A Probabilistic Approach for Determining the Change Interval

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ABSTRACT

Determination of the change interval is a crucial step in signal timing. In the recommendations of the Institute of Traffic Engineers for determining the change interval, the length of the yellow light is so calculated that the "reasonable" driver can pass the stop line before the onset of the red light. Field data show that the normative, reasonable driver model fails empirically, particularly at low approach speeds. The common approach to determine the change interval fails to consider the possibility of rear-end accidents. It does not offer rational, empirical measures for evaluating the joint risk of right-angle and rear-end collisions for various durations of change intervals and for different combinations of yellow and red clearance intervals. A proposed alternative approach relies on the stopping probability function of traffic at the intersection approach. It is shown that the range of the indecision zone that can be inferred from the stopping probability function is related to the risk of rear-end accidents. Similarly, the stopping function and the speed distribution are related to the risk of right-angle collisions. Finally, it is demonstrated how the concepts of stopping probability function and indecision zone might be used in practice to determine the change interval.

Determination of the change interval is a crucial step in signal timing. Whereas other aspects of timing focus on the efficiency of moving traffic through a signalized intersection, the change interval relates directly to safety, specifically, those elements associated with reassigning the right-of-way to conflicting traffic streams. The basic rationale and the computational procedure for a change interval have not changed significantly over the past half-century. Essentially deterministic, they address the presumed behavior of individual drivers by modeling it after a special sort of driver--the "ideal" or "reasonable" driver. When faced with a yellow light, this driver always stops if it is possible to do so. That possibility is entirely predetermined by the ideal driver's known reaction time and known acceptable deceleration rate. The only probabilistic element in the prevailing approach to determining a change interval is the choice of approach speed attributed to the ideal driver--the percentile value of the design speed.

Generally, the deterministic approach has served traffic engineers reasonably well. The formulas for figuring the change interval are straightforward, and adjustments and corrections for special cases can be easily applied. Recently, however, there have been growing pressures to maximize the efficiency and effectiveness of existing traffic control devices (1) as well as increased legal demands for professional accountability (2).

The need exists, therefore, for objective, measurable evaluation criteria by which one can assess whether a given change interval is indeed an optimal one. The number of accidents is doubtless the most defensible evaluation criterion. Given the practical limitations of accidents as evaluation measures, however, other measures are required.

The present paper proposes an alternative approach to determining and evaluating the change interval. The argument is advanced that the prevailing approach fails to consider the possibility of rear-end accidents. It does not offer rational, empirical measures for evaluating the joint risk of right-angle and rear-end collisions for various durations of change intervals and for different combinations of yellow and red clearance intervals. The proposed alternative, on the other hand, is based on an empirically derived stopping probability function of traffic passing through an intersection. The range of the indecision zone that can be inferred from the stopping probability function is related to the risk of rear-end accidents. Similarly, this function and the speed distribution are related to the risk of right-angle collisions. Finally, it is demonstrated how the concepts of the stopping probability function and the indecision zone might be used in practice to determine the change interval.

THE REASONABLE DRIVER AND DETERMINATION OF CHANGE INTERVALS

The Technical Council Committee of the Institute of Traffic Engineers (ITE) in 1985 published the ITE Proposed Recommended Practice: Determining Vehicle Change Intervals (3). Other procedures for planning change intervals may be found in the literature (2-7). The main difference among the various procedures is the general length of the change interval and the split between the yellow light and the red clearance interval. The common element in almost all the sources is the model of the reasonable driver. Two basic assumptions form this model:

1. A driver is capable of estimating stopping distances according to the laws of kinematics.
2. Drivers' decisions to stop or to cross accord

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with the physical possibility of stopping or crossing; that is, at the onset of the yellow light, a driver closer to the intersection than the stopping distance will proceed through the intersection and a driver further from the intersection than this distance will decide to stop.

In the ITE recommendations, the length of the yellow light is so calculated that the reasonable driver can pass the stop line before the onset of the red light. The red clearance interval is intended to enable a driver to leave the conflict zone of the intersection before the onset of the green light for the succeeding phase.

Despite the intensive use of the reasonable-driver model, there remains an obvious question that should be asked: To what degree is a driver approaching an intersection capable of a reasonable decision? That is to say, what is the probability that a driver situated at the stopping distance from the intersection (at the onset of the yellow light) will stop? In order to answer this question, the stopping probability curves of other researchers (8-11) were used, and drawn for different stopping distances according to the various approach speeds. The stopping distances were then calculated according to the ITE recommendations for the yellow light. The results are shown in Figure 1.

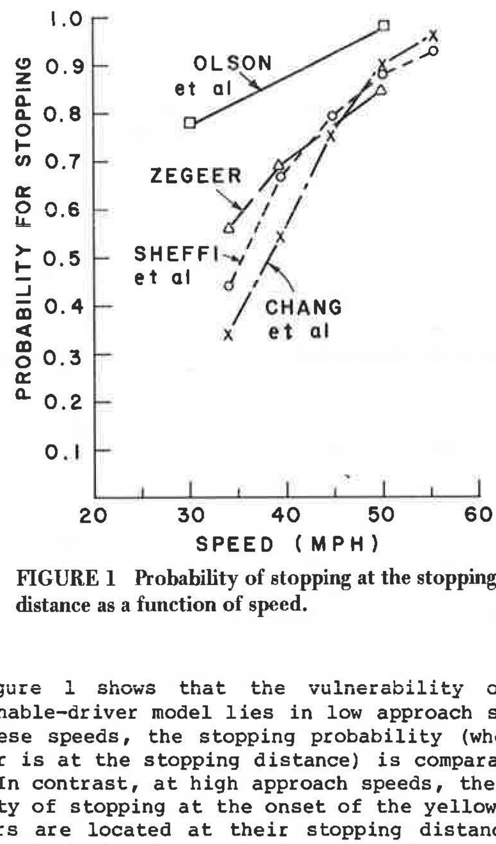

FIGURE 1 Probability of stopping at the stopping distance as a function of speed.

Figure 1 shows that the vulnerability of the reasonable-driver model lies in low approach speeds. At these speeds, the stopping probability (when the driver is at the stopping distance) is comparatively low. In contrast, at high approach speeds, the probability of stopping at the onset of the yellow (when drivers are located at their stopping distance) is relatively high. The conclusion drawn from empirical data is that the model of the reasonable driver is substantiated only at high approach speeds; at low approach speeds, this model does not hold for a high percentage of drivers. This behavioral phenomenon suggests that drivers' stopping decisions are more strongly influenced by distance from the stop line than by their approach speeds. Chang et al. found evidence that drivers' decisions reflect higher sensitivity to distance than to speed (10).

Because the reasonable-driver model does not apply to low approach speeds, a high probability of crossing on the red light results. The probability that at least one driver will cross at a red light during a certain cycle is shown in Figures 2 and 3. The presentation is for different traffic volumes and for different stopping probability curves. The calculations were made according to ITE recommendation (3) for the length of the yellow signal and on the assumption that all drivers were traveling at the same speed. For these calculations, the intersection approach (beyond the stopping distance) was divided into three zones. For each zone, the probability of stopping at the onset of the yellow light was taken from work of other researchers (8-11). This probability is actually a conditional probability of stopping, given the existence of a vehicle in the zone at the onset of the yellow. The unconditional probability of the existence of a vehicle in a zone at the onset of the yellow light was calculated according to a Poisson model for different speeds and traffic volumes.

The probability that at least one driver will cross the stop line at the red light during a certain cycle at a travel speed of 35 mph can be as high as 0.8 (Figure 2). It should be emphasized that at higher approach speeds (50 mph), this probability is significantly lower (Figure 3). These findings suggest that a high risk of right-angle accidents might exist at signalized junctions with a low approach speed (35 mph), a tendency mentioned elsewhere (10,12).

In reality, the probability of a red-light crossing is probably lower than that shown in Figure 2 because of the acceleration ability of drivers. According to Chang et al. (10), the average speed of vehicles moving from the onset of the yellow to the clearing of the intersection is 8 percent higher than their approach speeds before the onset of the yellow. The implications for safety are based on the fact that drivers are faced with an option zone where they can either stop or proceed. This option might lead to a stopping decision by some drivers and a crossing decision by others, thus enhancing a high risk of rear-end collisions.

A common flaw in the conventional recommendations for selecting change intervals is the lack of measures for evaluating the risk of rear-end collisions. It is well known that a high percentage of the accidents at signalized intersections are of this type [over 50 percent according to Hanna et al. (13)]. Another drawback is that the lengths of the yellow light and the red clearance interval are determined separately and then added to give the total length of the change interval. These two parameters, however, are interdependent; lengthening one of them can reduce a certain type of accident but increase another type. For example, a Michigan study (14) showed that lengthening the red clearance interval decreased the number of right-angle accidents but increased rear-end accidents. Clearly, some method for a joint determination of yellow and red clearance intervals is desirable.

PROPOSED APPROACH

The main characteristic of the proposed approach is its use of the stopping probability function, which describes the stopping pattern of all drivers at the intersection approach. In the use of this function, this approach differs from the conventional approach in that it is based on the behavior of all drivers rather than on an ideal (or reasonable) driver.

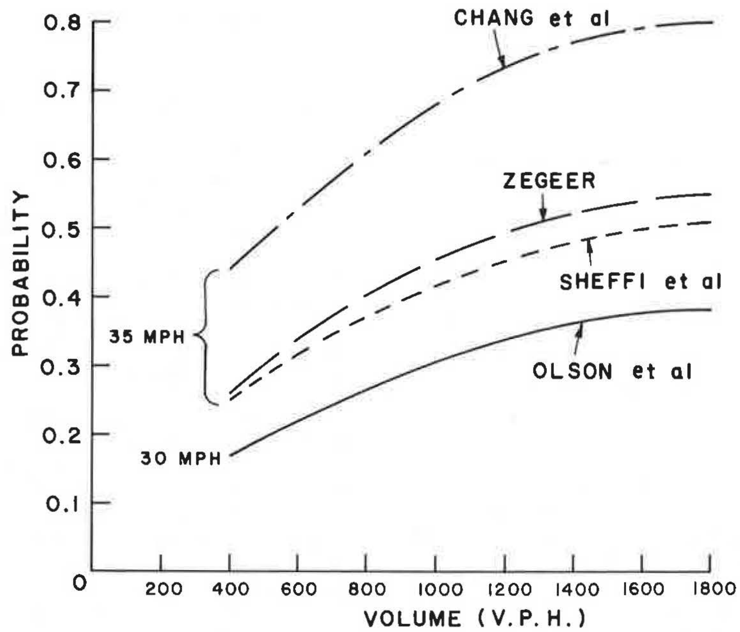

FIGURE 2 Probability that at least one vehicle will cross on red at a 35-mph approach speed.

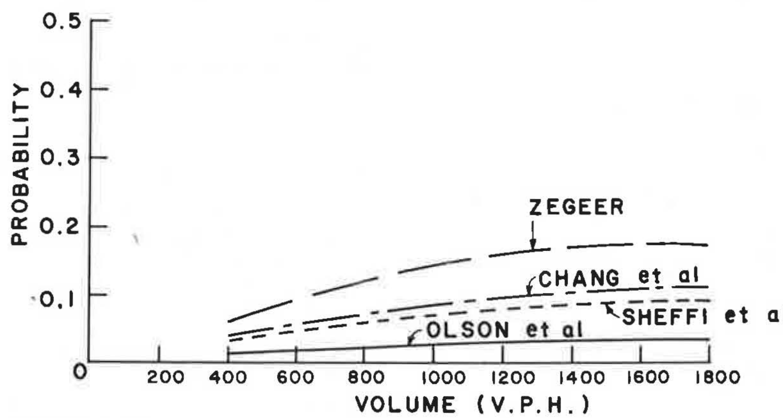

FIGURE 3 Probability that at least one vehicle will cross on red at a 50-mph approach speed.

Stopping Probability Function

At the onset of the yellow light, a driver approaching an intersection has to decide whether to cross or to stop. The aggregated stopping decisions by all drivers faced with a choice create the stopping function for a given approach to a signalized intersection. The ideal stopping pattern is created when the approach can clearly be divided into two zones: a crossing zone and a stopping zone.

A driver present in the crossing zone at the onset of a yellow light will keep moving, whereas one caught in the stopping zone will decide to stop. In this ideal situation, the probability of stopping is a step function (Figure 4). All vehicles found at a distance shorter than the critical value at the onset of the yellow will continue and cross the intersection; vehicles at distances greater than the critical value will come to a stop.

There would never be any rear-end collisions at such an ideal intersection because the major cause of such accidents--a driver stopping followed by a driver deciding to cross--is eliminated. Similarly, right-angle collisions would be minimized by the selection of a change interval enabling drivers caught at a shorter distance than the critical one to clear the intersection. Such an ideal cannot be achieved, however, because vehicles approach an intersection at different speeds; moreover, driver decisions, like most human characteristics, are not discrete and deterministic, but continuous and probabilistic.

The most problematic zone of the intersection approach is that where crossing and stopping decisions are accepted at a probability of 50 percent (15). As a result, drivers finding themselves in this zone at the onset of the yellow are subject to a high risk of rear-end collisions for the reason that a high probability exists for a stopping decision to be followed by a crossing decision. In other words, the probability of contradictory decisions in this zone is maximal, and therefore the probability of rear-end collisions is also high.

It is possible to define different zones of in-

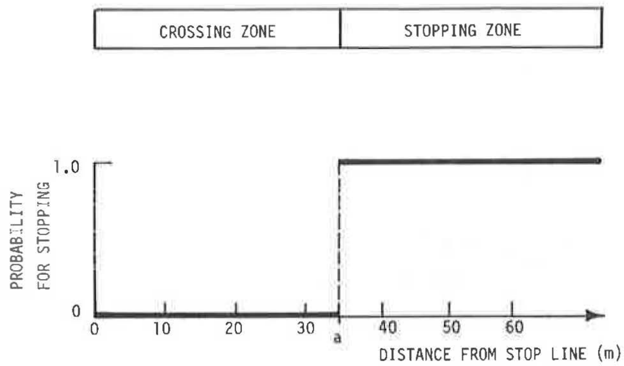

FIGURE 4 Stopping probability function at an idealized intersection.

decision, for example, a zone with a 40 to 60 percent stopping-decision probability. The choice of limits is to a great extent arbitrary. In fact, the indecision zone is traditionally defined as the area in which stopping decisions are accepted at a probability of between 10 and 90 percent.

Parsonson (16) gives an example of implementing the indecision-zone concept in signal design and suggests placing detector loops in this zone in order to prevent, in unsaturated cycles, a situation in which a driver is caught in the indecision zone at the onset of the yellow light.

Criteria for Evaluating Change Intervals

Risk of Rear-End Collisions

The shape of the stopping probability curve determines the range of the indecision zone; the more nearly similar this curve is to a step function, the smaller the range is; the flatter the curve (large variance), the larger is the range of the zone. The larger the indecision zone (for a certain definition, e.g., between a 0.1 and 0.9 stopping probability) and the higher the traffic volume, the greater the probability that vehicles will be in this zone at the onset of the yellow. As described earlier, these vehicles will then be subject to a high risk of rear-end collisions. Therefore, the range can be considered as a criterion for evaluating this risk. Accordingly, the smaller the range of the indecision zone, the more efficient the design of the change interval.

The flashing green phase may be used to illustrate the relationship between the range criterion and the risk potential for rear-end collisions. In Israel and in some European countries, it is customary for a flashing green light to appear between the green light and the yellow. In Israel, the duration of this flashing green is 3 sec; it is then followed by a yellow of 3 sec. Safety evaluations have shown that the flashing green significantly increases the number of rear-end collisions (17,18). Both simulation and field tests (18,19) have found that the range of the indecision zone in intersection approaches increases when a flashing green is installed. The range of the indecision zone is thus related to the high probability of rear-end collisions.

The range of the indecision zone apparently is related, too, to the length of the yellow light and to the approach speed. Lengthening the yellow might increase the option zone. Becker (19) found that in the option zone, 65 percent of the drivers decided to stop, whereas 35 percent made a crossing decision. Thus, the option zone is in effect an indecision zone.

Risk of Right-Angle Collisions

An empirical criterion for evaluating the probability of right-angle accidents can be defined as the percentage of crossing drivers who are protected by the change interval, in other words, the percentage of drivers who will cross the conflict area of the intersection before the green light appears for the succeeding phase (assuming that there is no acceleration and that the vehicle is moving at the design speed). In an ideal situation, in which the probability of stopping is a step function, protection would be provided for 100 percent of these drivers. In reality, it is impossible to assure this situation mainly for reasons related to capacity. Therefore, the substantive question that the designer faces is what percentage of protection should be provided.

In order to estimate the percentage of protected drivers, two elements must be known: the stopping probability function and the distribution function of the vehicle's speed.

The criterion of the percentage of protected drivers differs from the commonly used measure of effectiveness--the percentage of drivers passing through the red light. Because right-angle collisions are believed to be more directly related to the conflict area than to the stop line, the "protected" criterion focuses on the conflict area in the intersection. It appears that the stop line is more relevant to law enforcement efforts than is measuring the effectiveness of the change interval.

Determination of the Change Interval

Before the change interval is determined, the stopping probability function must be estimated. This should be done for different approach speeds, traffic volumes, and types of vehicles as well as for varying intersection lengths and grades. Once the estimation has been completed, the parameters for the change interval can be determined according to the particular characteristics of each intersection. The determination is based on a careful selection of the parameters according to the two criteria mentioned earlier. Following is a demonstration of the determination of the change interval for a hypothetical intersection.

Assuming that an earlier study found that the approach speed of a certain intersection can be divided into two levels--fast (Vf) and slow (Vs)--and that these speeds are the 85th and 15th speed percentiles, respectively, the stopping probability function may be estimated for each speed group for each of two design alternatives:

Alternative A: Y_A sec yellow, followed by a red clearance interval;

Alternative B: Y_B sec yellow, followed by a red clearance interval.

The two functions are shown in Figure 5. An evaluation of the two alternatives by the two criteria points to the superiority of Alternative A. With this alternative, the range of the indecision zone is smaller and a larger percentage of drivers is protected by a given clearance interval.

After the determination of the length of the yellow light, the red clearance interval (RCI) may be determined according to this formulation:

$$RCI = \max \{[(a + W + L)/Vs], [(b + W + L)/Vf]\} - YEL$$

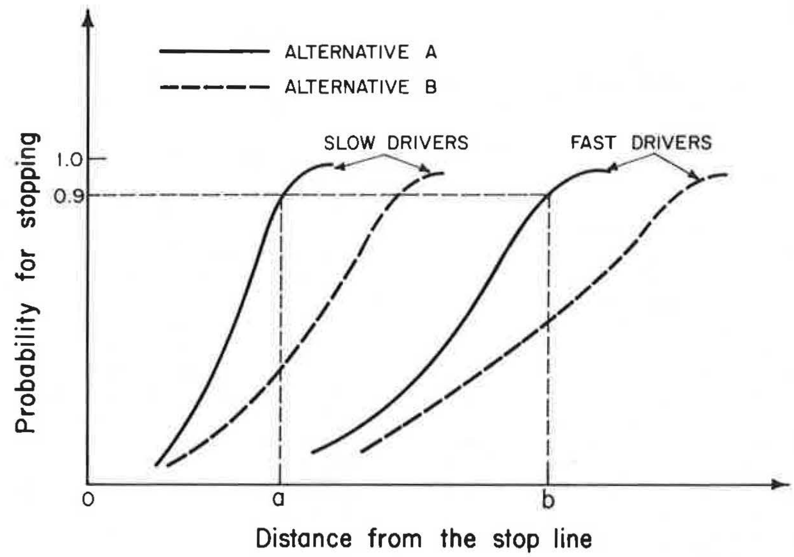

FIGURE 5 Hypothetical stopping functions for two design alternatives of the change interval.

where

a,b = distance from the intersection at which the probability for stopping is predetermined (e.g., 90 percent) for slow and fast drivers, respectively;
W = distance from the stop line to the far end of the conflict area;
L = length of the design vehicle;
Vs,Vf = speed of slow and fast drivers, respectively; and
YEL = length of the yellow light.

This procedure assumes that the number of rear-end accidents will be small because of the short range of the indecision zone. On the other hand, protection will be provided by the change interval for a known percentage of crossing drivers.

DISCUSSION OF RESULTS

The fundamental tool recommended for determining change intervals is the stopping probability function. The two criteria for evaluating the change intervals are determined by this function. The importance attributed to the stopping probability function requires more thorough research for a better understanding of the different factors that influence this function. The primary need is to understand the interrelated influences of approach speed, length of yellow signal, and length of the red clearance interval.

A strong interrelationship and trade-off exist between the design parameters of the change interval (the length of the yellow and the red clearance interval); therefore, a simultaneous determination of the two parameters is required, not a separate decision for each. The possibility exists that in the optimum situation, the yellow light would be short relative to ITE recommendations, but the red clearance interval would be long. For example, shortening the yellow light would decrease the range of the indecision zone (and consequently the probability of rear-end collisions). This change would require lengthening the red clearance interval to prevent right-angle accidents.

It should be noted that the use of the stopping probability function eliminates the need for estimating the reaction time and the deceleration rate of individual drivers. From a research point of view, emphasis can shift to studying traffic behavior at intersections as a function of geometry, yellow duration, speed, distance, and so forth.

One of the factors that might influence the probability of stopping is the driver's estimate of the length of the intersection. In a given situation, drivers might overestimate the length and, as a result, the probability of stopping might increase. This wrong impression might bring about a decrease in the change interval. On the other hand, if drivers underestimate the intersection length, the probability of crossing might increase, as might the change interval as well.

Although the main application of the stopping probability function and indecision zone concepts in this discussion focused on the change interval, they can be used in studying other problems, such as evaluating advance-warning signs, traffic-pedestrian interaction, or gap-acceptance behavior.

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Discussion

Howard Stein*

The critique of the ITE procedures for timing signal change intervals by the authors is based on the assumption that the ITE formula and procedures are based on the behavior of a reasonable driver. They argue for an approach to signal change interval timing that is based on driver stopping probabilities calculated for individual intersections. Potential trade-offs between rear-end and right-angle crashes that might result from changes in signal timing relative to the ITE formula are also discussed.

The ITE procedures are not based on some arbitrary reasonable driver but on extensive research and observation of thousands of vehicles and their drivers' responses to yellow signals (1-4). This research led to the adoption of values currently recommended in the ITE procedures. The most controversial parameter in the ITE procedures is the acceptable driver deceleration rate for stopping after the yellow signal. Research has documented that for most intersections, the majority of drivers who can decelerate at 10 ft/sec^2 or less will, in fact, do so. The ITE procedures allow for the calculation of a minimum time required for drivers who choose not to stop to be able to clear the intersection before cross-street traffic is allowed to proceed. Consequently, the ITE procedures have incorporated a conservative estimate of driver stopping probability. The authors' recommendation that stopping probability curves be developed for individual intersections would be a cumbersome task and is unnecessary for most intersections.

The authors are also concerned that at a given distance upstream from the intersection, some drivers will make the choice to go through the intersection and others will stop; they label this an "indecision zone." The authors recommend short change intervals, hypothesizing that drivers in this zone are subject to a higher risk of rear-end collisions. Their discussion is academic because driver reaction is largely independent of actual yellow time and intersection geometry. The ITE procedures provide a safer, conservative approach to timing yellow signals based on having longer yellow signals that provide sufficient time for the driver who will make the wrong stop-or-go decision.

Two recent studies have compared the adequacy of signal change intervals relative to the ITE procedures with rear-end and right-angle crash rates (5,6). Both these studies reported evidence that directly contradicts the authors' hypothesis and recommendations: Intersections with short change intervals relative to the ITE formula had significantly higher rear-end and right-angle crash rates compared with intersections with more adequate change intervals. Notably, the intersections with the highest crash rates tended to have slower traffic and wider cross streets than the intersections with lower crash rates. The interpretation of these results is that the drivers of vehicles at these poorly timed intersections did not have real choices in responding to the signal change interval. The change intervals were, perhaps, adequate to serve as warning time but lacked clearance time. Drivers did not significantly adjust their behavior for the inadequate timing; they were forced to brake abruptly to avoid entering the intersection or go through the intersection without protection from cross-street traffic.

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ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

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Authors' Closure

The critique by Stein of our paper addresses two important issues: the empirical-behavioral basis for ITE recommended procedures for the change interval and the duration of the change interval.

By pointing out the documented limitations of the reasonable-driver model, we do not imply that the model is arbitrary, only that it is limited and, perhaps, not necessary. There are indeed behavioral data about drivers' deceleration rates for stopping after the yellow signal. However, the data describe only drivers who decided to stop. Consequently, ITE procedure incorporates empirical deceleration values for drivers who might decide to stop, but it does not express the actual tendency to stop.

Olson and Rothery (1), whose work is quoted by Stein, specifically state: "Required decelerations between 8-12 ft/sec² form a transition region where some drivers stop and others elect to continue through without stopping." Data collected by Zador (2) confirm this differential tendency; at yellow change situations requiring a 10-ft/sec² deceleration for stopping, only 45 percent of the affected drivers stopped; when the required deceleration was 8 ft/sec², 70 percent of the affected drivers stopped.

Our probabilistic approach, based on stopping probability curves, does consider drivers' willingness to stop. The curves will express the behavior of all drivers in a variety of geometric combinations for various approach speeds and under the influence of other traffic, roadway, and signal factors.

We do not suggest that it is necessary to estimate the stopping probability curves at each junction. Rather, one selects the relevant curves from a data base (just as ITE procedure does not recommend estimating anew drivers' deceleration rate or their reaction time at each junction). At the same time, with our proposed procedure it is possible to fine-tune the change interval at existing signals. By measuring stopping probabilities and identifying the indecision zones, the traffic engineer can assess the influence of situational factors unique to a particular junction.

With respect to the second issue, Stein attributes to us a recommendation to use short change intervals. We disclaim such a view because we are quite aware of earlier confusions in the United States regarding yellow, clearance, and change intervals. What we have suggested is a study of the potential effectiveness of trading off the duration of yellow and the duration of the all-red interval while keeping the total duration of the change interval as long as necessary. This is in order to optimize the design of the change interval in terms of both side-front and rear-front collisions.

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Publication of this paper sponsored by Committee on Traffic Control Devices.