Methodology for Evaluating Traffic Detector Designs

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The design of the traffic detection scheme at an intersection can have a considerable impact on traffic safety and efficiency. A detector design (i.e., the detector layout and controller timing) that is not "tuned" to the geometrics of the intersection and its traffic demands can result in higher motorist delays than would be obtained with pretimed control. The detector design can also have an effect on safety. Designs that continually present the yellow signal to drivers when they are in the zone of indecision are likely to be associated with more accidents than designs that detect these drivers and extend the green signal for them until they are clear of the intersection. The safety and efficiency of a traffic detector design can be determined from the probability of max-out [a max-out occurs when the green is extended by a continuous stream of arrivals until the maximum green duration is reached (and a conflicting call is continuously held on one or more phases)] and the amount of time spent waiting time for gap-out and subsequent phase change. A detector design that minimizes these measures of effectiveness should provide safe and efficient operation. Achieving the optimal combination of these measures can be difficult because of complex interactions among detector design elements (i.e., detector location, detector length, vehicle speed, passage time setting, and call-extension setting). The methodology described in this paper will allow the designer to determine the optimal combination of design elements in terms of safety (via infrequent max-out) and operations (via a short waiting time for phase change).

Traffic-actuated control can be used to improve both traffic efficiency and safety at an intersection. The extent to which it improves the efficiency of operations is dependent on the detector layout and its associated controller settings (henceforth referred to as the "detector design"). Designs that are not "tuned" to the geometrics of the intersection and its traffic demands can result in higher motorist delays than would be obtained with pretimed control.

The detector design can also have an effect on safety. Studies of driver behavior at intersections indicate that there is a zone on the approach wherein driver response to the yellow presentation is unpredictable and uncertain; some drivers may decide to stop, whereas others may determine that it is safer to proceed through the intersection. As a result, there is an increased potential for rear-end accidents at the end of the phase when two or more drivers are simultaneously in this zone of indecision. Some agencies use advance detection in this zone to monitor traffic flow and extend the green to any vehicles in the indecision zone (thereby preventing the presentation of a yellow signal). These designs are believed to be safer than designs without advance detection because they

effectively reduce the number of potential accident events (e.g., rear-end collisions) occurring at the intersection.

A methodology for evaluating existing traffic detector designs on intersection approaches is described. This methodology is applicable to either presence or pulse-mode detection on low- or high-speed approaches. It is based on a constant passage time (or vehicle extension) setting on the controller and thus is not directly applicable to volume-density controllers using a gap-reduction feature. Evaluation criteria include the frequency of phase max-out [a max-out occurs when the green is extended by a continuous stream of arrivals until the maximum green duration is reached (and a conflicting call is continuously held on one or more phases)] and the time waiting for gap-out after queue service. Designs that minimize these criteria should provide both safe and efficient operations.

TRAFFIC DETECTOR DESIGN PHILOSOPHY

Traffic detector designs are generally formulated to achieve both safe and efficient traffic operations. The degree to which each goal is achieved is based primarily on intersection approach speeds—efficiency receives most of the attention on low-speed approaches, whereas safety may receive greater attention on high-speed approaches. Most detector designs are based on the principle that the stop line detector will be used for traffic queue service (i.e., minimize delay). Designs with advance detection are based on the principle that the advance loop will be used to minimize the number of times that drivers are caught in the indecision zone at the end of the phase (i.e., maximize safety).

Recent research by Lin (1) on actuated intersection operation indicates that the length of the stop line detection zone and its detector unit settings have a significant impact on motorist delay. The stop line detector should be designed to minimize the frequency of premature phase gap-out and the frequency of calls to empty approaches. Detector length and vehicle extension combinations that minimize delay have been reported by Lin (1).

Advance detector design is based on the location of detectors at one or more locations to provide indecision-zone protection to vehicles traveling within the design speed range. This design speed range typically bounds the range of speeds commonly found on the approach. Detectors are then located throughout the indecision zone on the basis of the design speed range. In operation, these detector loops are positioned such that a vehicle traveling at a speed within the design speed range will be able to maintain a continuous call for green

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(assuming that it initially enters the detection zone during the green) until it clears the intersection. Vehicles at speeds above or below the design speed range will still place calls and extend the green; however, they will not be provided protection for the full length of their indecision zone.

EVALUATION METHODOLOGY

Maximum Allowable Headway

The methodology described here is based on the use of a detector design's maximum allowable headway (MAH) to evaluate the safety and efficiency of its operation. MAH represents the maximum time separation between successive calls for continued green (note that MAH is not necessarily the minimum vehicular headway). The relationship between MAH and the passage time setting is shown in Figure 1 for the simple case of one phase serving one traffic lane. The MAH for a phase serving several lanes can be much more complicated and may, in fact, not truly be a constant value.

The detector design evaluation is made on a phase-specific basis and requires that all lane groups served during the phase be identified. The lane group definition used here is consistent with that provided in the *Highway Capacity Manual* (2). Any turn movement made from an exclusive lane (or lanes) would be designated as a lane group. The approach lanes allocated to the through movement and any turn movements not provided an exclusive lane would also be designated as a lane group. Shared lanes with one high-volume movement should be examined to determine if one lane operates as a de facto exclusive lane and thus a separate lane group.

Once the lane groups have been determined, the MAH for each group must be determined. The procedure for combining the lane-group MAHs into an equivalent MAH for the phase is described in a later section. In general, the MAH for a detector design in any one lane group represents the maximum allowable headway between successive calls from vehicles in that group. In order to gap-out a phase, each lane group would have to experience successive call headways that exceed its respective MAH.

The lane group MAH is dependent on a number of design parameters, including the number of loops serving the lane group, the length of these loops, and the distribution of vehicle speeds for the lane group. Because of the wide range of design parameters, selected design types are treated individually instead of one generalized procedure being developed. Because the use of advance detection represents the most fundamental difference among designs, it will be used as the primary point of departure in describing the MAH calculation.

Engineers responsible for advance detector design typically adopt one of two general design goals. Some engineers prefer to carry the clearing vehicle just through the indecision zone. In this paper, this design is referred to as a Goal 1 design. Other engineers prefer to carry the vehicle to the stop line. This is referred to as a Goal 2 design. Thus, the desired design goal represents a secondary point of departure in the MAH calculation.

The procedure for calculating the lane-group MAH is based on several assumptions. One is that single detector units will be used to monitor all adjacent lanes at any one point on the approach for a given lane group. This type of detection could be achieved by having a single, wide loop at the given point or by having one loop in each lane at this point and wiring them together. A second assumption is that the design speed range for the advance detectors (if any) will include at least 70 percent of all vehicles in the lane group. A third assumption is that all advance detectors will operate together such that a vehicle moving at a speed within the design speed range will maintain a continuous call for green as it traverses these advance loops. A final assumption is that the time headway between successive calls is exponentially distributed.

Lane Groups with Only a Stop Line Detector

For this type of design, the MAH is equal to the MAH for the stop line detection zone (MAH_s). This quantity can be calculated using the following equation:

$$MAH_s = PT + CE_s + \frac{L_{ds} + L_v}{V_a} \tag{1}$$

where

PT = passage time (PT) (or vehicle extension) setting (sec),
CE_s = call-extension (CE) setting on the stop line detector unit (sec),
L_{ds} = length of the stop line detection zone (m),
L_v = detected length of vehicle (m), and
V_a = average running speed on the intersection approach of the subject lane group as measured during the unqueued portion of the green (mps).

Equation 1 is based on the assumption that the detector unit is operating in the presence mode. If it is operating in the pulse mode, then MAH_s would equal the PT setting.
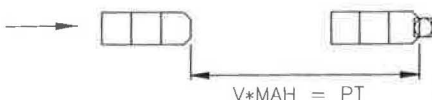
Presence Mode
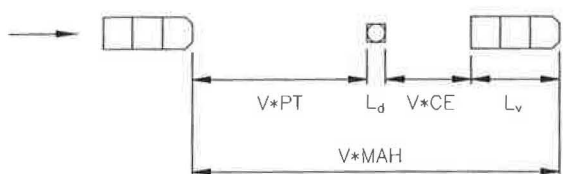
Pulse Mode

FIGURE 1 Relationship between maximum allowable headway and passage time, where *MAH* = maximum allowable headway; *PT* = passage time setting on the controller; *CE* = call-extension setting on the detector unit; *V* = free flow speed; *L_d* = length of detector in the direction of travel; and *L_v* = detected length of vehicle.

*Lane Groups with One or More Advance Loop
Detectors*

For those lane groups with one or more advance loop detectors, the MAH is a function of the average vehicle's travel time from the first advance loop detector to the end of the indecision zone. The location of the end of this zone depends on the design philosophy adopted. If a Goal 1 philosophy is taken, the end of the indecision zone is defined to be about 1 or 2 sec of travel time upstream of the stop line detector. If a Goal 2 philosophy is taken, the end of the zone is defined to be at the stop line.

Regardless of which philosophy is adopted, the settings on the stop line detector unit must be considered in determining the MAH. If the stop line detector is active (i.e., not operating with call delay) during the green, then the MAH will be increased by the magnitude of the CE setting on this unit and the PT setting on the controller. If the call-delay feature of the stop line detector unit is invoked during the green [such as with an EC-DC (extended-call/delay-call) detector unit], the detector is essentially inactive during the green and a clearing vehicle will not place a call at the stop line.

MAH for Goal 1 Designs   If the detector design for a lane group reflects a Goal 1 philosophy, its MAH can be calculated using the following equations:

$$MAH = MAH_a + MAH_s \qquad (2)$$

$$MAH_a = PT + CE_n + \frac{D_1 - D_n + L_d + L_v}{V_a} \qquad (3)$$

where

MAH_a = maximum allowable headway for the advance loop (or group of advance loops) (sec);
MAH_s = maximum allowable headway for the stop line detection zone (from Equation 1) (sec);
n = number of advance detectors, $n = 1, 2, 3, \ldots$;
D_1 = distance to the leading edge of the advance detector furthest from the stop line, as measured from the stop line (m);
D_n = distance to the leading edge of the advance detector nearest to the stop line, as measured from the stop line (m); and
L_d = length of an advance loop detector (all advance loops are assumed to have the same length) (m).

The additive property of the MAHs for the two detection zones stems from the independence assumption made when using the exponential distribution. This assumption is reasonable for lane groups with two or more lanes and should yield conservative (i.e., slightly higher) values for the single-lane lane group.

As with Equation 1, Equation 3 is based on the assumption that the detector unit is operating in the presence mode. If it is operating in the pulse mode, MAH_s would equal PT and MAH_a would be calculated with CE_n, L_d, and L_v equal to zero.

If the stop line detector unit is inactive (i.e., call delay in operation) during the green, MAH_s is zero and the MAH for a Goal 1 design would equal MAH_a only.

MAH for Goal 2 Designs   If the detector design in a lane group reflects a Goal 2 philosophy, its MAH can be calculated using the following equations:

$$MAH = \text{larger of} \begin{cases} MAH_t \\ MAH_a \end{cases} \qquad (4)$$

$$MAH_t = PT + CE_s + \frac{D_1 + L_v + SL - SB}{V_a} \qquad (5)$$

where

SB = distance between the trailing edge of the stop line detection zone and the nearest edge of the crossing travel path (m); and
SL = distance between the stop line and the nearest edge of the crossing travel path (m).

Equation 4 is based on the assumption that the advance and stop line detector units are operating in the presence mode. If they operate in the pulse mode, the values for CE_s, CE_n, SL, SB, L_d, and L_v should be set to zero for Equations 3 and 5.

If the stop line detector unit is inactive during the green, the MAH for a Goal 2 design would equal MAH_a, as calculated from Equation 3.

Max-Out Probability

One measure of intersection performance is the frequency of phase termination by max-out. As stated earlier, a max-out occurs when the green is extended by a continuous stream of arrivals until the maximum green duration is reached (and a conflicting call is continuously held on one or more phases). When a max-out occurs, the yellow indication is presented regardless of whether a vehicle is in the indecision zone. Of course, the more frequently drivers are caught in the indecision zone during the yellow, the more frequent will be situations where one driver decides to stop and a following driver decides to go. Thus, it is likely that the frequency of max-outs is positively correlated with the frequency of rear-end accidents.

One model for predicting the frequency with which a phase maxes out can be formulated by assuming that all calls extending the green emanate from a randomly arriving traffic stream. The distribution of these calls is assumed to be exponentially distributed with a mean flow rate (q) equal to the sum of the flow rates in each lane group served during the phase. This assumption is most valid for phases serving more than one lane because the frequency of small headways (i.e., those less than 2 sec) measured across multiple lanes is more consistent with that predicted by the exponential distribution.

The probability of a max-out can be equated to the joint probability of there being a sequence of calls to the phase in service, each with a headway less than the MAH. This probability can be stated mathematically as follows:

$$P(\text{max-out}) = (1 - e^{-qMAH})^n \qquad (6)$$

where

$q = q_1 + q_2 + \ldots + q_m;$
m = number of lane groups served during the phase;
q_i = flow rate in lane group i ($i = 1, 2, \ldots, m$) [in vehicles per second (vps)];
$MAH = (q_1 MAH_1 + q_2 MAH_2 + \ldots + q_m MAH_m)/q$ (sec);
MAH_i = maximum allowable headway for lane group i (sec); and
n = number of arrivals necessary to extend the green to max out.

The MAH calculated above represents the *equivalent* MAH for the general case where one or more lane groups served by a phase have differing MAHs. If all m lane groups have the same MAH_i, the equation for calculating the equivalent MAH simplifies to this common MAH_i. This equivalent MAH must be used in all subsequent evaluation equations.

The flow rate for various lane groups should be based on the demand traversing the group's detected area. For example, the flow rate for a left-turn lane group would equal the left-turn flow rate on that approach. When the length of an exclusive turn lane is less than the length of the detection zone for its adjacent through-movement lane group, the flow in the exclusive lane will also contribute to the flow in the through lane group. In these situations, it is recommended that the flow rate for the through-movement lane group equal the flow rate *entering* its detection zone. This approach is exact when the stop line detection zone is inactive during the green and is conservative when the stop line zone is active.

Equation 6 requires an estimate of the number of arrivals needed to max out the green. This estimate can be obtained

by dividing the maximum green duration by the average headway of all vehicles with headways less than the equivalent MAH. The equations for estimating the number of arrivals and the average headway are

$$n = \frac{G_{\max} - MAH - R}{h} \qquad (7)$$

$$h = \frac{\int_0^{MAH} tqe^{-qt}dt}{\int_0^{MAH} qe^{-qt}dt}$$

$$= \frac{\dfrac{1}{q} - \left(MAH + \dfrac{1}{q}\right)e^{-qMAH}}{1 - e^{-qMAH}} \qquad (8)$$

$$R = (G_q - h_c)(1 - e^{-q_c G_q}) \qquad (9)$$

where

$G_{\max}$ = maximum green duration of the subject phase (sec);
h = average headway for all vehicles with headways less than MAH (sec/veh);
G_q = queue clearance time of subject phase ($G_q \geq G_{\min}$) (sec);
R = time between first call on a conflicting phase and queue clearance (sec);
$G_{\min}$ = minimum green duration of subject phase (sec);
q_c = total flow rate in all conflicting phases (vps); and
h_c = average headway between calls from conflicting phases considering only those headways less than G_q (sec).

The value of h_c can be calculated using Equation 8 with G_q substituted for MAH and q_c substituted for q.

Figure 2 illustrates the relationship between the probability of max-out, total traffic demand for the subject phase, equiv-
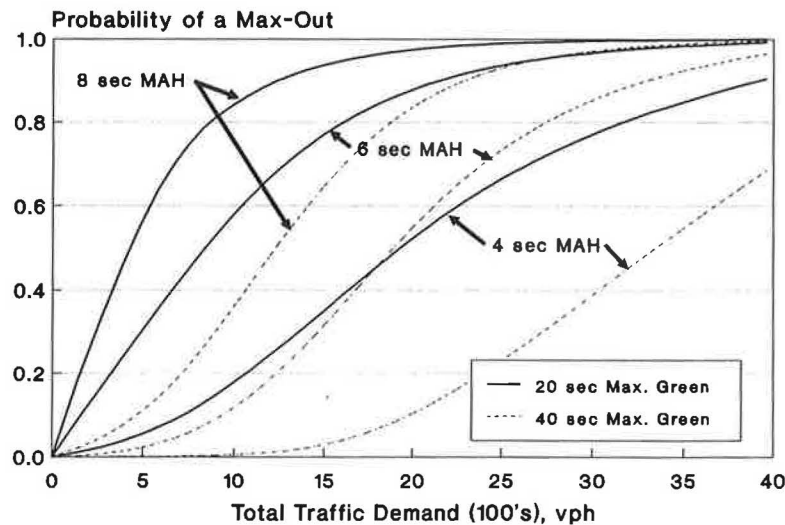

Probability of a Max-Out

FIGURE 2 Probability of a max-out as a function of traffic demand and maximum green duration.

alent MAH, and maximum green duration. Figure 2 is based on a q_c of 0.14 vps (500 vph) and a G_q of 15 sec. In general, the probability of max-out increases sharply with MAH and traffic demand. Examination of the effect of maximum green indicates a decrease in max-out probability with increasing maximum green duration.

To illustrate the use of Figure 2, assume that the subject phase has a total traffic demand of 1,100 vph and a maximum green duration of 20 sec. If the analyst can formulate a design that yields a 4-sec equivalent MAH, the probability of max-out will be less than 0.2. In other words, 8 of 10 signal cycles will terminate by gap-out and thus indecision-zone protection will be provided about 80 percent of the time.

If the analyst finds that the resulting design yields a MAH of 8 sec, the probability of max-out increases to almost 0.9. This implies that nine of ten cycles will end by max-out and suggests that there may be little to gain by installing an indecision-zone detection design if it yields an 8-sec MAH.

Waiting Time

The average wait by a traffic queue for a gap-out to occur in a conflicting phase can be determined by using a theoretical approach based on random arrivals to the phase being served. This time can be determined from the following equations:

$$W = (h * N + MAH)p + R \tag{10}$$

$$p = 1 - e^{-qMAH} \tag{11}$$

where

W = average wait by conflicting traffic for a gap-out to occur in the phase being served (sec);

h = average headway for all vehicles with headways less than MAH (sec/veh);

N = average number of extensions of green (i.e., headways < MAH);

p = probability of a headway's being less than the equivalent MAH); and

MAH = maximum allowable headway that will maintain a call for service (sec).

The average number of green extensions before the phase terminates is dependent on the traffic demand in the phase being served, the equivalent MAH, and the maximum green duration for this phase. The average number of extensions can be calculated as

$$N = \frac{\sum_{i=0}^{n-1} ip^i(1 - p) + np^n}{\sum_{i=0}^{n-1} p^i(1 - p) + n}$$

$$= \frac{p}{(1 - p)}(1 - p^n) \tag{12}$$

Figure 3 illustrates the relationship among the average waiting time, total traffic demand for the subject phase, equivalent MAH, and maximum green duration. This graph is based on a q_c of 0.14 vps (500 vph) and a G_q of 15 sec. In general, the waiting time increases with MAH and traffic demand. Examination of the effect of maximum green indicates an increase in waiting time with increasing maximum green duration. This trend is the opposite of that for max-out probability, wherein it was noted that larger maximum greens reduced the probability of max-out. In summary, larger maximum greens may improve safety (via less frequent max-outs) but degrade operations (via longer delays).

To illustrate the use of Figure 3, assume that the subject phase has a total traffic demand of 1,100 vph and a maximum green duration of 20 sec. If the analyst can formulate a design that yields a 4-sec equivalent MAH, the average wait for gap-out will be about 14 sec. If the analyst finds that the resulting design yields a MAH of 8 sec, the average wait increases to about 19 sec. Moreover, if the analyst chooses to increase the
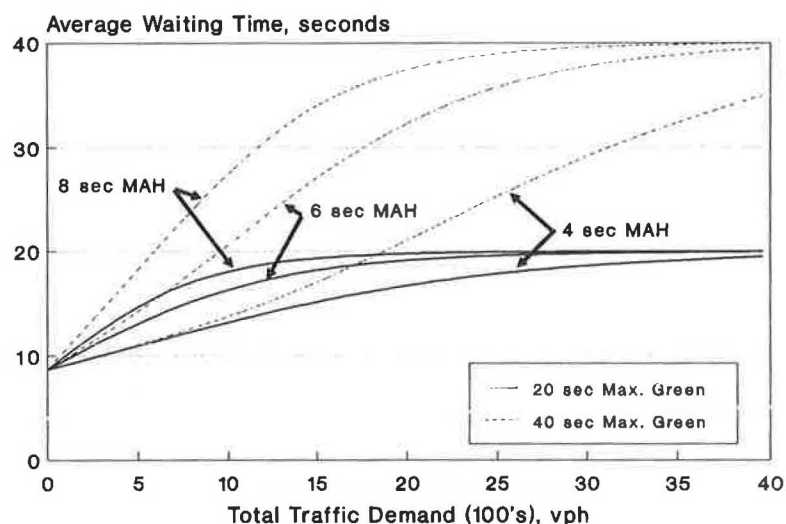

FIGURE 3 Waiting time as a function of traffic demand and maximum green duration.

maximum green duration to 40 sec (to reduce the max-out probability), the corresponding delay will stay at about 14 sec for a 4-sec MAH; however, it will increase to 29 sec for an 8-sec MAH.

Techniques To Reduce MAH

A detector design should offer a balance between safety and efficiency. This balance can generally be achieved by properly locating the detection zones and tuning the PT and CE settings. Designs with advance detectors tend to add additional complexity to the selection of the optimal PT and CE settings. In fact, detection can extend so far back on an approach that it may be impossible to find PT and CE settings that yield both safe and efficient operation. If this situation occurs, three techniques are offered that can help reduce the overall MAH and still provide safe and efficient operation.

One technique for reducing the MAH is to narrow the design speed range. Application of this technique requires a trade-off between the width of the design speed range and the length of the MAH for a detector design. A wider speed range will provide more safety by providing indecision-zone protection for a larger percentage of vehicles; however, it also tends to increase the MAH. Longer MAHs decrease safety because they increase the frequency of max-out and the delay to waiting conflicting traffic. As a minimum, the adjusted design speed range should always include 70 percent or more of the traffic stream (i.e., at least the 15th- to 85th-percentile speed range). The MAH will increase about 20 percent for every 10-mph increase in the design speed range.

A second technique is to adopt a design goal of carrying the last clearing vehicle only through the indecision zone (rather than into the intersection) upon gap-out. This technique was previously described as the Goal 1 design. To achieve maximum efficiency, the stop line detector unit should operate in an EC-DC mode during the green. The combination of a Goal 1 design and an EC-DC stop line detection unit can yield MAHs that are about 30 percent shorter than those from a Goal 2 design.

A third technique for reducing the MAH is to increase the number of advance detectors. In general, the MAH decreases with the number of advance loops provided on the approach. However, the return diminishes rapidly such that there is negligible reduction in MAH for designs with more than three advance loops. A two-advance-loop-detector design will increase the MAH about 1 percent over the three-loop design.

A one-advance-loop design will increase the MAH about 8 percent.

There is an added benefit, beyond MAH reduction, from using two or more advance loops in the detector design. Multiple advance loops can provide advance screening of vehicles traveling slower than the design speed range. These vehicles will not be able to extend the green between the first and subsequent loops, and yet a safe gap-out will be possible because these vehicles have not entered the indecision zone.

CONCLUSIONS

The safety and efficiency of a traffic detector design can be determined from the probability of max-out and the time spent waiting for gap-out and subsequent phase change. A detector design that minimizes these measures of effectiveness should provide safe and efficient operation. The performance of a design can be assessed by determining the maximum time separation that it will allow between vehicle calls to the controller (i.e., the maximum allowable headway). For situations where the design serves only a portion of the traffic lanes served by a phase, the analysis must proceed on a phase-specific basis and the performance evaluation would relate to the overall phase operation.

Achieving a detector design with optimal performance characteristics can be difficult because of complex interactions between the design elements (i.e., detector location, detector length, vehicle speed, passage time setting, and call-extension setting). In general, a large MAH will have an adverse effect on performance by increasing the max-out probability and the length of wait for phase change. The methodology described in this paper will allow the designer to determine the optimal combination of design elements in terms of safety (via infrequent max-out) and operations (via a short waiting time for phase change).

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