Determining Vehicle Change Intervals

A Proposed Recommended Practice

Institute of Transportation Engineers
525 School St. S.W.
Washington, D.C. 20024-2729

The ITE Proposed Recommended Practice "Determining Vehicle Change Intervals" has been developed by ITE Technical Council Committee 4A-16. A summary of the Committee's full report was published in the May 1985 issue of ITE Journal.

Comments are being sought on this report to assist the consideration for adoption as a Recommended Practice of the Institute. Comments should be submitted by January 1, 1986. Comments, questions, and any requests for a public hearing should be directed to:

Institute of Transportation Engineers
525 School Street, S.W.
Suite 410
Washington, D.C. 20024-2729
Phone: (202) 554-8050

Any comments and suggested revisions received will be considered by Technical Committee 4A-16 before forwarding of the report to the ITE Standards Approval Board for a final decision on adoption as a Recommended Practice of the Institute.

Jack A. Butler, Jr., (A) is chairman of ITE Committee 4A-16. At the time the Committee Report was prepared, he was manager of the Signal Division, Clarke County (Georgia) Dept. of Transportation. He is now software product analyst at Transyt Corp. of Tallahassee, Florida.

Other members of the Committee are Kenneth Agent (A), Dharam C. Bobra (A), Martin G. Buehler (M), Eugene A. Burbidge (A), Robert L. Carstens (F), Dick Davis (M), Gary A. Funk (A), Alberto Santiago (A), Robert M. Shanteau (A), and Hart L. Solomon (A).

Members of the Department & Standing Committee on Traffic Operations are: Richard T. Klatt (F) (Chairman), Earl E. Newman (F), Robert T. Alguire (M), Jeffrey M. Arey (M), Ronald E. Magahey (M), Harry B. Skinner (FL), James W. Sparks (M), and Greg T. Smith (M).

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Introduction

A vehicle change interval is that period of time in a traffic signal cycle between conflicting green intervals, and is characterized by a yellow warning indication often followed by a red clearance indication. The yellow indication tells an approaching driver that the right of way is about to be assigned to a conflicting traffic flow. In some locales, a red clearance indication is provided to allow vehicles in the intersection to clear before the green is displayed to conflicting traffic.

Literally thousands of pages have been written on the subject of vehicle change intervals by scores of authors. Accidents at a signal controlled intersection are often caused by improper driver actions during the change in right of way assignment. Many engineers believe that change interval timing is a major determinant of the accident potential of a signal controlled intersection. Given the importance of change intervals and the amount of study devoted to them, why has the profession yet to decide on the "correct" method for their determination?

Divergent and strongly held positions are common when engineers discuss vehicle change intervals. Some believe that a uniform change interval is best. Others believe that uniform change intervals are wrong and even dangerous. Some engineers go through elaborate timing procedures, while others simply divide the approach speed by ten and use the resulting value for the change interval. Some use an interval length that "feels right." Even among engineers who agree on the method many disagree on its application.

It is the objective of this Committee to evaluate the various proposed methods for determining and applying vehicle change intervals, and to arrive at a consensus conclusion as to which is a valid and usable approach. Conflicting reports were examined and accurate approaches identified. It was found that much data were incorrectly acquired and that erroneous conclusions were derived from valid data.

Often, though, valid data simply could not be found. It also became evident that data could not answer all questions. How safe is safe enough? What is a reasonable driver? Are data derived from field observations valid when considering a worst case design methodology?

This report is divided into two basic parts. The first presents recommendations; the second describes the deliberations leading up to the recommended procedures. In order to understand the procedures, one must carefully study the arguments presented and the logic used in evaluating them.

Many recommendations address legal issues, either in the form of proposed wording of laws or in order to conform to those laws. Therefore, one must endorse the legal basis of this report's recommendations for the proposed methodology to be acceptable. Recognize, however, that adoption of a uniform method cannot precede the adoption of uniform laws.

The legal basis for the recommendations of this report is the "permissive yellow rule," which allows vehicles to enter the intersection on yellow. The two "restrictive yellow rules," which either state that vehicles cannot enter on yellow or can enter on yellow only when it is unsafe to stop, are impossible for the driver to obey or for the police to enforce.

This report addresses only the vehicle change interval that follows the green indication. Many countries have adopted an inter-green interval that precedes the green indication. The purpose of the inter-green is to reduce start-up delay. The adoption of the proposals contained in this report is not inconsistent with the concept of the inter-green.

The basic application of this proposed recommended practice involves the use of a formula following a kinematic model of stopping behavior to determine the duration of the yellow indication. Next, the engineer evaluates the need for a red clearance interval and, if required, calculates it using a second formula.

PART I

Proposed Procedures for the Use and Timing of Vehicle Change Intervals

Goals and Objectives

Goal

Recommend legal definitions for the various aspects of the change interval and a defensible methodology for calculating and evaluating them.

Objectives

1. The implementing methodology must appear reasonable to the general public and be readily defensible in a court of law.
2. The methodology should allow easy identification of violators by law enforcement agents.
3. The policies must consider that the provision of reasonable safety is superior to the desire for operational efficiency when these signal timing objectives conflict.
4. Extensive field and office work, major equipment revision, and other costly procedures should be avoided.

Definitions

The definitions presented below are those found in the *Uniform Vehicle Code*[1] and the Federal Highway Administration's *Manual on Uniform Traffic Control Devices (MUTCD)*[2], except as noted. The proposed methodology is designed to implement the legal framework provided by the definitions. Agencies operating under different laws may need to adapt the methodology accordingly; however, following the prescribed procedures will meet or exceed the requirements of most current laws.

1. **Green Indication:** Vehicular traffic facing a circular green indication may proceed straight through the intersection, or turn right or left as allowed by opposing traffic, except as such movement as modified by lane use signs, turn prohibition signs, lane markings, or roadway design. Vehicular traffic facing a green arrow indication, shown alone or in combination with another indication, may cautiously enter the intersection only to make the movement indicated by such arrow, or such other movement as is permitted by other indications shown at the same time. But vehicular traffic, including vehicles turning right or left, shall yield the right of way to other vehicles and pedestrians lawfully within the intersection or an adjacent crosswalk, at the time such signal indication is exhibited.

2. **Yellow Indication:** Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter. A circular yellow or yellow arrow indication, as appropriate, shall be displayed immediately after every circular green or green arrow interval. Vehicles may legally enter the intersection while the yellow indication is displayed.

(The inclusion in the yellow definition of the requirement for a displayed yellow after every green goes beyond the wording of the *MUTCD*, which requires a "clearance interval" after every green. However, the *MUTCD* does not require that the interval be displayed "following the termination of a green arrow indication which has been displayed simultaneously with a continuing circular green indication in the same face." [Section 4B-6, Para. 5(d)] In order to present the motorist with a consistent stop/go decision environment the exception described in the *MUTCD* would have to be omitted.)

3. **Red Indication:** Vehicular traffic facing a steady circular red or red arrow indication alone shall stop at a clearly marked stopline, but if none, before entering the crosswalk on the near side of the intersection, or if none, then before entering the intersection, and shall remain standing until an indication to proceed is shown. Vehicles which legally entered the intersection while a green or yellow indication was displayed may continue to cross the intersection.

(The red indication definition does not exclude Right Turn on Red, as allowed in many areas, or such other movements as described by signs permitting certain movements during the display of the red indication.)

Yellow Warning Interval Timing and Application Procedures

Determining the Initial Yellow Warning Interval

The formula for determining the length of the yellow interval is

$$y = t + \frac{v}{2a + 2Gg}$$

where,

- y = length of the yellow interval, to the nearest 0.1 second;
- t = driver perception/reaction time, recommended as 1.0 second;
- v = velocity of approaching vehicle, in ft/sec (or m/sec);
- a = deceleration rate, recommended as 10 ft/sec^2 (3.05 m/sec^2);
- G = acceleration due to gravity, 32 ft/sec^2 (9.8 m/sec^2);
- g = grade of approach, in percent divided by 100 (downhill is negative grade).

The formula shown above is based on the standard uniform deceleration kinematic model that has been recommended in the ITE *Transportation and Traffic Engineering Handbook*[3], modified to include an adjustment due to the effects of grade on deceleration as proposed by Parsonson and Santiago.[4]

While the determination of the slope of roadway approaches is rather straightforward, the remaining variable, v (vehicle speed), can be more difficult to determine. The speed is generally taken to be that represented by a locally chosen percentile of approach speeds, usually the 85th percentile.

Some agencies may believe the collection of speed data to be a violation of Objective 4. It may be possible to use the posted speed limit as the approach speed. Such a policy may not be unreasonable given that drivers approaching at higher speeds are violating the law. Care should be taken to assure that the speed limit is reasonable.

Determining the approach speed to use for timing the yellow interval for protected turn phases is more complicated than for through phases due to the changing approach speed of vehicles preparing to make a turn. Turning vehicles may be either approaching at through vehicle speed and slowing down to a safe turning speed, or accelerating from a stop condition in a queue.

The formula shown above is possibly inappropriate for calculating the yellow time for a protected turn phase; however, the application of a more complete model is very cumbersome, and its use may violate Objective 4. Appropriate selection of approach speed can allow one to produce a good approximation of the timing that would have been produced by employing the more rigorous model.

Consider two possible cases. A vehicle is approaching an intersection at a through vehicle speed, which we will assume is higher than what could be safely used to execute the turn. A green left turn arrow is being displayed. The driver begins braking to slow the vehicle to the turning speed. The signal display changes to a yellow arrow. The driver must choose whether to stop by increasing his rate of deceleration, or continue on and execute the turn, perhaps at a higher speed than initially planned.

The second case is entirely different. The driver in a vehicle stopped in a queue accelerates from a stop condition, perhaps to a speed higher than that at which the turn will be accomplished if there is some distance to the point at which the turning maneuver begins. Should the signal display change to a yellow arrow now, stopping would require going from an accelerating mode to a stopping one.

In the first case, perception/reaction time is considerably reduced as the driver's foot is already on the brake pedal. In the second case, perception/reaction time is probably increased over that for through vehicles, and the propensity to stop may be diminished.

The through vehicle procedure may produce an adequate initial yellow interval length if the normal perception/reaction time is used, and the vehicle speed used is the average of the through vehicle speed and the turn execution speed. Vehicles decelerating from a through vehicle speed may be traveling faster, but the excessive perception/reaction time may provide the necessary adjustment. Similarly, the higher speed used may offset the perception/reaction time of accelerating vehicles.

Note, however, that the above procedure applies primarily to leading turn phases. The yellow interval length for lagging turn phases, when overlapped with a through phase on the same approach, should be calculated for both movements. The longer of the two should be used for the combined yellow interval.

Measure of Effectiveness

The primary measure of effectiveness for the yellow interval is the percent of vehicles entering the intersection after the termination of the yellow indication; that is, during the red following the yellow.

The logic behind the methodology for determining the length of the yellow interval is that the duration should provide adequate time for a vehicle to traverse the stopping distance required by a reasonable driver. A driver closer to the intersection will proceed through the intersection when presented with a yellow indication. A reasonable driver further away from the intersection at the onset of the yellow indication will decide to stop, and has sufficient distance to do so safely. The values used for the several variables are selected to determine the time to travel the stopping distance.

When the percent of vehicles that are last through the intersection which enter on red exceeds that which is locally acceptable (many agencies use a value of one to three percent), the yellow interval should be lengthened until the percentage conforms to local standards.

Factors that May Influence the Length of the Yellow Interval

Sometimes physical conditions exist which may also affect the likelihood of last through vehicles to enter on red; that is, cause the stopping probability curve to deviate from the norm. Some of these conditions are:

1. Signal Head Visibility: The displays may be too small, washed out by competing background light sources (such as the sun, streetlights, especially low pressure sodium fixtures, billboards, and commercial signing), blocked by overhanging vegetation, poorly located with respect to the driver's range of vision, or obscured by geometric alignments or other vehicles. Correction of the visibility deficiencies should be completed and evaluated before yellow interval timing is changed.

2. Approach Grade: Excessive downhill grades may produce very long stopping distances. Extreme grades, both uphill and downhill in excess of five percent, may seriously diminish the driver's desire to stop. At such locations, advisory speed plates on "SIGNAL AHEAD" sign assemblies may have some effect, but additional active measures, such as "PREPARE TO STOP WHEN FLASHING" sign and flashing beacon assemblies, may be required. The "PREPARE TO STOP" flashing beacon(s) should be positioned at least as far from the intersection as the upstream end of the stopping distance. The beacon would begin flashing prior to the onset of yellow so that a driver approaching the signal will see the flashing beacon before the yellow interval begins.

3. Vehicle Mix: While not definitely proven, it seems likely that truck drivers utilize lower rates of deceleration than automobile drivers, and that truck drivers are less likely to stop for a traffic signal. It has been shown that because they tend to have longer headways than other vehicles, trucks are proportionately more likely to be the last vehicle through or the first to stop.[5] It has also been shown that truck braking performance does not compare favorably with that of automobiles during abrupt stopping maneuvers.[6] Longer yellow interval times may be required on approaches which have a high percentage of truck traffic. National guidelines for quantifying what consitutes a "high percentage" have not been established.

4. Railroad Crossings: Uneven railroad crossings have the effect of decreasing speeds as drivers decelerate to avoid discomfort when crossing. Irregular vertical alignment has a similar effect, the result of which is that drivers may take longer to reach the intersection than they may have anticipated. This error can lead to drivers deciding they can reach the intersection before the onset of the red indication when, in fact, they cannot. As a result, vehicles enter on red.

5. Other Factors: A study conducted by Yauch[7] found that as average vehicle headways on an approach decrease, drivers' tendency to enter the intersection during the yellow and red clearance intervals increases for a given speed. It was also found that drivers approaching from the far side of the through roadway in a "T" intersection entered longer after the onset of yellow than at other locations. There is also some indication that cycle length, as it defines the potential delay to a stopping vehicle, affects the tendency of drivers to enter during the change interval.

Increasing the length of the change interval will not always correct the problem, as drivers may be making a conscious decision to enter when they could have stopped. Hulscher[8] has proposed enforcement procedures to address such behavior. He describes a method of random photographic surveillance which is designed to increase the perceived risk to a driver entering on red. Selective enforcement efforts of other types are also useful.

Red Clearance Interval Timing and Application Procedures

Determining the Need for a Red Clearance Interval

To a substantial extent, the need for red clearance intervals is predicated on the local jurisdiction's policy regarding the necessity of an absolute provision of time for vehicles which entered on yellow to clear the area of conflict before the right of way is reassigned.

As vehicles may legally enter the intersection during the display of the yellow indication, the yellow interval is not a clearance interval, as Bissell and Warren[9] and others have shown.

If it is the policy of the local agency to provide clearance time, the traditional practice has been to either add the time to the yellow interval, or to use what has previously been called the "all red interval," herein refered to as the red clearance interval. It is the policy of ITE that if clearance time is to be provided, it should be in the form of a red clearance interval. (See discussion in a later section.)

Adopting a policy that clearance time should always be provided removes the need to identify those situations which warrant its provision. However, where clearance time is not routinely given, various methods have been used to indicate when red clearance time is needed. Most of these have been arbitrary, and unsupported by valid data.

Red clearance time is provided to prevent accidents which may arise from the presence of conflicting vehicles in the intersection. Agent[10] proposed a formula which can identify those locations which are experiencing a higher number of "correctable" accidents than the average for the locale:

$$c = a + (K\sqrt{a}) + 0.5$$

where,

c = critical number of accidents;

a = average number of accidents at all locations;

K = selected level of statistical significance (for example, 95% certainty = 1.65).

A location which experiences a number of correctable accidents, such as right angle types, equal to or greater than c has an accident rate which exceeds the norm at the level of statistical significance provided by K. Such a location would be a good candidate for the installation of red clearance intervals on the appropriate phase(s). However, it can be inferred from this procedure that most intersections would be relatively free of such accidents. Bissell and Warren[9] suggested a value of one right angle accident per million entering vehicles as a guide.

Determining the Initial Red Clearance Interval

Depending on the policy of the local agency, the initial red clearance interval timing is determined by one of the following:

$$r = (1)\ \frac{w + L}{v} \quad \text{or}$$

$$(2)\ \frac{P}{v} \quad \text{or}$$

$$(3)\ \frac{P + L}{v}$$

where,

r = length of the red clearance interval, to the nearest 0.1 sec.;

w = width of the intersection, in feet (or meters), measured from the near side stop line to the far edge of the conflicting traffic lane along the actual vehicle path;

P = width of intersection, in feet (or meters), measured from the near side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual vehicle path;

L = length of vehicle, recommended as 20 ft (or 6.1 m.);

v = speed of the vehicle through the intersection, in feet per second (or meters per second).

Although receiving limited evaluation until recently, intersection width can take a wide range of values depending on its definition and method of measurement. In this report, intersection width is defined by the actual path followed by a vehicle executing the related movement. In the case of a turning vehicle, intersection width is measured along the curved path traveled by the vehicle from the near side stop line to the far edge of the area of conflict.

The difference between the three formulas listed above relates to defining the area of conflict, the intersection width, and the location of the vehicle at the end of the red clearance interval. Formula (1) is intended to place the vehicle entirely out of the area of conflict with vehicular traffic which is about to receive a green indication. Formula (2) is designed to place the vehicle to a point directly in front of pedestrians waiting to cross the far side crosswalk. Formula (3) should provide time for the clearing vehicle to be out of the area of conflict with both vehicular and pedestrian traffic.

Consideration of pedestrians is a relatively new provision. It is included as a result of a major study of pedestrian behavior and signal control strategies.[11] The study found that the first pedestrian to enter the crosswalk at the onset of WALK/green has less than a one second start-up delay. Given that the pedestrian queue can be located as close as a few inches from moving traffic lanes, protection of pedestrians from clearing vehicles may be as critical as that of entering vehicles.

The recommended application of the formulas is to use Formula (1) where there is no pedestrian traffic, the longer of Formulas (1) or (2) where there is the probability of pedestrian crossings, and Formula (3) where there is significant pedestrian traffic or the crosswalk is protected by pedestrian signals. Note that in application, most crosswalks are located such that the far side is closer to the intersection than the 20-foot vehicle length used.

It may be possible with some controllers to delay the onset of the WALK indication relative to the start of the related green. With this operation, the WALK is delayed by an amount of time equal to the excess of the results of Formula (3) over (2). The advantage of this is that vehicular traffic is less delayed, although the savings is generally very small.

In determining what traffic flow(s), pedestrian and vehicular, may conflict with clearing vehicles, the timing engineer should consider all possible phase sequences.

As with calculating yellow intervals, the selection of an appropriate value for vehicle speed is very important. The effect of vehicle speed on the length of the red clearance interval is the opposite of that on the length of the yellow interval; that is, as crossing speed increases, the length of the clearance interval decreases.

In order to provide a reasonable red clearance time, the use of the same value for vehicle speed is not always valid. This is especially true for protected turn phases (see earlier discussion on pages 5-6). The preferable method for identifying vehicle speed involves speed sampling, but estimation methods are also available.

Parsonson and Santiago[4] proposed that the entire change interval (yellow plus clearance) be calculated at both the 15th and 85th percentile approach speeds, with the change interval's length equal to the greater of the two. As modified by Butler[12], in the rare cases where the 15th percentile speed produces a longer interval, the red clearance time calculated at the 85th percentile speed is increased by the difference. The original yellow timing calculated at the 85th percentile speed is retained. The assumption is that part of the yellow is used to provide the additional clearance needed by slower vehicles.

If one has a speed sample available for each approach at the intersection, the determination of 15th and 85th percentile speeds is not difficult, but as discussed earlier, the conducting of spot speed studies may not be feasible. It may be possible to estimate the relevant percentiles by assuming that the 15th percentile speed is approximately two standard deviations below the 85th percentile. As the standard deviation found in most speed samples is in the range of 3-6 (5-18 kph), it may be reasonable to assume that the 15th percentile speed is 10 mph (16 kph) less than the 85th percentile speed.

Turn maneuver speeds used for red clearance timing are those that are used in executing the turn, so the speed used should normally be less than that used in calculating the yellow interval time. Accordingly, the simplest way to identify the average turning speed is to make sample runs.

Because of the lower speed, generally 10-25 mph (16-40 kph) depending on the severity of the maneuver, the difference between the 15th and 85th percentile speeds may not be as great as that for through vehicles.

Measures of Effectiveness

As with the yellow interval, the test of a red clearance interval is whether the desired result is produced. Do vehicles really clear the area of conflict, as defined by the selected equation's intent and the desired compliance percentage? Of course, if the yellow interval is too short, vehicles will still be in the area of conflict even if the red clearance interval is correct. It is therefore appropriate to first evaluate the yellow interval.

One manifestation of an inadequate red clearance interval is a high incidence of right angle and, where applicable, left turn accidents. The statistical test described earlier for identifying candidate locations for the addition of clearance time is equally valid in evaluating existing red clearance timing.

Many of the factors that affect the yellow interval, particularly vehicle mix, may also impact the red clearance interval. The presence of a large percentage of trucks may increase the speed range, resulting in a higher than normal standard deviation for the data.

PART II
Literature Review and Committee Deliberations

Choice of Driver Behavior Model

Three models of stopping behavior, with a variety of modifications, have been proposed over the years: (1) constant yellow, (2) kinematic, and (3) stopping probability. While each has its supporters and detractors, the constant yellow model has lost most of its following in the United States. The kinematic model is the traditional one found in the ITE *Handbook* and is the one proposed for use in Part I. Stopping probability, as determined by field observations, is the most theoretically correct model, but reliable field data to implement it do not yet exist.

The basic premise of the constant yellow model is that a uniform yellow interval is needed to allow drivers to be able to react in a reliable manner. The premise assumes that drivers learn the length of the yellow and can decide whether sufficient time to reach the intersection is available whenever faced with a yellow indication.

Research has consistently shown that drivers do not, in fact, adapt to the length of the yellow.[13,14] A uniform yellow interval does not provide drivers with a uniform stopping decision. The selected standard time would be arbitrary, and cannot include sufficient time to traverse the stopping distance in all instances, unless set to a very high value, and would result in some drivers entering on red as the required stopping effort is unacceptable. A high value for the length of the yellow causes unnecessary delay at locations with shorter stopping distances.

The foundation of the kinematic and stopping probability models is the determination of the stopping distance and the time to traverse it. The basic assumption is that drivers who can stop, will. A driver further than the stopping distance from the intersection will stop, one closer will proceed through. It is thus apparent that the yellow is timed for the driver who decides not to stop and should not provide time to stop as some have incorrectly proposed. Once a driver decides to stop, the displayed signal indication becomes meaningless.

The formula used to implement the kinematic model is simply the traditional stopping distance formula divided by vehicle speed. The kinematic model's application is a compromise attempt to estimate stopping probability and is based on many assumptions, such as uniform deceleration, perception/reaction time, and the speed of approaching vehicles.

The recommended values for the first two assumptions are discussed in the next section; vehicle speed was discussed in Part I. Because of the probable dependency of the many variables, it is not possible to identify the exact percentile for the design speed, although it is generally considered to be the 85th percentile or more given the conservative values used.

The stopping probability model proposed by Olson[13] and Shanteau[15] assumes that driver decisions can be reliably predicted by using samples of observed driver behavior taken in the field. A local engineer would still need to determine vehicle speed, grade, etc. for each approach, which would be used to find the required yellow interval length on a stopping probability graph applicable to those field conditions. Using this method, the engineer can select the desired design driver percentile. The problems associated with determining appropriate values for perception/reaction time and deceleration are removed.

The difficulty with applying the model at this time is the absence of valid data. Certainly, much data have been collected, but in an inconsistent manner, and not under a sufficient range of conditions.

To properly collect the needed data, the speed and distance of the last vehicle through and the first to stop must be recorded for a large number of vehicles. Such data would give the probability of a vehicle traveling at a particular speed to stop at any given distance and grade. The length of the yellow interval would be found by identifying the speed and stopping probability desired and dividing the related stopping distance by the approach speed.

The stopping probability model's application still requires the local engineer to make decisions regarding the range of driver behaviors to be considered. The advantage of the procedure is that local decisions on the percentile driver (the locally defined "reasonable driver") are more readily implemented.

Neither the constant yellow nor the stopping probability model provide guidance for determining the length of the red clearance interval. For this reason, and until sufficiently valid data exists for the implementation of the stopping probability model, the Committee sought to identify the best way to apply the kinematic model.

Sources of Recommended Values for Certain Variables

Two variables, perception/reaction time and deceleration rate, have recommended values to use in applying the yellow interval formula. The application of the red clearance formula involves the use of a recommended value for vehicle length. In the following sections, the data available and their evaluation which resulted in the recommendations are presented.

Perception/Reaction Time

The variable, t (perception/reaction time), attempts to represent the time used by drivers in recognizing the onset of the yellow interval, in evaluating the stop/go problem, and, if the decision is to stop, in applying the brakes. A variety of test procedures have been used to determine the proper value to use. These tests have generally been one of two types: (1) Use test subjects in a simulated stop/go situation or (2) observe unsuspecting drivers in the field using time-lapse photography.

Results from two available simulated decision studies reported average "alert driver" response times of 0.64 second (95th percentile of 1.0 second)[16] and 0.8 second.[17] Three field observation studies reported mean perception/brake reaction times of 1.14 seconds[18], 1.16 seconds[19], and 1.3 seconds.[20] Eighty-fifth percentile values have ranged as high as 2.0 seconds.

The difficulty in using the field observation data to establish the time for perception/reaction is the manner in which it was collected. Time-lapse photographs of an intersection approach are examined to identify the time passage from the onset of yellow to the moment the stopping vehicle's brake lights came on. This procedure suffers from two shortcomings: (1) the time for drivers not stopping, the ones for whom the yellow is timed, are excluded because their vehicles' brakes are never applied and (2) there is no indication of the leisureliness of the drivers' reactions.

On the last problem, stopping vehicles will generally not be presented with the design stopping decision, which involves a worst case scenario. They are by definition further from the intersection than the stopping distance at the onset of yellow and can safely and comfortably stop using perception/reaction times and deceleration rates less than those assumed by the formula.

Since drivers approaching a signal controlled intersection may be considered to be alert for the onset of yellow, it is possible that they care constantly making the stop/go decision in anticipation of a yellow indication. Evaluation by Butler[21] of stopping behavior reported by Wortman and Matthias[20] indicates that the combination of values recommended in Part I produces a yellow interval that conforms to actual driver behavior. For these reasons, the traditional value of one second for the perception/reaction time was retained.

Deceleration Rate

In recent years, the generally accepted value for the rate of deceleration has fallen from 15 ft/sec^2 (4.58 m/sec^2) to 10 ft/sec^2 (3.05 m/sec^2). The Committee was unable to ascertain the source of the original 15 ft/sec^2 value found in the earlier (pre 1983) versions of the ITE *Handbook*; however, Solomon[22] may have found the source in an improperly converted table of English/Metric traffic engineering standards produced more than 20 years ago. Regardless, no research could be found supporting the use of 15 ft/sec^2. As far back as 1960, Gazis, et al.[18] found that deceleration rates of approximately 10 ft/sec^2 were being used by first to stop drivers.

Olson and Rothery reported in 1972 that their research showed that drivers were "virtually certain to stop if their required deceration rate was less than 8 ft/sec^2 (2.44 m/sec^2) and virtually certain to continue if the deceration rate required was in excess of 12 ft/sec^2 (3.66 m/sec^2)."[23]

More recently, Wortman and Matthias[20] found similar deceleration rates while observing six intersections. They reported mean rates ranging from 7.0 to 12.9 ft/sec^2 (2.14 to 3.93 m/sec^2). At three intersections, 8 to 30 percent of the last to enter vehicles crossed the stop line on red. These locations had yellow time deficiencies, relative to the proposed methodology presented in Part I, directly proportional to the percentage of red indication violation by last to enter vehicles.[21]

Projecting the required deceleration rate that drivers approaching at the reported 85th percentile speeds would have to use to keep from entering on yellow, assuming a 1.0 second perception/reaction time, it was found that they ranged from 12.3 to 16.3 ft/sec^2 (3.75 to 4.97 m/sec^2).[21] Drivers apparently rejected the higher deceleration rates. This finding lends further support to the contention that drivers do not adapt their behavior, at least beyond a certain point, to the length of the yellow interval time.

Becaue field observation data for deceleration suffer from the same shortcoming with regard to the leisureliness of driver behavior as does perception/reaction time, a value of 10 ft/sec^2 (3.05 m/sec^2) appears to be reasonably conservative.

Vehicle Length

The value of 20 feet (6.1 meters) for vehicle length has been used for many years, but his length is both longer than the average car and shorter than virtually all trucks.

Given that it may be safely assumed that drivers wish to avoid an accident, it seems reasonable to anticipate that drivers will not enter the intersection until it appears to be clear. A vehicle longer than 20 feet, such as a truck, has been visible for at least a second or more while passing in the field of view of the first in queue (platoon) driver under even the worst visibility conditions.

A first in queue driver will delay entering the intersection at the onset of green until the truck clears. In fact, the legal definition of the green indication requires him/her to do so. A first in platoon driver approaching the intersection upon the onset of yellow on the preceding phase can adjust his/her speed to allow the crossing vehicle to clear.

It might be argued that the preceding discussion removes the need for the inclusion of vehicle length entirely. However, it is possible that approaching vehicles may be so close to the intersection, or the truck moving so slowly, as to be unable to adjust their speed adequately in the limited time available.

It is also possible that approaching or stopped drivers are watching the signal face in anticipation of the green indication and do not see clearing vehicles, regardless of their legal obligation to watch for such vehicles. While it would be hard to ignore a crossing truck, the smaller cars prevalent today may not be recognized readily in a driver's peripheral field of vision.

In keeping with the conservative considerations presented previously, the vehicle length variable is retained, and is recommended to be 20 feet (6.1 meters).

Evaluation of the Use of Red Clearance Intervals

Few topics can so easily generate strong feelings among traffic engineers as can the use of red clearance intervals. This was equally true among the members of the Committee. When it came to a final vote, five members strongly supported a recommendation that red clearance intervals be used after every yellow and four members felt that such mandatory use of red clearance intervals was possibly justified.

Two members and some commenters were adamant in their opposition to the recommendation, believing instead that red clearance intervals should be used only in certain instances. They believe that red clearance intervals excessively reduce intersection capacity relative to their safety benefits.

One commenter, and others elsewhere, have predicted that the use of red clearance intervals would lead to drivers using more of the yellow time as green, and eventually entering on red. Such behavior could lean to an increase in disrespect for traffic control devices. One reviewer stated that the use of red clearance intervals would lead to violation of the red similar to the current trends towards violating the yellow indication. If the yellow interval definition proposed in this Report is endorsed, then there is no way to violate the yellow indication; no external driver response is required.

Potential disrespect for the red clearance interval is a serious concern. However, no research has been found to support the contention that the presence of a red clearance interval increases the probability for the last vehicle to enter to do so on red. A major study of 47 intersections conducted by the TJKM consulting firm for the U.S. Federal Highway Administration (FHWA) reported that "the violation data showed that drivers have no significantly different tendencies to enter a signal (controlled intersection) on a red indication whether or not an all-red interval is present."[24]

The Wortman and Matthias[20] study's results were the same, as were those of a study conducted by the Chairman at nine intersections which had had red clearance intervals added to all phases at least two years prior to the evaluation.[25] It therefore seems likely that as drivers do not adjust their behavior to the length of the yellow interval, neither do they adjust significantly to the presence of red clearance intervals.

This finding leaves the issue of safety vs. efficiency. When these considerations conflict, Objective 3 presented earlier states that "the provision of reasonable safety is superior." Thus, to a substantial degree, the choice is determined by the policy of the local jurisdiction as to what is reasonable.

The TJKM study reported that the addition of red clearance intervals had no statistically significant effect on total intersection delay.[24] It seems logical that if red clearances affect delay, it does so adversely; however, the affect seems to be small.

One Committee member felt the sacrifice in capacity to be too severe at congested intersections operating close to capacity. However, the finding by Yauch[7] that vehicle headway had the highest correlation with red indication violation by last to enter drivers would seem to indicate that such intersections would benefit most from the accident reduction potential of red clearance intervals described below.

The effect of red clearances on safety does seem to be quite clear. The TJKM study found a reduction in the accident rate for the study group to be 0.33 per million entering vehicles (decrease from 1.67 to 1.34).[24] Accident severity was also reduced. The accident type most affected was the right angle collision.

The City of Los Angeles conducted a study in 1973 of 36 high accident locations which found that the addition of red clearance intervals reduced total accidents 19 percent, with the most dramatic improvement being in right angle collisions, which fell 41 percent.[26] A second study in 1977 of 148 intersections found a right angle accident reduction after the addition of red clearances of 40 percent.[27] The Regional Municipality of Hamilton-Wentworth, Canada, experienced a 21 percent improvement in right angle accidents in the first year after including red clearance intervals at all intersections.[28]

To be sure, not all researchers have reported such dramatic improvements. The City of Portland, Oregon, removed red clearance timing from 20 intersections. In the central business district, accidents did not increase, but at isolated intersections with higher approach speeds, the accident rate increased.[29] Hulscher[8] reported that adding red clearance intervals to 58 intersection controllers did not affect the accident rates.

Bissell and Warren[9] rely on the legal requirement for vehicles just receiving the green to yield to clearing vehicles in order to justify the omission of red clearances except as required to address an existing accident problem. They define "problem" as "an accident rate higher than 1.0 right angle accidents per million entering vehicles." This line of reasoning ignores the fact that the presence of a red clearance interval may have prevented the accidents.

Although interpretations conflict, some authors have reported successful lawsuits against local traffic engineers in which incorrectly timed change intervals have been at fault.[4,30] Whether or not these reports are correct, it seems apparent that serious legal liability may exist.

A peripheral argument against the uniform use of red clearance intervals is the cost of modifying signal timing, particularly with regard to rebuilding electromechanical controller camstacks. A program of general timing evaluation, based on considerations such as accident experience and traffic volume, could be carried out over a period of several years so that the costs in any one year were not great.

Given the possibility of exposure to legal liability, the probable beneficial effects, and even though intersection capacity may be slightly diminished, it is recommended that local jurisdictions give serious consideration to adopting a policy calling for a red clearance interval after every yellow interval. While the clearance time could be added to the yellow interval with possibly similar effects, it seems more prudent to apply the time to a red interval in order to address the fact that vehicles may legally enter the intersection on yellow.

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Note: Summaries of references 17, 19, 26, 27, and 29 were found in Chapter 5 of *Synthesis of Safety Research Related to Traffic Control and Roadway Elements: Vol. 1*, produced for the Federal Highway Administration in Dec. 1982 by George F. Hagenauer, Jonathan Upchurch, Davey Warren, and Merton J. Rosenaum through Texas A&M University.