percent. In most cases, the pedestrian was hit while crossing on green in the crosswalk immediately in front of the turning vehicle. However, in a few instances a pedestrian was hit while crossing on a red signal (which is illegal in most states) in the crosswalk on the lane the vehicle is turning into.

In addition to these four major types of RTOR accidents, there were two others that were very infrequent.

1. Two RTOR vehicles sideswipe. Sometimes two vehicles collided while making an RTOR simultaneously when there were double right-turn lanes, or when one of the vehicles used the shoulder.

2. The RTOR vehicle induces an accident. In two cases the RTOR vehicle, although not involved in the accident, created a situation that resulted in an accident. Once the cross-street vehicle collided with another cross-street vehicle to avoid hitting the RTOR vehicle. In another case (which happened in Ohio and was brought to our attention), the RTOR vehicle apparently induced a following vehicle to cross the intersection on red resulting in an accident with a cross-street vehicle coming from the opposite direction. This latter accident resulted in a fatality, the only one during the whole course of study.

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Abridgment

Driver Behavior During the Yellow Interval

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Every driver has experienced the anxiety of approaching an intersection as the signal turns yellow. The driver must then decide quickly whether to stop or to go through before the signal turns red. The change period is one of the most important and least studied intervals of the signal cycle.

This investigation has a threefold purpose: to provide an understanding of driver characteristics during the yellow interval, to determine the ability of drivers to stop in time, and to present a method for determining the length of the clearance interval for urban intersections. The data collected in this study of one intersection help answer the following questions: What do drivers do when the signal changes to yellow? How fast a deceleration rate will drivers accept when the signal changes to yellow? How long should the clearance period be to satisfy the drivers' needs?

RESULTS

Probability of Stopping as a Function of Distance

At the intersection studied, 816 close-decision vehicles were recorded. The probability of stopping was plotted against the cube root of the distance from the stop line at the instant the signal turned yellow, and the results are shown in Figure 1.

Probability of Stopping as a Function of Approach Velocity

The total distribution was stratified in order to obtain distributions of the probability of stopping for vehicle speeds of 16.1, 24.1, 32.2, and 40.2 km/h (10, 15, 20, and 25 mph). From these distributions the probability of stopping given distance from the stop line was deduced.

The resulting distributions are shown in Figure 2, which gives a series of distance values that corresponds to a certain probability level for the speeds. The log of the velocities was plotted against the corresponding distances by using a constant probability of stopping. The results are shown in Figure 3, which reveals a linear relationship between distance from the stop line and the log of approach velocity. The theoretical relationships denoted by the straight lines in Figure 3 were replotted on rectangular coordinate graph paper. The result, shown in Figure 4, reveals the curvilinear relationship between distance and approach velocity when plotted as a function of the probability of stopping. The curves give results when 15, 50, 80, and 95 percent of stops are successful.

Probability of Stopping as a Function of Potential Time

Potential time is that required for a vehicle to reach the stop line after the signal turns yellow, assuming a constant velocity. Figure 5 shows the probability of stopping as a function of potential time.

Deceleration Rates

In order to obtain the maximum deceleration rates acceptable to drivers having a choice of either proceeding through or stopping, the sample of stopping vehicles was stratified to represent only the vehicles that stopped most quickly. Several stopping vehicles were observed during each cycle, but the sample was stratified to include only the vehicle that stopped first. At the intersection studied, 166 first-to-stop, close-decision vehicles were recorded. The resulting distribution is presented in Figure 6.

Ability to Stop

Figure 7, a curve representing the probability of stopping as a function of deceleration, shows that half the drivers chose not to accept a deceleration rate faster than 2.8 m/s^2 (9.1 ft/s^2), a fifth did not accept a rate of 2.1 m/s^2 (7.0 ft/s^2), but a tenth did accept a rate over 4.9 m/s^2 (16.0 ft/s^2).

Method of Determining Length of Yellow Interval

There are two basic conditions that must be considered when the yellow interval is timed: when a driver will choose to stop and when a driver will choose to go through an intersection. It can be shown that the required length of the yellow interval can be computed by evaluating the terms of the following general equation (derivation not included).

$$Y = R + (V/2a^-) + [(W + L)/V] - [K + (2d/a^+)^{1/2}] \qquad (1)$$

where

- R = driver decision and reaction time (1.1/s) (1);
- V = 85 percentile approach speed;
- a^- = deceleration accepted 85 percent of the time [2.0 m/s^2 (6.5 ft/s^2) from Figure 7];
- W = distance from stop line to the line where the vehicle is shadowed;
- L = length of vehicle [5 m (17 ft) for automobiles];
- K = reaction time of cross-flow traffic (0.4 s) (2, p. 23);
- d = distance between vehicles and cross-flow traffic; and
- a^+ = maximum acceleration of cross-flow traffic [4.9 m/s^2 (16.0 ft/s^2)].

Or, Y equals decision time plus deceleration time plus clearance time minus cross-flow acceleration time. The parameters of this equation for the intersection studies are shown in Figure 8.

INTERPRETATIONS

Probability of Stopping as a Function of Distance

An approximate mathematical model for the probability of stopping (P_s) that adequately describes driver behavior during the yellow interval is as follows:

$$P_s = (1720 \times 10^{-4} D^2) - (257.4 \times 10^{-5} D^3) \qquad (2)$$

where D is how far back from the stop line a vehicle is at the instant the signal turned yellow. P_s is a percentage. This equation can be used in conjunction with computer simulation.

Probability of Stopping as a Function of Velocity

Figure 3 shows that for a given probability the relationship between approach velocity and distance from the stop line is logarithmic. The equation for the straight lines in Figure 3 relating velocity and distance for a constant probability of stopping was found to be

$$D = m \log V - b \qquad (3)$$

where D is distance from stop line, V is velocity, m is constant, and b is constant.

In Figure 4 the equation for the curves that relate velocity and distance was found to be

$$V = (10^{D/m})(10^{b/m}) \qquad (4)$$

Probability of Stopping as a Function of Potential Time

Figure 5 shows that, when the signal turns yellow, out of 100 vehicles having a potential time of 1.9 s, 15 stopped. Vehicles having a potential time of 2.9 s have a fifty-fifty chance of stopping or going through. At a potential time of 5.5 s, 5 out of 100 went through, and 95 stopped. Figure 5 also shows that 37 percent of the drivers entered the intersection after the yellow interval ended (potential time of 3.2 s). Fifteen percent entered 1 s after the red interval began (potential time of 4.2 s), and 5 percent entered 2.2 s after the red. The observation that 37 percent of the vehicles entered and crossed the intersection after the beginning of the red interval makes it clear that the existing yellow interval at the intersection of 3.2 s is inadequate.

CONCLUSIONS

Driver Characteristics

At the intersection studied, 37 percent of the vehicles entered and crossed the intersection after the 3.2-s yellow interval. Eighty-five percent of the close-decision drivers chose both to stop at the intersection when they were farther than 30.5 m (100 ft) from the stop line at the instant the signal turned yellow and to go through the intersection when they were within 13.1 m (43 ft) of the stop line. At a distance of approximately 20.4 m (67 ft) from the stop line, 50 percent of the close-decision

Figure 1. Probability of stopping during yellow interval.

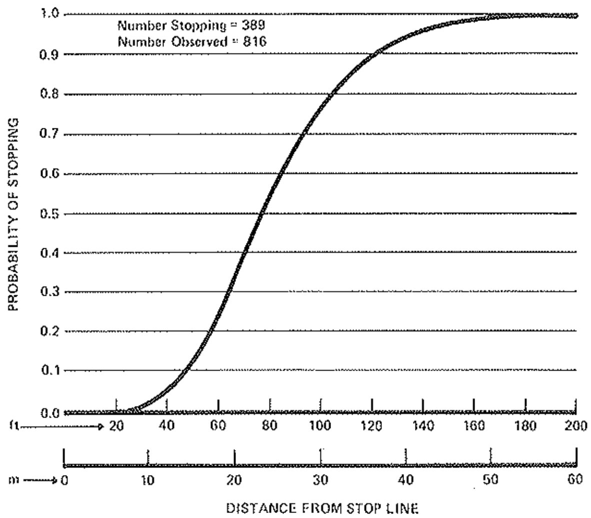


Figure 2. Probability of stopping as a function of velocity and distance from stop line.

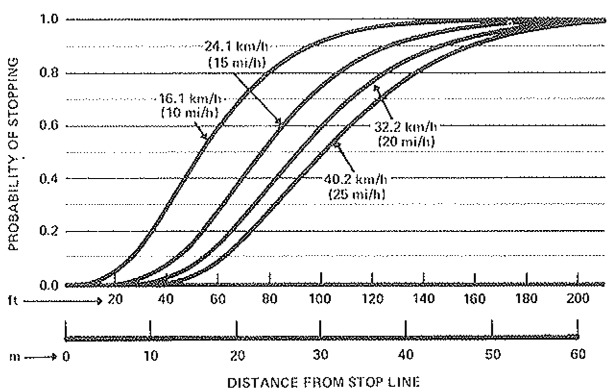
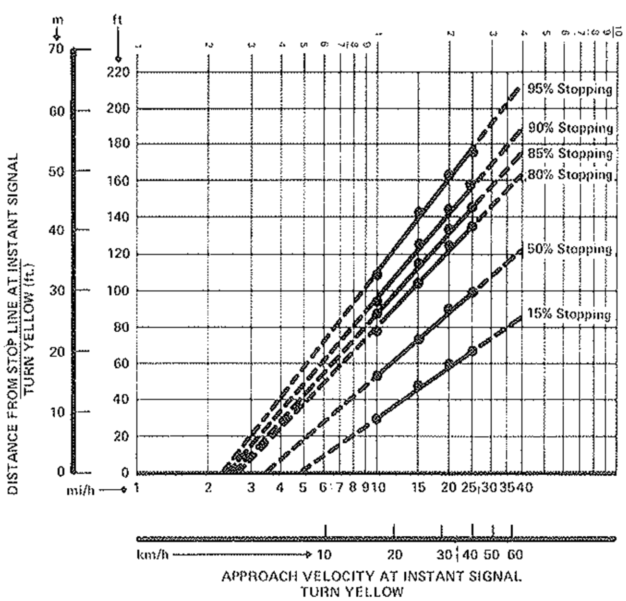


Figure 3. Log of probability of stopping as a function of distance and velocity.



drivers stopped, and 50 percent went through.

Ability to Decelerate

The average maximum deceleration rate accepted by

Figure 4. Distance of vehicle from stop line and approach velocity as a function of percentage stopping.

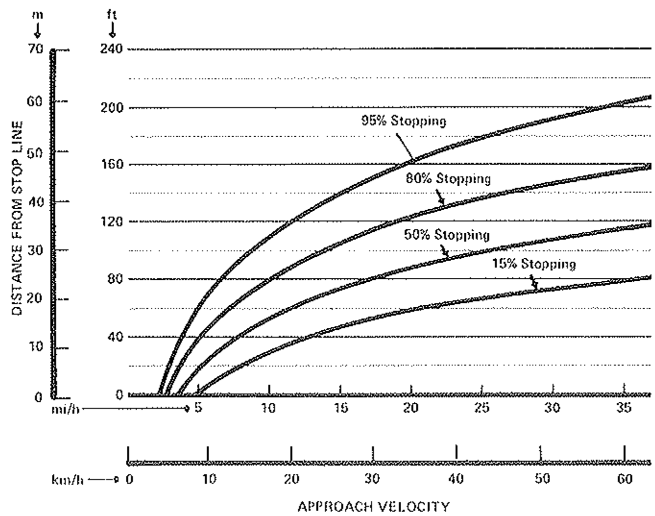


Figure 5. Probability of stopping during yellow interval versus potential time to stop line.

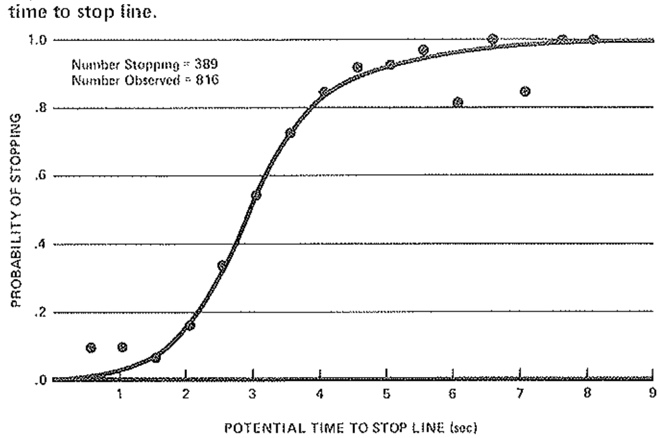


Figure 6. Cumulative frequency distribution of average deceleration rates for 166 stopping vehicles.

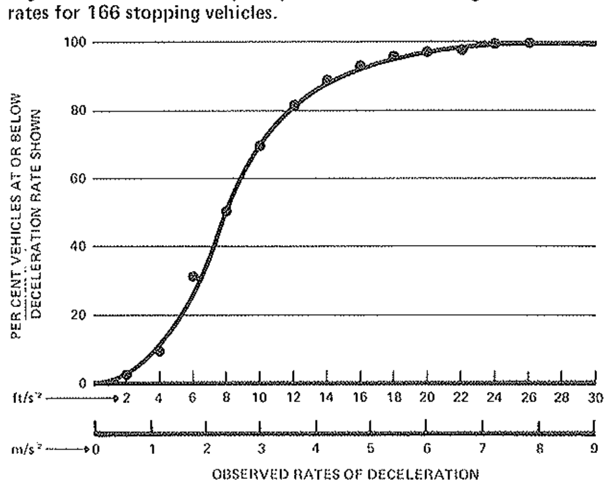


Figure 7. Probability of stopping during yellow interval versus accepted deceleration rate.

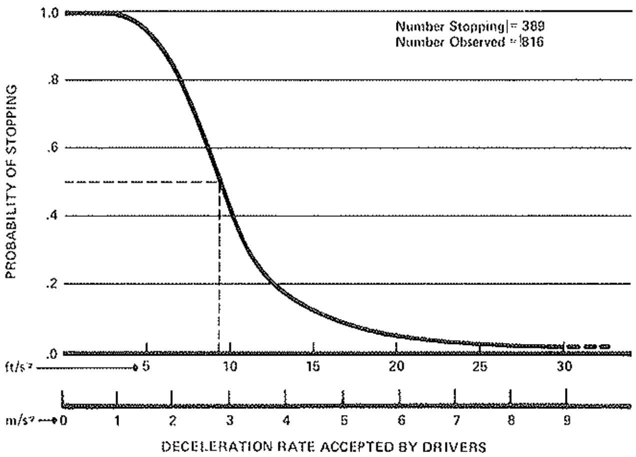
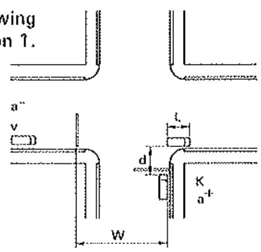


Figure 8. Intersection showing parameters used in Equation 1.



the vehicles stopping most quickly is 2.0 m/s^2 (9.7 ft/s^2). Drivers confronted with a close decision during the yellow interval will accept a deceleration rate of 2.0 m/s^2 (6.5 ft/s^2) 85 percent of the time.

Method of Determining the Length of the Clearance Interval

The minimum length of the clearance interval can be calculated to adequately serve drivers' needs and to meet law enforcement purposes by using Equation 1.

It should be noted that the time calculated from this equation is that needed for clearance. This can be provided by the yellow interval in combination with an all-red interval. Using this technique, a city or county can standardize the length of the yellow interval (say, 3.6 s for 60-s cycle phase) and provide additional clearance time with the all-red interval. If this equation is to be correctly applied, engineers should conduct field studies in their own locations to determine local values for the unknown parameters.

The reader should note that the terms of Equation 1 are not new and that various permutations of them have been recorded in the literature since 1929 (3). The value of Equation 1 is that it is theoretically correct and includes all parameters involved in the clearance decision. Engineers should develop probability of stopping versus time charts similar to Figures 1-7 for their own cities. In this way the decision time $[R + (V/2a^-)]$ can be computed by how drivers actually behave in the area being studied. The time deduction for cross-flow acceleration needs to be applied with caution, and a value of zero should be used if light jumping is possible (yellow interval visible to waiting traffic).

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Optimization of Pretimed Signalized Diamond Interchanges

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This paper describes a computer program that can determine the best strategy for a pretimed signalized diamond interchange to minimize the average delay per vehicle. This program, PASSER III, is one of a series of signalization programs developed for the Texas State Department of Highways and Public Transportation. All basic interchange signal phasing sequences, including all possible patterns from lead-lead, lag-lead, lead-lag, and lag-lag phasings, are evaluated by the program. Interchange performance is evaluated by using average vehicle delay; exterior delay is calculated by Webster's delay equation; and interior delay is determined from deterministic delay-offset techniques. Minimum delay analyses of 18 sample problems were made. Many signalization phasing patterns were found to provide optimum operation over the set of problems evaluated. While four-phase overlap and three-phase timing plans were normally found to provide good operation, other signalization patterns may produce even better operation.

The signalized diamond interchange is a critical facility for providing high performance levels along urban freeway corridors. Efficient movement of traffic through the interchange and the quality of service provided motorists depend to a large measure on the type of signalization used. However, there seem to be dif-