection.

Furthermore, Pant and Xie [17] also 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 vehicles' approaching speeds. However, PTSWFS and FSSA increased vehicular approaching speeds because drivers attempted to sneak through yellow signal phases. The continuous flasher did not inform the driver of changes in signal state. However, it helped reducing approach speeds. The benefits of these signs also depend on road geometry. The study recommended installation of CFSSA before PTSWFS.

A human factors study by Smith, Hammond, and Wade (2001) [18] in Minnesota used simulation studies to study the speed, braking and acceleration patterns in simulated situations with advance warning systems and without them. The results indicated that, at lower speed limits more drivers stopped when there was no advance warning beacons, but fewer stopped when the speed limits were higher. They concluded that the AWFs assisted decision making at intersections and promoted safer driving.

McCoy and Pesti [5] 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 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 trapped 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.

Recently developed systems like Blank Out Dynamic Advance Warning System (BODAWS) [6] in Utah, Advance Warning for the End of Green Signal (AWEGS) [12] in Texas and Integrated Platoon Priority System [14] in Minnesota use advance detectors along with the dilemma zone detectors. The usage of advance detector in these warning systems is to provide warning prior to the end of green without replacing the dilemma zone protection offered at the intersection. The performance of these systems was evaluated in terms of delay, stops, and AW time. These advanced warning systems have proven effective in reducing the red-light-running, decreasing speeds of vehicles approaching the intersection and also in reducing the crashes. However, these systems are not so effective for high-volumes of traffic. A study in Utah, after the installation of BODAWS indicated that eight months later there was an increase in red-light-running [11]. The users tried to beat the light when the flashers started flashing.

In addition to this, the latest systems, although have the advanced logic, are not effective for high-volumes of traffic when simultaneous-gap-out logic is applied [7]. Lead flash time tends to be longer than anticipated when a predicted gap-out activates the flashers, but vehicles at the dilemma zone detectors on the opposite approach extend the green and prevent controller from gapping out [13]. Issues appear with false activation of beacons or lengthy flash times that can increase driver incompliance to the warning.

4.2. Summary of Drawbacks of Existing Systems

There are several issues with the current methods. Many design factors related to geometry and signal timing are directly affecting user behaviour, especially after a long-term installation (Figure 3). All the factors directly affect the driver behaviour and especially compliance and respect as driver adjustment factors. Determination of technical issues could lead to potential improvements in operational effects of AWF systems.

Some of the previous installations had issues with reducing the number of crashes but increase in red-light running. In addition, not all the installations proved significant correlation with reduction of crashes, or the safety analysis was not conducted in long periods after the installation. The problem with introducing this control device is the potential negative effects to driver behaviour. The device might have positive effects in influencing conservative drivers but can increase aggressiveness among highly aggressive drivers by increasing the percentage of RLR and their approach speeds. Some of the potential technical issues that might contribute to negative effects of this control device are presented below.

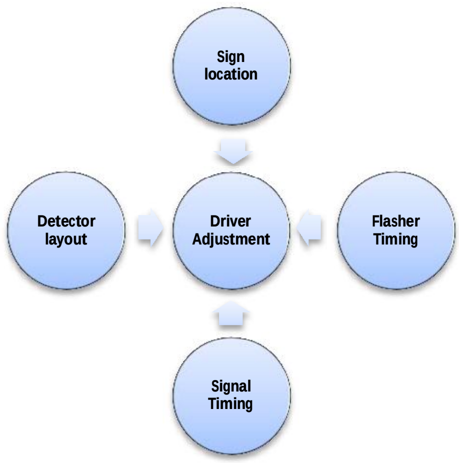

Figure 3. Factors influencing driver adjustment to AWF

- **Fixed time flashing – fixed lead flash time**
  Flashers activated on start of yellow provide no warning to the vehicles approaching the intersection at the end of green. Vehicles that do not receive the warning are not offered dilemma zone protection. Even with the extension of yellow duration, vehicles caught in the dilemma zone are not fully protected.

  Flashers that are activated at the onset of yellow are not solving red light running or intersection crashes that occur due to dilemma zone issues, because they do not provide advance warning about the end of green. The trailing overlaps replace the dilemma zone protection offered by the green extension system used in many actuated signals.

  Fixed lead flash time usually leads to driver adaptation to its duration and increases the number of drivers that try to beat the light and proceed through the intersection. In addition, it can eliminate any existing dilemma zone protection by leading more drivers into dilemma zone, and can increase delay on minor approaches if green-extension-system is applied at the intersection

- **Duration of lead flash time**
  Incompliance increases over time if the warning/flash times are not conservative. Over time, it has been observed that the motorists learn to beat the light if the flash times are long enough. The timing of the flashers is critical to reduce incompliance.

- **Queue detection**
  Majority of the system do not have queue detection dependent extension of flashing time during initial green. This is especially important when there is significant sight obstruction before the signal and where queue length can lead to rear-end crashes.

- **Treatment of heavy vehicles**
  Heavy vehicles require to be treated differently, as they require additional braking effort to stop. Finally, this method does not treat heavy vehicles or very fast vehicles any differently, which is not desired because they need additional braking effort to stop at the signal.

- **Directional variability of traffic**
  Systems like AWEGS, BODAWS and the Integrated Platoon Priority System use advance detectors to detect a gap in traffic and predict if the controller will gap out or not. If simultaneous gap out logic is employed, the controller ends the green simultaneously on both the major approaches. In this case, the advance detectors may predict a gap-out, but the controller will not end the phase until a gap is seen on the opposite approach as well. This will cause the beacons to start flashing on one approach, while the green is still on. The warning times tend to be longer in this case, especially if the volumes are high on one of the approaches.

- **Specific detector settings**
  Some systems, (e.g., AWEGS based on Nader's guide) assume specific detector settings that are applicable to some states. Transferability of this technology might require significant calibration or even redesign.

5. POTENTIAL AREAS FOR IMPROVEMENT

The design of AWF should be carefully done since it is an important control element that affects driver behaviour. It is also important to ensure that the control device is not overused since it can be an effective tool but only at intersections that need it. The intersection selection criteria need further enhancement. The installation of AWEGS should be divided into two separate issues:

1. Where the sign should be installed?
2. How should the sign be installed?

The objectives for installation should:

- Improve safety and driver response
- Reduce overall delay
- Reduce design and maintenance costs
- Include speed, vehicle type, and traffic directional variability

Several potential points appear for determining the installation guidance and development. Beside previously, conventionally considered factors, new factors should be taken into account. For example, the percentage of daily users through the intersection might lead to driver's response to control device. Daily users might respond differently to a sign they are used to, as compared to the ones that are not used to the AWF. In addition, the potential for different lead flash time according to congestion detected on the approach should be considered. Educational programs for drivers before and after the sign installation should be developed. Finally, the integration of the control device with enforcement camera for RLR should be considered.
Some of the future development of AWF will be related to Vehicle-Infrastructure Integration [19]. Proposed integration will enable the vehicle communication with the controller, obtaining the information regarding the status of the signal. The logic will then decide whether car should proceed or stop at the intersection. However, before such technology is available, one of the potential implementations is development of Advance

Flashing logic as a part of modern controller software. Some of the previous developments had issues due to the utilization of external computer that communicates with traffic signal controller. In some cases, logic inside industrial computer could not predict the reaction of controller accurately due to their operational independence. The potential solution could be developing controller features that would deal with the decision on advance flashing as a part of controller software logic. This control logic should focus on improvements of safety – by preventing false beacon activation and decrease the lead flash time duration; and efficiency – by utilizing controller overlap capabilities. The additional objectives are to decrease design and maintenance costs and accommodate speed, vehicle type, and directional variability of traffic.

6. CONCLUSION

Over the years, efforts have been made to develop systems that can provide advance warning to motorists about the end of green signal, so that they can safely stop at the intersection. Advance Warning Flashers installations across North America proved to have both positive and negative impacts. Research efforts have proved that these systems have reduced red light running, crashes and even delays at the isolated high-speed signalized intersections. However, some of the studies have not proved significant positive benefits, especially related to user compliance after some period after installation.

This paper is focusing on theoretical basis for deployment and different generations of AWFs. Comprehensive review of previous developments and installations has shown the potential areas for improvement. One of the potentials for improvement is integration of AWF operational logic as a part of the controller software. The flexibility of modern Advanced Transportation Controller software is recognized as perfect environment for the development of future improvements to control logic.

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