TRAFFIC SIGNAL DETECTOR LOCATIONS

PROPER POSITIONING INCREASES EFFICIENCY & SAFETY

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ABSTRACT

In recent years it has been the goal of traffic engineers to try to get the most out of the systems that they develop. By designing the most efficient systems the overall costs of transportation should be slightly easier to manage. As with all transportation infrastructure the design of traffic signals should be undertaken to produce the maximum benefits for the costs outlayed.

The design and location of the vehicle detectors used for traffic actuated signals has for many years been taken for granted. The locations in which they are installed may not be the optimum for the efficient performance of the signal. In this report we will see that the placement of vehicle detectors near the stop lines of the intersection seriously degrades the performance of the signal. The more efficient placement of the detectors at a location some distance in advance of the stop line can greatly aid in the efficiency of the system by increasing traffic flows, decreasing individual and total vehicle delays, and by improving safety for the driving public.

INTRODUCTION

Traffic signal operations have been well developed and refined over the years as part of traffic engineering. The problem of interrupted traffic flow has been a major concern as it affects not only flow rates and delay but also safety for the traveling public. In recent times, traffic signals have developed from simple fixed time control using electro-mechanical time clocks, which was the major method of traffic control up to 30 years ago, to highly sophisticated computerized traffic actuated controllers.

The main advantage of traffic actuated control is the ability to be responsive to highly fluctuating traffic patterns thereby reducing the overall delay to traffic at an intersection. The advantages obtained from the efficient operation of a traffic signal come in several forms. At a properly controlled intersection accident rates will be lower, the traffic flow will be increased, and delays will be minimized all of which have direct economic benefits. Additionally environmental benefits will be realized such as lower air pollution, which is directly related idling and accelerating vehicles, and lower noise pollution caused by braking, accelerating, and idling of heavy vehicles.

A major requirement for efficient signal operation, and all too often overlooked, is the proper placement of the vehicle detectors. For traffic controllers to be responsive to the traffic patterns information must be collected from the intersection on a real time basis and processed by the controllers microprocessor. The only method available to collect this information is through various methods of vehicle detection. The correct design and placement of these vehicle detectors is critical to the efficient operation of the signal, however, in many installations the placement of the detectors is treated as a secondary concern even though vast amounts of money is afforded to the selection of the controller unit.

In this study we will consider two simple scenarios of detector placement, that of locating detectors at the stop line and that of locating the detectors some distance in advance of the stop line. These scenarios comprise the vast majority of isolated, non-interconnected traffic signals. The study is based on the placement of inexpensive pulse type inductive loop detectors using small area detection and does not consider the application of large area detection using presence detectors or wide area detection using more sophisticated techniques such as video imaging. These later subjects are quite complex and best studied independently. Many other methods of small area detection are available such as magnetometers, piezometric sensors, ultrasonic devices, and radar and are equally applicable to the theory of small area detection.

The area of study looks only at isolated intersections which are independently controlled by their own fully traffic actuated controller. This also includes intersections which form part of an interconnected network and have been released from the system control to run independently during off-peak hours. The detection schemes studied apply to the straight through movements at an intersection where the vehicle headway is not altered by the affects of turning vehicles. However, the application of the detector placement theory can be applied to left and right turn lanes with only minor modifications.

SIGNAL CONTROL STRATEGIES

Several different strategies are employed for the control of traffic signals ranging from non-actuated fixed timed to fully traffic responsive volume-density control. Fixed time, also known as pre-timed, controllers are of limited use for isolated intersections and require no traffic detection. Traffic actuated controllers are by far the most common control method used for isolated intersections. These traffic actuated controllers can range from semi-actuated, to fully traffic actuated, to traffic responsive volume-density. All traffic actuated controllers require vehicle detection on all legs of the intersection for efficient operation.

The general operation of traffic actuated controllers is described as follows:

- The green time for each phase is determined by the volume of traffic on the corresponding street and may vary from cycle to cycle. A maximum green time is predetermined and set within the controller.

- The request for green time is placed by a vehicle detector actuation during the red phase of a conflicting traffic movement. The minimum initial green time available is predetermined and set within the controller. This minimum initial green time is usually set to be adequate for the number of vehicles waiting between the stop line and the vehicle detector.

- Each additional vehicle which actuates the detector during the green phase calls for a vehicle green interval extension of a predetermined length. This extends the minimum green time up to the maximum green time set in the controller. Figure 1. illustrates the vehicle interval extension process. If a gap in between vehicles occurs which is larger than this preset vehicle interval extension, and a call has been placed by an opposing phase, then the controller will ‘gap out’ and the green will be terminated for that phase. If enough traffic is present for the controller to reach the maximum green time then the controller will ‘max out’ and the green time will be terminated.

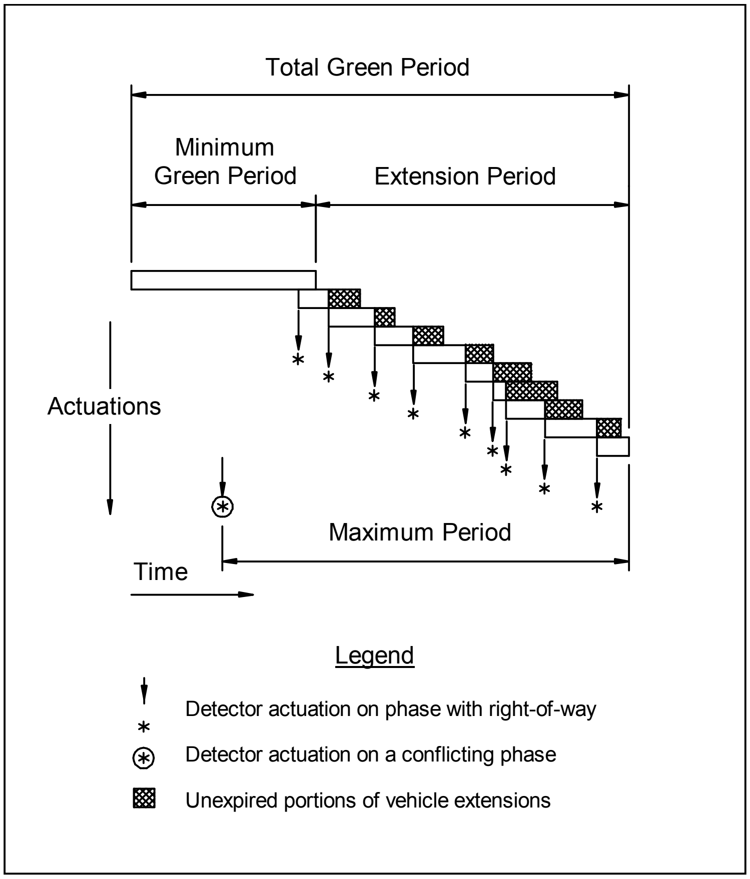

Figure 1. - Actuated Controller Intervals

Source: Reference 11.

Some variations in the operation specific types of traffic actuated controllers is described as follows:

SEMI-ACTUATED CONTROLLERS

- Semi-actuated controllers are used at intersections where the minor street has traffic volumes significantly lower than the major street. The priority of operation is to minimize the interruption of traffic on the major street while still providing adequate service to the minor street.

- Vehicle detectors are required only on the minor street. The detectors will input a call for green time as well as calls for vehicle interval extensions up to a preset maximum limit.

- The major street has a preset recall to its green phase. No detector call is required and the green will always revert to major phase when the minor street has been serviced. The major street will have a preset minimum green time, and will continue to rest in green on that phase until a call has been placed by the minor street.

FULLY-ACTUATED CONTROLLERS

- Fully-actuated controllers are used where both streets at an intersection have relatively equal volumes. These controllers are particularly efficient where the traffic flows are sporadic and uneven. The priority of operation is to minimize the total delay by minimizing stops on all phases.

- Vehicle detectors are required on all legs of the intersection. These detectors will input calls for initial minimum green time as well as vehicle interval extensions.

- Any or all phases of the signal can be set for automatic recall to green which will give the corresponding phase the minimum green time without a vehicle actuation. If all phases have automatic recall set then the signal will cycle through all the phases, giving each phase a minimum green time, even if no traffic is present on a particular leg. If recall is not set on any phase then the signal will service only those phases that have traffic actuations and skip the others. In the absence of any traffic, such as nighttime operation, the controller can either rest on the last served green phase or rest on red on all phases. If recall is set on only one phase the signal will revert to green on that phase once during every cycle. In the absence of traffic the signal will rest on green on this phase. This is a common setting for many intersections as one of the legs is usually considered slightly more major than the others.

VOLUME-DENSITY CONTROLLERS

- Volume-density controllers are similar in operation to fully actuated controllers, however, contain more advance features for analyzing the traffic volumes on the green phase being served and the traffic density on the red phase being held. This information is then processed and the timing patterns altered for a more efficient operation. These controllers are the most efficient means of operation signals at isolated intersections.

- The most important feature of volume-density controllers is the ability to reduce the green vehicle extension interval depending on the density of opposing traffic. As the measured density of the opposing traffic increases the vehicle extension interval for green time is reduced linearly (known as gap reduction) to some preset minimum extension time. Figure 2. illustrates the gap reduction process.

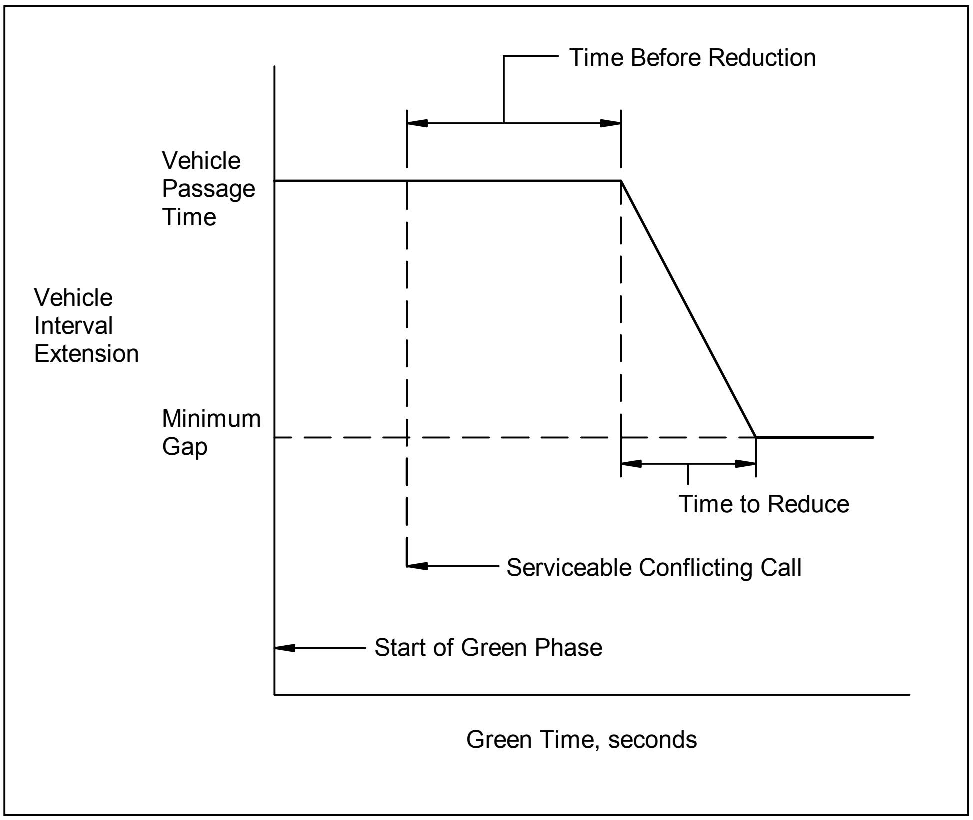

Figure 2. - Gap Reduction Process

Source: Reference 11

- The controller has the ability to increase the minimum green time depending on the number of vehicles queued behind the stop line. Figure 9. illustrates the variable initial timing process.

- In order to function properly these controllers must obtain information early enough to react to the fluctuating traffic patterns. Detectors must be place well in advance of the stop lines for such information to be useful.

- A special version of the volume-density controller, known as a 'Modified-Density Controller', has many of its features but requires less information from the intersection. Traffic flow statistics are obtained from the detector actuations of the previous cycle with the assumption that the present cycle being served has the same characteristics as the cycle preceding it. This may be acceptable for situation where traffic flow is relatively deterministic, however, is not efficient where intersection have highly unpredictable and random flows.

REASONS FOR CORRECT DETECTOR PLACEMENT

The operation of traffic actuated signals is highly sensitive to the correct placement of the vehicle detectors. Incorrect placement will degrade the efficiency of traffic flows as well as have detrimental effects on the safety of the intersection. Several factors, directly affected by the placement of the detectors, are outlined as follows.

Incorrect detector locations will add to the lost time per phase and consequently the total lost time per cycle of the signal. An increase in lost time will add to the increased individual and total delay and cause the signal to operate at a lower level of service.

Detectors placed only at the stop lines will issue calls too late for signals that have entered their rest mode. Advance detectors can ensure the early actuation of a green signal prior to a vehicle stopping and reduce the stopped delay. Conversely, in some special safety situations it may be advantageous to require the vehicle to stop before proceeding through the intersection. This is easily handled by programming a set time delay in the actuation of a remote detector.

Every driver that arrives at a signal during its change interval from green to yellow experiences the dilemma of whether to stop or to proceed. This dilemma leads to more accidents within the intersection as well as more rear-end accidents prior to the intersections.

The proper design and placement of detectors can reduce the requirement for advance warning signs on higher speed intersections by greatly reducing the dilemma zone. This cost saving in itself can offset the added costs of additional or remotely located advance detectors.

A special case for remote detectors is for signal pre-emption on freeway off-ramps. In situations of abnormally heavy exit flows there is a possibility of traffic backing up into the through lanes on a freeway, degrading the traffic flow on the freeway and creating a hazardous situation. The proper placement of remote detectors on the off-ramp can monitor exit flows and force off the green phase on the cross-over street.

Detectors placed in advance of the stop lines at rural and sub-urban intersections can monitor individual vehicle speed and be used for traffic calming purposes.

LOST TIME AND DELAY

The improper placement of detectors can increase the lost time per phase and therefore the total lost time per signal cycle. This lost effective green time leads to an increased individual and total delay for vehicles using the intersection. For a signal installation which is operating near capacity (i.e. with $0.85 < v/c < 0.95$) it is highly likely that the green time on a particular phase will be terminated by a vehicle interval extension gapping out rather than by the green time maxing out. Studies have shown that at efficiently designed intersections, that is intersections operating near capacity where the mean service rate is greater that the mean arrival rate, the signal timings can be set such that 90% of the signal terminations will involve a gap out and only 10% of the signal terminations will involve a max out (a max out corresponds to a cycle failure). Maxing out of the signal phase, and hence a cycle failure, will be caused by random fluctuations in the arrival rate and can be predicted by employing a stochastic delay model. A stochastic delay model, such as the delay equation contained in the 1994 *Highway Capacity Manual*, includes two separate terms.

1994 *Highway Capacity Manual* Delay Formula:

$$d = d_{UD}DF + d_{OD}$$

$$d_{UD} = 0.38C\frac{\left[1-(g/C)\right]^2}{1-(g/C)(v/c)}$$

$$d_{OD} = 173(v/c)^2\left[((v/c)-1)+\sqrt{((v/c)-1)^2+\frac{m(v/c)}{c}}\right]$$

where:

d	=	average stopped delay, sec/veh
d_{UD}	=	uniform delay, sec/veh
d_{OD}	=	random or overflow delay, sec/veh
DF	=	delay adjustment factor for control type (= 0.85 for fully actuated controllers)
C	=	cycle length, sec
c	=	capacity of the critical lane for the particular phase, vph
g	=	effective green time for the particular phase, sec
m	=	overflow delay calibration term due to arrival type and platooning (= 16 for uncoordinated phases)
v/c	=	volume to capacity ratio

The first term, d_{UD}, details the uniform delay caused by uniformly arriving vehicles. The second term, d_{OD}, details the random or overflow delay due to the fact that the random arrivals (generally Poisson distributed) lead to vehicles overflowing from one cycle to the next causing cycle failures. The following Figure 3. represents the percent delay contained in the uniform and overflow delay terms as a function of the volume to capacity ratio (v/c).

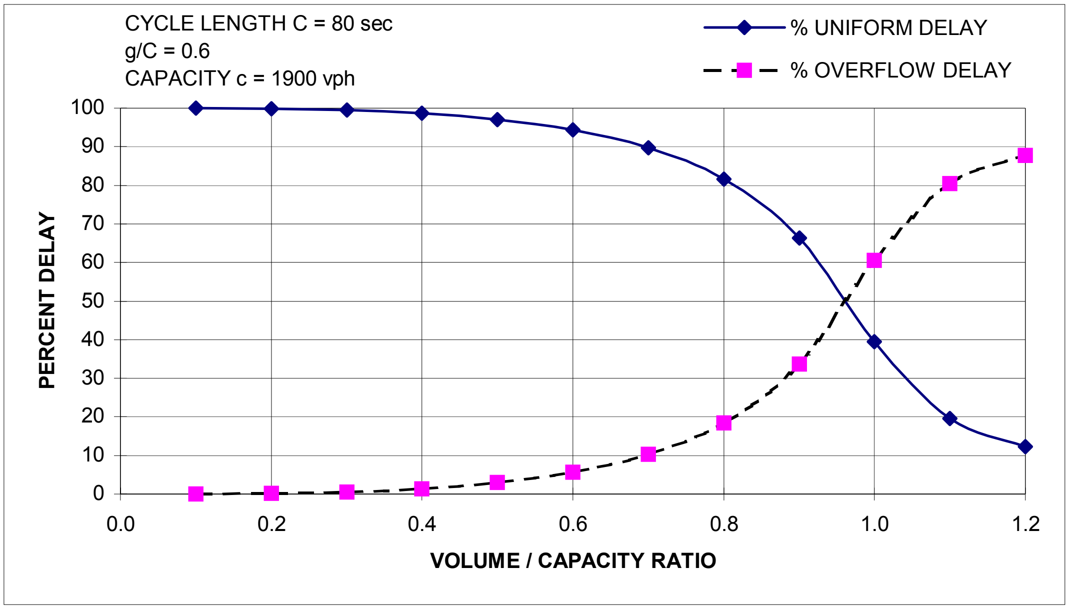

Figure 3. - Percent Uniform and Overflow Delay vs Volume/Capacity Ratio

The overflow delay does not become the dominant term of the total delay until the volume to capacity ratio exceeds 0.95. It can be inferred from this data that the cycle will probably not have noticeable failures until the v/c ratio reaches 0.95 and that most signals phases will terminate on a gap out.

For signals where the detectors are placed at the stop line all actuations for vehicle extensions will provide the green interval extension time for the following vehicle. For the last vehicle arriving this extended green time is unnecessary and only adds to the delay of the cross street vehicles waiting for their green. Furthermore, as shown above, this situation happens for the majority of the signal cycles as most of the phases will terminate by gapping out. This can add significantly to the total vehicle delay if many cross street vehicles are waiting for the green and is further compounded for multi-phase signals which may have protected left turn movements.

For a 2 phase intersection using a vehicle interval extension of 3 sec this additional lost time will add up to 6 sec/cycle. This is well above, and must be added to, the expected change interval lost time of 1.5 sec/phase and the start-up lost time of 2 sec/phase as detailed in the 1994 *Highway Capacity Manual*. For an average cycle length of 40 sec:

Expected lost time (due to change interval and start-up):

total lost time per cycle	=	3.5 sec/phase	=	7.0 sec/cycle
cycles per hour	=	3600/40	=	90 cycles
total hourly lost time	=	90 x 7	=	630 sec
total effective green time	=	3600 - 630	=	2970 sec/hr

Additional lost time (due to detector at stop line):

total lost time per cycle	=	3 sec/phase	=	6 sec/cycle
total hourly lost time	=	90 x 6	=	540 sec
new effective green time	=	2970 - 540	=	2430 sec/hr

The total effective green time for the signal has been reduced from 2970 sec/hr to 2430 sec/hr, a reduction of 18%, by placing the vehicle extension detector at the stop line. This additional lost time is unnecessary and would be eliminated if the detectors were placed in advance of the stop line at a distance equal to the average travel speed divided by the vehicle interval extension time (in this case also known as the vehicle passage time). The percent increase in the effective green time for the example detailed above would be 22%. This can also be translated into a capacity flow rate increase of 260 vph across the entire intersection using a Greenshields saturation headway of 2.1 sec/veh.

Placement of a detector to eliminate this extra lost time is be done using the formula:

$D = S \times P$

where:

D = distance from the stop line to the far edge of the detector for a pulse detector
S = average speed of vehicles through the intersection at the distance D from the stop line
P = vehicle interval extension time (vehicle passage time)

For a vehicle interval extension time of 3 sec and a average approach speed of 50 km/h (both which are common for many intersections) the required distance for a pulse detector would be:

$$D = \frac{50000\,m/h}{3600\,sec/h} \times 3\,sec = 42\ m$$

The placement of the detectors in advance of the stop line at the calculated distance ensures that the last approaching vehicle will reach the stop line just as the yellow clearance period is initiated.

Using various vehicle interval extension and passage times Figure 4. shows the relationship between percent increase in the effective green time, by locating the vehicle interval extension detectors in advance of the stop line, and the cycle length:

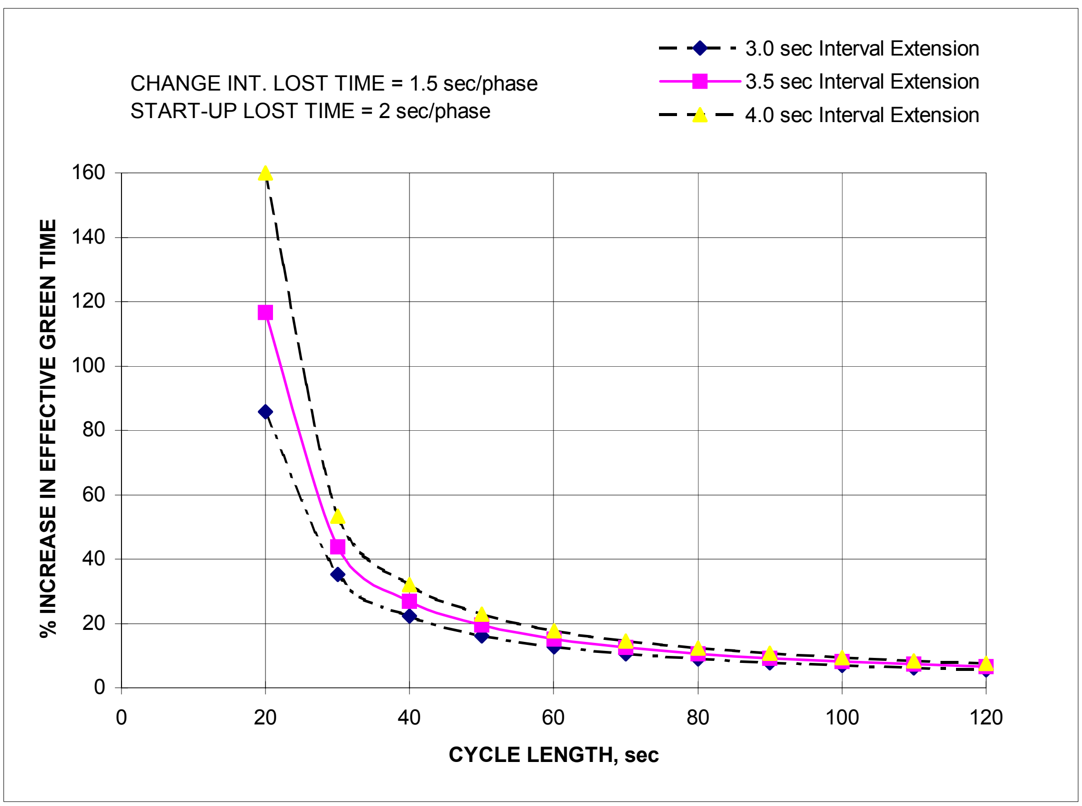

Figure 4. - Percent Increase in Effective Green Time vs Cycle Length

It is apparent that the percent increase in the effective green time decreases as the cycle length increases. However, for fully traffic actuated signals there is no set cycle length as the cycles vary continuously due to uneven traffic volumes. In practice most intersections will operate below an individual cycle length of 70 sec when the volumes are less than capacity. At this point the increase in effective of green time, already around 12%, starts to rise rapidly and will have considerable impact on performance of the system.

The standard performance measure of the level of service for signalized intersections is the average stopped delay for individual vehicles in sec/veh. By employing the 1994 *HCM* delay equation (detailed above) the sensitivity of the delay to the percent increase in effective green time can be analysed. Using a 3 sec vehicle interval extension, Figure 5. shows the relationship between the percent decrease in individual average stopped delay and the percent increase in the effective green time. Figure 6. shows the relationship between the percent decrease in average stopped delay and the cycle length for the same parameters.

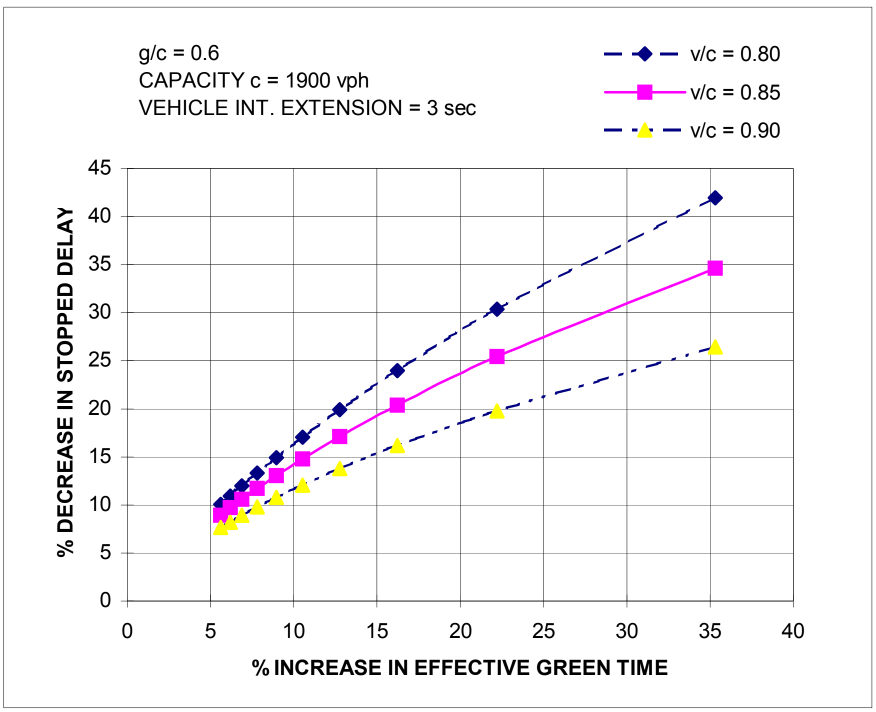

Figure 5. - Percent Decrease in Stopped Delay vs Percent Increase in Effective Green Time

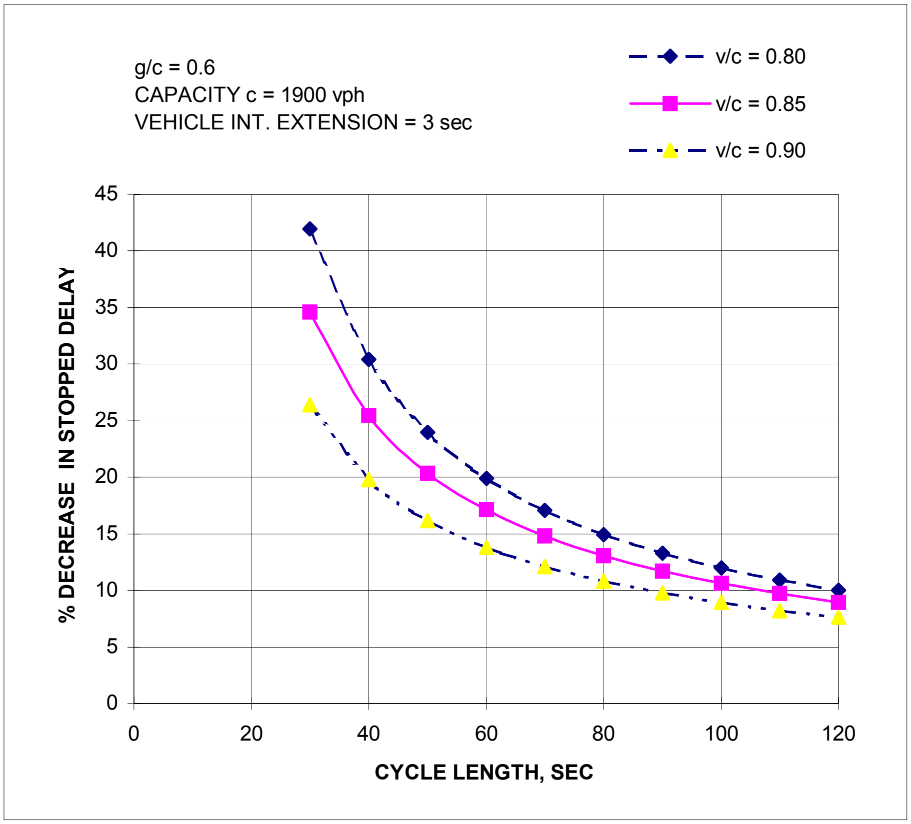

Figure 6. - Percent Decrease in Average Stopped Delay vs Cycle Length

For a 70 sec cycle length, a v/c ratio of 0.85 (near capacity status), an intersection speed of 50 km/h, a vehicle interval extension of 3 sec, and a detector setback of 42 m, the average stopped delay per vehicle is reduced by 15% in comparison to a signal installation which has the detectors set at the stop line.

The examples used above have been calculated for the demonstration of detector placement only and are not indicative of the optimal distance to place the detector. This optimal distance will depend on the selected vehicle interval extension time and the approach speed of the traffic. However, it adequately displays that the most inefficient place to locate the vehicle detector is at the stop line.

DILEMMA ZONE

As vehicles approach an intersection and the signal enters its change interval and displays the yellow a decision must be made whether to proceed through the intersection or whether to stop. This decision has serious safety consequences as an abrupt stop may cause a rear-end accident while proceeding through the intersection may lead to a right-angle collision. At high speed intersections, defined as intersections where the approach speeds exceed 60 km/h, this problem is of great concern.

At a certain range of distances from the stop line, which depend upon the speed of the approaching vehicles, the driver may be undecided whether to accelerate and cross the intersection or whether to brake sharply and stop the vehicle. This area of indecision is known as the ‘dilemma zone’. Some researchers, using empirical data (Ref. 5.), have arbitrarily defined the dilemma zone as the area in which at one end 90% of the drivers will stop their vehicles and at the other end 90% of the drivers will accelerate their vehicles. A more theoretical approach to defining the dilemma zone is as follows (Ref. 19.):

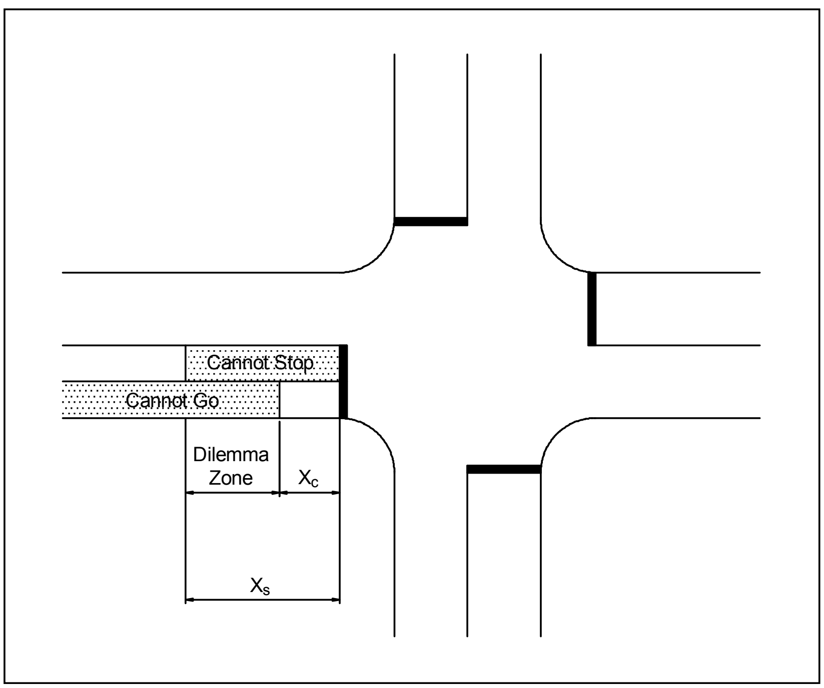

Figure 7. - Dilemma Zone

Source: Reference 19

The following inequality must be maintained to ensure a safe and complete stop:

$$X_s \geq Vt + \frac{V^2}{2d}$$

where:

X_s = distance from stop line to start of yellow
V = approach speed
t = perception/reaction time
d = constant deceleration rate

This formula varies slightly from the standard stopping sight distance formula which is derived for a panic stop. Typically, for comfort and safety (which are the main criteria for the dilemma decision) the deceleration rate, d, should not exceed one third to one half that of gravity. The distance X_s is the minimum distance from the stop line that a vehicle can comfortably and safely stop. A driver closer to the stop line will perceive that he or she will not be able to stop in time and falls into the area labeled 'Cannot Stop'.

If the driver is to accelerate and enter the intersection prior to the red signal (provincial laws only require that the vehicle has entered the intersection prior to the red display not to have completely cleared the intersection) the following inequality must be maintained:

$$X_c \leq \frac{V(Y+R) + a(Y+R-t)}{2}$$

where:

X_c = clearance distance
V = approach speed
t = perception/reaction time
a = acceleration rate
Y = yellow change interval
R = red clearance interval

Using Gazi's equation the acceleration rate can be approximated by the following:

a = 4.9 - 0.213V (metric)

The distance X_c is the maximum distance from the stop line for which a vehicle can enter the intersection prior to the signal changing to red. A driver farther back of this distance would not reach the intersection in time and will fall into the area labeled 'Cannot Go".

A dilemma zone occurs for the situation in which $X_s > X_c$ and the areas overlap as illustrated in Figure 7. Several strategies have been developed to alleviate the dilemma zone problem although the more complex methods involve large area detection and will not be perused here. The simplest method involves the placement of the vehicle detectors in advance of the stop line. By placing the detector at the far end of the dilemma zone (distance X_s) and setting the vehicle interval extension equal to the passage time required for the for the vehicle to travel from the detector to the stop line, the driver will have assured green time and the signal will change to yellow as the stop line is crossed. Vehicles traveling faster than the average speed will enter the intersection sooner than required and pose no problem. Vehicle traveling slower than the average speed will experience the yellow signal before they reach the stop line, however, it is quite likely that they will have reached the end of the dilemma zone (distance X_c) and will be able to safely accelerate into the intersection.

For higher speed intersections and at intersections using advanced volume-density controllers with gap reduction capabilities a series of detectors are placed at increasing distances from the stop line. Several methods for calculating the proper detector spacing are detailed in the *Traffic Detector Handbook* (Ref. 19.).

ADVANCE WARNING

Many signals on high speed roads and highways are equipped with advance warning flashers to help deal with the dilemma zone. When the opposing traffic puts in a call for green time and the signal timing on the serviced phase has either gapped or maxed out and additional clearance period will be activated in the form of an advance warning flasher. Although providing safety for the traffic on the higher speed highway additional lost time may be added to the cycle if there are no vehicles to clear between the advance warning sign and the stop line.

The reduction of the dilemma zone problem by the proper installation of remote detectors may result in the elimination of the need of the advance warning signs with considerable associated cost savings. This may be particularly true for highways that have slower speeds of around 70 km/h which comprises a large percentage of the signals in our area.

For higher speed highways of 80 km/h and 90 km/h the use of multiple detectors at increased spacing from the stop line may be appropriate. Although not fully researched for this paper the principle is basically the same as the single detector system providing adequate passage time to allow the vehicle to cross the stop line. In this case vehicle passage time need only be adequate to travel to the next detector at which point the process starts over again.

This process of multiple detector installations is best studied within the context of large area and wide area detection using some of the new advanced systems such as video image processing.

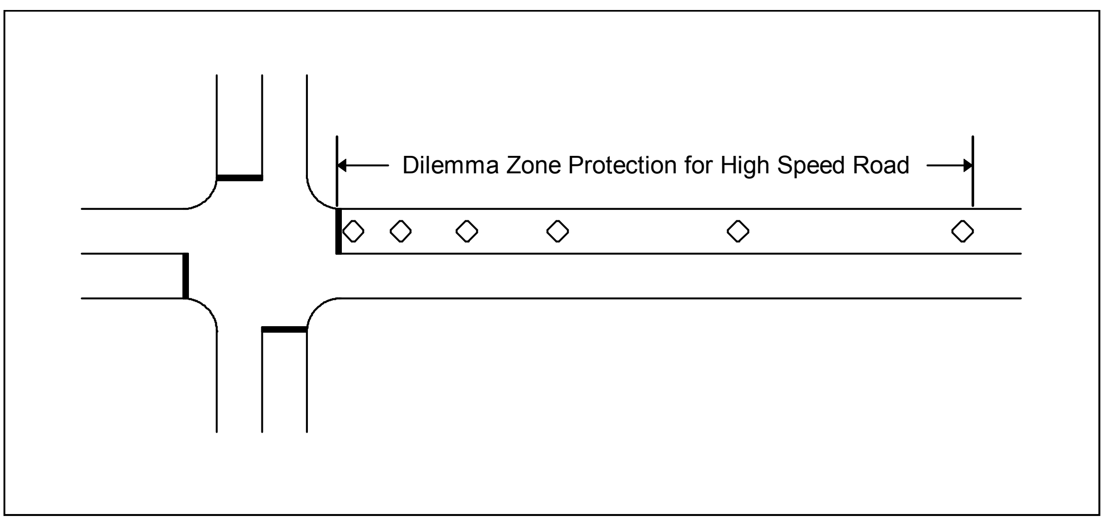

Figure 8. - Multiple Detector Installation

EARLY ACTUATION

Many traffic signals which are set with recall on the major street will rest in green on that phase, even after the maximum green time has elapsed, until an actuation has been placed by a vehicle in an opposing phase. As the entire major street has been served the controller will give immediate service to the cross street, however, the major street still requires a clearance period. If the cross street detector is placed at the stop line the approaching vehicle is forced to brake, slow down, and stop to initiate the detector call. Furthermore the vehicle must wait stopped at the intersection while the major street clearance period times out. This has needlessly wasted time and fuel efficiency for this traffic.

One possible location for the detector is in advance of the stop line at a distance previously calculated for the lost time concept. This will allow the actuation to be placed while the traffic on the crossroad is still moving and may provide adequate time for the clearance period of the major steer to time out. Using the distance of 42 m calculated for the lost time concept:

$$D = S \times (Y + R)$$

where:

D = distance traveled by the approaching vehicle after the actuation
S = speed of the traveling vehicle (say 50 km/h)
Y = yellow change interval on the major street (say 4 sec)
R = red clearance interval on the major street (say 1 sec)

$$D = \frac{50000 \text{ m/h}}{3600 \text{ sec/h}} \times (4 + 1)\text{sec} = 70 \text{ m}$$

This distance is greater than the previously calculated detector distance of 42 m. However, it can be presumed that upon seeing the red signal the driver will slow down upon approaching the signal. If the drivers speed slows to 25 km/h as the detector is crossed the distance traveled will be 33m and the driver will get the green light before the stop line is reached. If this is not adequate the detector should be placed farther back with a corresponding increase in the vehicle interval extension time. Another solution would be to place an additional detector farther back from the stop line and use it for vehicle phase actuation only and continue to use the closer detector for vehicle interval extension.

Many traffic engineers are of the opinion that it is safer for the traffic on the cross street to be forced to stop at the red signal before proceeding through the intersection. Although no data has been found to support this theory a delay for inputting the actuation into the controller could be programmed in the system while maintaining the detector in its remote location for vehicle interval extension purposes.

As with other areas of discussion the example used above does not calculate the optimal location for the cross street detector only that the least effective place for the detector is at the stop line.

TRAPPED VEHICLES

An area of concern to many traffic signal designers is the problem with vehicles that are trapped between the advance detector and the stop line. This occurs when the green time maxes out and there are still vehicles in the queue. One solution that is possible with all standard traffic actuated controllers is to automatically place a call for the next green phase if the controller has maxed out. As a max out is a rare occurrence the efficiency to the entire system has not been compromised. A second solution is to install an auxiliary detector at the stop line, known as a call detector, which will input phase actuations only and will not input vehicle interval extension actuations. This detector may also be required if there are driveways between the stop line and the vehicle extension detector.

Many technicians also worry that in order to achieve a definite actuation the vehicle should be stopped over the detector and that driving over the detector may not put in a proper call. These fears are not well founded as detector technology is well advance and there is no reason to suspect that pulse detectors tied into the locking memory system of the controller are inadequate. Again this fear could be alleviated by the installation of an auxiliary detector at the stop line although this is not necessary.

A further efficiency is possible by programming in a variable initial green time. As more traffic is queued in the zone between the detector and the stop line the initial green interval may be extended for each additional vehicle. The vehicles are simply counted by the detector during the red phase. If only one vehicle has entered the zone, and this is therefore the only vehicle to be served the minimum green time can be rather short. If several cars have entered the queue between the stop line and the detector then the minimum green will be extended by a preset amount for each vehicle. Once the queue has backed up to the detector location no more vehicles will pass over it and no more time will be added on to the initial green time. At this point the vehicle interval extension will be enabled as the queue starts to move.

The minimum green allowable for the initial timing should be set for at least one car being present at the stop line. This green time should be at least the minimum headway required for the first vehicle in a queue and is 2.6 sec. As reported by King and Wilkinson (Ref. 21.) the first to fifth vehicles have varying startup headways between 3 sec/veh down to 2.1 sec/veh with all vehicles beyond the fifth having constant headways of 2.1 sec/veh. For practical purposes this startup headway could be averaged out and put at about 2.5 sec/veh.

For example if the detector is placed 33 m behind the stop line and the average vehicle length is 6 m then up to 5 or 6 vehicles may be stored in front of the detector. The initial green time for the situation of 5 vehicles with a minimum green extension time of 2.5 sec/veh would be 12.5 sec.

Figure 9. illustrates the process of the initial green time extension:

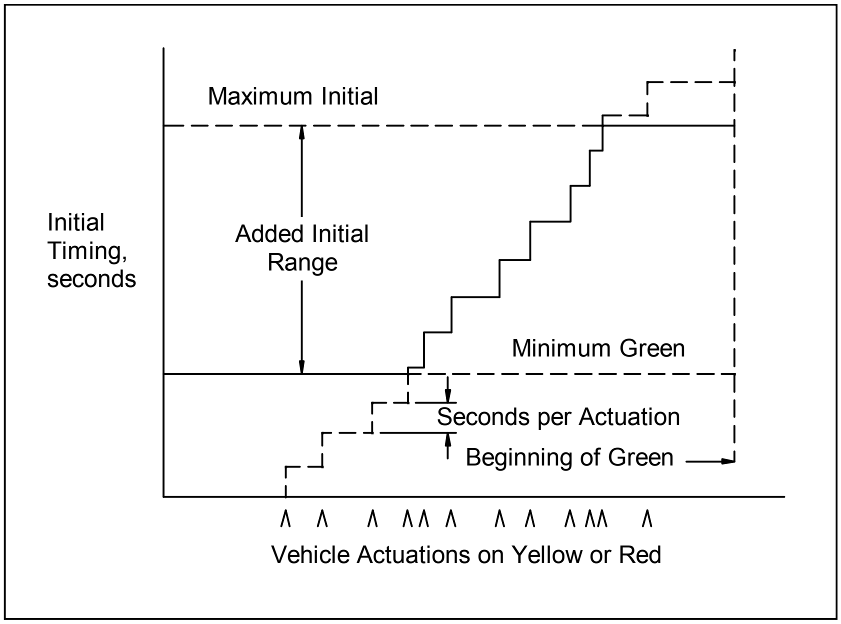

Figure 9. - Variable Initial Timing

Source: Reference 11

SPEED ACTUATED SIGNAL

A special situation can occur when it is desirable to force traffic to stop at a signal for safety or traffic calming reasons. Such a situation may be present at rural or sub-urban neighborhood intersections in which the approaching traffic is found to be in excess of the speed limit. In order to calm the traffic the speeding vehicles could be forced to stop while the vehicles traveling at the posted speed could be given uninterrupted passage through the intersection. Such intersections, typically low volume, should be fully actuated with the controller set to rest on red on all phases. When traffic approaches on one of the intersection legs the green signal is immediately transferred to that leg as no clearance period is required for the opposing traffic. A set of two pulse detectors can be placed upstream of the stop line, using the same location principles as used for early actuation, however these detectors will also be used for speed monitoring. If the speed of the approaching vehicle is measured to be too high a call will not be placed to the controller for several seconds forcing the vehicle to slow down or to stop completely. Vehicles traveling at or under the prescribed speed would place an immediate call to the controller and obtain a green signal prior to reaching the stop line.

Speed sensing is easily obtained by the placement of two pulse detectors placed a known short distance apart. As the vehicle crosses the leading edge of the first detector a timer starts and when the vehicle crosses the leading edge of the second detector the timer stops. From this recorded time, along with the known distance between the leading edges of each detector the speed can be calculated as the distance divided by the time. It is essential that the detectors be placed no farther apart than the typical gap distance between two vehicles. A spacing corresponding to one second of travel time from the trailing edge of the first detector to the leading edge of the second detector is usually sufficient.

SPECIAL CASE FOR RAMP CLEARANCE

A special case for remote detectors is a freeway off-ramp where the possibility exists for the traffic stopped by a signal at the top of the ramp to back up onto the main traveled portion of the freeway creating a dangerous situation and degrading the traffic flow. Such situations typically occur at diamond interchanges with short off ramps. The problem has previously been dealt with by giving a greater portion of the cycle length to the ramp even if it is not required for the typical volumes on the ramp. This produces an inefficiency along the cross street as unnecessary delay will be added. Assuming that the ramp and intersection at the top of the ramp were adequately designed the failure rate of the signal should be very low and usually occur only during peak traffic flows. This, however is the worst time to back up onto the freeway.

A simple solution is to install a remote queue detector with a predetermined delay. When a queue is detected to have formed to a certain location near the bottom of the ramp a call can be put into the controller to force off the green phase on the cross street and give priority to the ramp. The ramp will then clear out using normal initial green plus vehicle extension principles. This detector must be a presence detector which will detect if a vehicle has stopped over top for the preset delay time.

The problem encountered is to determine the appropriate location for the queue detector. If the detector is too close to the intersection false alarms will be produced and the cross street will be pre-empted too easily causing the traffic on the cross street to suffer unnecessary lost time. If the detector is placed too close to the bottom of the ramp the traffic may continue to build up the queue due to the time lag it takes to get the traffic moving. The optimal position will be where the back of the queue has begun to discharge at the same rate as the traffic is entering the queue. At this point the service flow rate will be greater or at least equal to the arrival rate. The back of this queue must not enter the freeway and should be at worst at the end of the ramp gore.

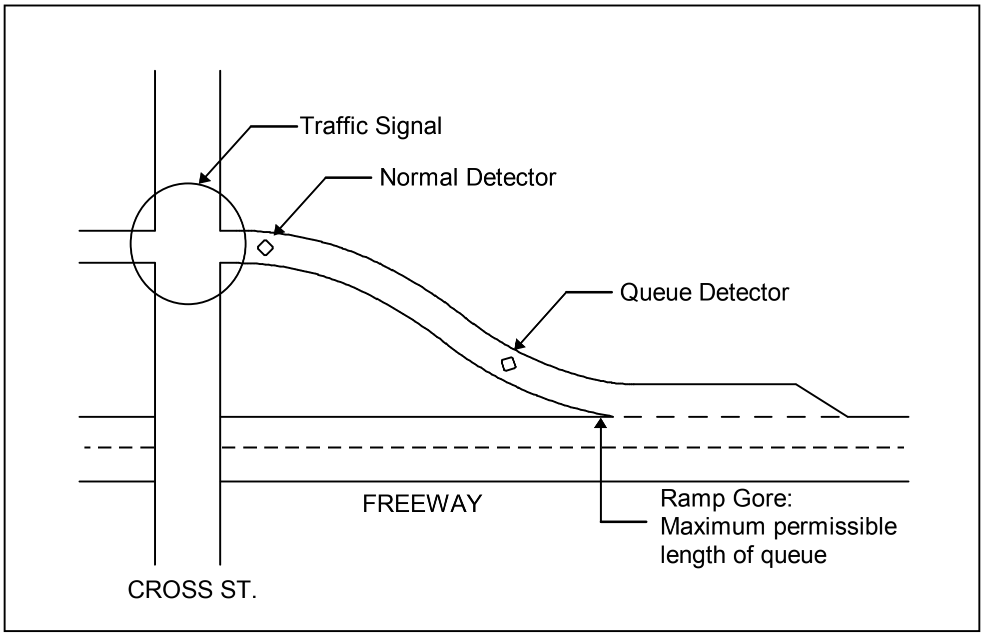

Figure 10. - Ramp Detector Locations

Using deterministic queueing theory it is possible to develop an equation for the position of the queue detector. Assuming that the queue will actuate the traffic signal and that the ramp traffic will start to discharge there will be additional secondary queueing due to the lag in the movement of the traffic. This will cause the queue to lengthen for the following time period:

$R = D + Y + T$

where:

R = time for the additional secondary queue build up

D = detector delay

Y = cross street clearance period including the red clearance

T = time duration of the original queue

The time duration of the original queue is:

$$T = \frac{u \times r}{u - l}$$

where:

u = mean service rate
L = mean arrival rate
r = effective red time of the opposing phase

Having now determined the time for the additional secondary queue build up R we need to find the length of the added queue:

$$Q = \frac{L \times R}{3600} \text{ in vehicles}$$

At an average length of 6 m per vehicle the length of the secondary queue from the detector to the end of this queue will be Q x 6. This is the minimum allowable distance from the gore of the ramp to the detector to ensure that the queue will not back up onto the freeway.

As specified this analysis has used deterministic queuing theory assuming a predetermined uniform arrival rate. However, in practice the arrival rate of the vehicles will be randomly Poisson distributed, and stochastic queuing analysis should be undertaken.

COST ANALYSIS

Of major concern to most jurisdictions installing traffic signals is the increased capital costs associated with any new equipment. This may lead some individuals to be concerned about added costs of placing the detectors remote from the stop line.

In most situations the traffic signal system is integrated with the street lighting system along the sides of the road. This provides an existing conduit system which can be easily used for the detector lead-in cables at no extra cost. In situations where it is required to have additional auxiliary detectors at the stop line a total of 12 extra detectors would be required for an intersection with 2 straight through lanes and a separate left turn lane. At an average cost of $500 per inductive loop detector the total increase in cost to the signal installation would be $6000. This is minor in comparison to the approximately $100,000 that a complete installation costs at today's prices. In fact most installations already are equipped with a set of 2 detectors at the stop line per lane. All that is required is to have the second detector located farther back to increase the efficiency and safety of the signal.

CONCLUSIONS

Proper placement of vehicle detectors can significantly increase the performance of a traffic signal installation not only by increasing traffic flow, but also by reducing individual and total delay and by increasing safety to the traveling public. It is the conclusion of this report that the proper position for detectors is at some distance in advance of the stop line. Continuing to place detectors close to the stop line provides no significant cost savings when compared to the overall cost of the traffic signal. The overall extended costs associated with vehicle accidents combined with the increased costs in fuel consumption by delayed or impeded vehicles far outweighs the incidental costs of remote detector placement.

This positioning of the detectors in advance of the stop line aids in the elimination of the dilemma zone, the area in which drivers are confused about whether it is safe to go or it is imperative to stop. This placement also aids in the flow of traffic by reducing unnecessary and extended stopping. Further advantages can also be obtained in special areas of traffic calming and ramp pre-emption.

While this report concentrated on straight through movements in the absence of increased headway demands caused by turning vehicles the basic theory holds for turning lanes and multi-phase signals. Further research can be done on the subjects of large area and wide area detection employing modern methods of vehicle detection such as video imaging systems. A wealth of information on the efficient use of detectors is available, many of which are listed in the reference section of this report.

The traffic demands of today are becoming increasingly complex and it is the duty of all traffic engineers to design the most efficient, cost effective, and environmentally friendly systems.

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