Driver Behavior at Signalized Intersections in Relation to Yellow Intervals

April 1980

Paul L. Zador, Ph.D.

Insurance Institute for Highway Safety
Washington, D.C.

ABSTRACT

The stopping behavior of 1,762 drivers was observed at two signalized intersections, one in Maryland and one in Georgia, using time lapse photography.

Only about ten percent of the drivers chose to stop upon yellow onset when to do so required a deceleration rate of 15 $ft/sec.^2$--the rate suggested by the Transportation and Traffic Engineering Handbook for setting yellow clearance intervals. The results show that reducing the limiting deceleration rate from 15 ft/sec^2 to 10 ft/sec^2 in the formula for setting yellow clearance intervals would substantially reduce the numbers of vehicles still in the intersection when the cross traffic signal turns green.

INTRODUCTION

Recommended procedures for setting the time intervals for the different phases of traffic signals are contained in two widely used traffic engineering handbooks--The Transportation and Traffic Engineering Handbook [1] and The Manual of Uniform Traffic Control Devices for Streets and Highways [2]. The Handbook [1] states:

> "[T]he purpose of a yellow clearance interval is twofold: (1) to advise the motorists that the red interval is about to commence and to permit the motorists to come to a safe stop and (2) to allow vehicles that have entered the intersection legally sufficient time to clear the point of conflict prior to the release of opposing pedestrians or vehicles."

The Handbook also contains a formula to be used for setting yellow clearance intervals. The Manual [2] contains essentially the same but indirect definition of the yellow clearance interval when it prohibits ". . . an unexpected crossing of pathways of moving traffic. . . during any green interval. . .". Unlike the Handbook the Manual does not contain a formula for setting yellow clearance intervals but limits itself to the statement that "yellow vehicle change intervals should have a range of approximately 3-6 seconds."

According to survey results cited by May [3] traffic engineers often choose to employ the formula in the Handbook [1] for setting yellow intervals. The formula includes the perception-reaction time of drivers, average vehicle lengths and, most importantly, a limiting value for the deceleration rates of vehicles*. The values generally used for these parameters are based on assumptions and not relevant obervations.

Following the suggestion of Olson and Rothery [4], the Handbook specifies that the ". . . yellow period should be such that a driver could just stop his vehicle [emphasis added] on seeing the yellow light before entering the intersection or he could continue at uniform speed and cross the intersection before the beginning of the red interval." The Handbook then prescribes the "reasonable limiting value" of 15 ft/sec to the deceleration rate of drivers for design purposes.

This paper presents data on the actual deceleration rates of vehicles when their drivers were faced with yellow onset at two urban arterial intersections.

Experimental Design and Data Collection

The observations analyzed in this paper were carried out at two reasonably isolated suburban arterial street intersections -- one located in Maryland and the other in Georgia. Both were four-legged intersections on divided highways with simple geometrics and both had good pavements on level approaches. The

---

*The Handbook sets yellow duration equal to $t + \frac{1}{2}\frac{v}{a} + \frac{W+L}{v}$, where t is driver reaction time (= 1 sec), v ft/sec is mean approach speed, a ft/sec is limiting deceleration, (= 15 ft/sec) , W ft is intersection width and L ft is vehicle length (= 20 ft).

signals at these intersections could not be activated by through traffic at the approach of interest.

Time lapse photography was used to record the motion at a rate of five frames per second of all vehicles found in the "catch zone". The catch zone was defined as follows: an upstream cut-off was chosen as the point from which a car with an initial speed of 10 mph in excess at the local average speed could come to a full stop at the traffic signal using a uniform deceleration of 0.25g (8 ft/sc^2); the downstream cut-off was chosen as the point from which a vehicle traveling 10 mph below the average at yellow onset could just clear the cross street prior to red. (See Table 1.)

From these records, the longitudinal and lateral vehicle coordinates were calculated using a method developed by Huber and Tracy [5] and reduced to a Fortran program by Bleyl [6].

Vehicles were observed in peak and off-peak traffic at both sites. Observations were made both under wet and under dry pavement conditions at the Maryland but not at the Georgia site. At both sites, the initial (short) yellow was subsequently extended and the observations were then repeated with the extended (long) yellow for all combinations of these conditions. The experimental design and road geometry are summarized in Table 1.

The details of the site selection, method of observation, equipment, data extraction and validation are given in Stimpson et. al. [7].

Analysis and Results

The data analyzed in this paper pertain to those vehicles observed in the catch zone at the time of yellow onset that were either the last to cross or the first to stop in their lanes during that cycle. (These vehicles will be termed "decision vehicles.")

Initial approach speeds were estimated for all decision vehicles from the position data. These were used to calculate the constant deceleration needed to bring the car to a full stop at the stop line. This was done using the formula $a = v^2/2d$ where v is approach speed and d is the distance from the front bumper to the stop line at the time (about 0.5 seconds after yellow onset) the constant deceleration was initiated.

As the first step of the analysis, the values of the decelerations required to stop by decision vehicles were ranked in an ascending order, this ranked sequence of decelerations was partitioned into fifteen equal sized class intervals. Then the number of vehicles that actually stopped was determined for each deceleration class interval. This produced sixteen deceleration class interval end points, a_i, and fifteen stopping probabilities, p_i, computed as follows:

$$p_i = 15 \frac{S_i}{N} \qquad , \quad i = 1, \ldots , 15 \qquad (1)$$

In formula (1) N is the total number of decision vehicles, and S_i is the number of vehicles among the N/15 vehicles in the deceleration class interval between a_i and a_{i+1} that stopped.

For the second step of the analysis, the stopping probabilities were smoothed to reduce random fluctuations. This was done using the formula:

$$f_i = \frac{p_i + 2p_{i+1} + p_{i+2}}{4} \qquad , \quad i = 1, \ldots , 13 \qquad (2)$$

The smoothed probabilities were then tabulated against their "plotting postions" which were defined on a logarithmic scale as the mid point of the class interval boundaries:

$$x_i = \frac{\ln a_{i+1} + \ln a_{i+2}}{2} \quad , \quad i = 1, . . ., 13 \tag{3}$$

The values f_i are, in effect, estimates of the probabilities that vehicles that require a deceleration of $a_i = e^{x_i}$ for just stopping by the stopping line will, in fact, stop.

Table 2 presents x_i and f_i for the whole sample of 1,762 decision vehicles as well as for three subsamples. The first subsample includes all decision vehicles observed at the Maryland site on dry pavement. The second subsample includes all decision vehicles observed at the Maryland site on wet pavement. The last subsample includes all decision vehicles observed at the Georgia site on dry pavement. These results are graphed in Figure 1.

These results clearly show that only about 10 percent of all drivers chose to stop when stopping required a deceleration of about 15 ft/sec^2 ($15 = e^{2.71}$). It is also noteworthy that the decelerations which about half the drivers were willing to accept were 9.70 ft/sec^2 and 9.67 ft/sec^2 on dry pavement at the Maryland and Georgia sites and 9.03 ft/sec^2 at the Maryland site on wet pavement.

Discussion and Recommendations

The Transportation and Traffic Engineering Handbook states that "An incorrect choice for the length of yellow period . . . can lead to the creation of a dilemma zone. This is an area close to an intersection in which a vehicle can neither stop safely nor clear the intersection before the beginning of the red interval without speeding."

The Handbook presents a Table for the "Theoretical Minimum Clearance Intervals for Different Approach Speeds and Crossing Street Widths" (p. 815) that are calculated on the assumption that a deceleration of 15 ft/sec is a "reasonable limiting" value for drivers faced with a stop-go decision. The data presented in this paper clearly show that very few drivers decelerate at that rate when faced with a yellow traffic light.

In a previous paper by Stimpson et. al. [7], results based on the same data were presented showing that at the Maryland site more than one out of every six vehicles travelling on dry pavement that were last to cross upon yellow onset spent at least 0.2 seconds in the path of the cross street traffic after the cross street signal changed to green. Such a high conflict rate clearly does not achieve the intent of the recommendation cited from the Handbook, and obviously is undesireable. Yet, the yellow interval at this site at the time of these observations was 4.6-4.7 seconds and it exceeded the value obtained from the formula in the Handbook (see footnote to Introduction) -- 4.3 seconds -- by almost 10 percent.

As part of the study that provided the data analyzed here, the yellow duration was extended at that Maryland site to 6.0-6.1 seconds and the frequency of last-to-cross vehicles that were still in the intersection when the cross street signal changed to green dropped dramatically to one out of every hundred.

Using the formula for calculating yellow duration from the Handbook, the values of 4.6 seconds and 6.0 seconds used in the original experiment imply limiting decelerations of 12.8 and 7.3 respectively at the Maryland site. In other words, when these deceleration rates are used in the formula instead of the 15 ft/sec^2 rate, the yellow intervals become 4.6 seconds or 6.0 seconds respectively.

Figure 2 shows the dependence of the proportions of last-to-cross vehicles clearing the intersection at least 0.2 seconds after the cross street signal has changed to green against the limiting values of decelerations based on data from both sites and for both the initial short yellow and the extended yellow durations. This figure shows that as the limiting value of the deceleration increases from 7.3 ft/sec^2 to 21.6 ft/sec^2 the proportion of last-to-cross vehicles that were still in the intersection 0.2 seconds after the cross street signal had changed to green increased steadily from one percent to 78 percent.

The evidence cited in this paper clearly demonstrates that the correct intention of the Transportation and Traffic Engineering Handbook recommendation to reduce the dilemma zone by allowing most vehicles to safely stop or to cross prior to cross street green is defeated by the incorrect choice of the limiting deceleration value of 15 ft/sec^2. The data analyzed in the present paper, also shows that a limiting value for the deceleration in excess of 10 ft/sec^2 will ensure that at least one out of 10 vehicles that are the last to cross after yellow onset will be found in possibly hazardous conflicts with cross street traffic, because they will be still in the intersection when the cross street signal has changed to green. A previous analysis of the same data (Stimpson et. al., 1980) also showed that slight extensions of yellow durations at the two observed intersections did not influence stopping decisions, as a result, substantially fewer vehicles were still in the intersection after the cross street signal changed to green*.

The evidence from the present study convincingly shows that the limiting value of the deceleration used for setting yellow intervals should not exceed 10 ft/sec^2.

*In the study cited intersections with yellow clearance intervals were studied. Where yellow plus all red clearance intervals are in use the combined duration of these phases should be considered equivalent to yellow clearance intervals.

Table 1

Design Matrix for Observing Driver Response
to Yellow Onset and Site Characteristics at Two Sites

Design Matrix

Duration of Yellow	Traffic Condition	Pavement Condition	Site: Maryland	Site: Georgia
Short	Off-Peak	Dry	Yes	Yes
		Wet	Yes	No
	Peak	Dry	Yes	Yes
		Wet	Yes	No
Long	Off-Peak	Dry	Yes	Yes
		Wet	Yes	No
	Peak	Dry	Yes	Yes
		Wet	Yes	No

Site Characteristics

	Maryland	Georgia
Cross-street Width	60 ft.	101 ft.
Catch Zone(1) Down Stream Cut-off	65 ft.	25 ft.
Catch Zone(1) Upstream Cut-off	320 ft.	320 ft.
Speed Limit	35 mph	45 mph
Short(2) Yellow	4.6-4.7 sec	4.2-4.4 sec
Long(2) Yellow	6.0-6.1 sec	5.6-5.8 sec
Number of Lanes Observed (3)	2	2

---

(1)Catch zone was measured from stop-line. Cut-off distances were calculated to include dilemma zones for majority of approach speeds.

(2)Slight variation in actual yellow duration was observed during study.

(3)Traffic in left turn lanes was not observed.

TABLE 2

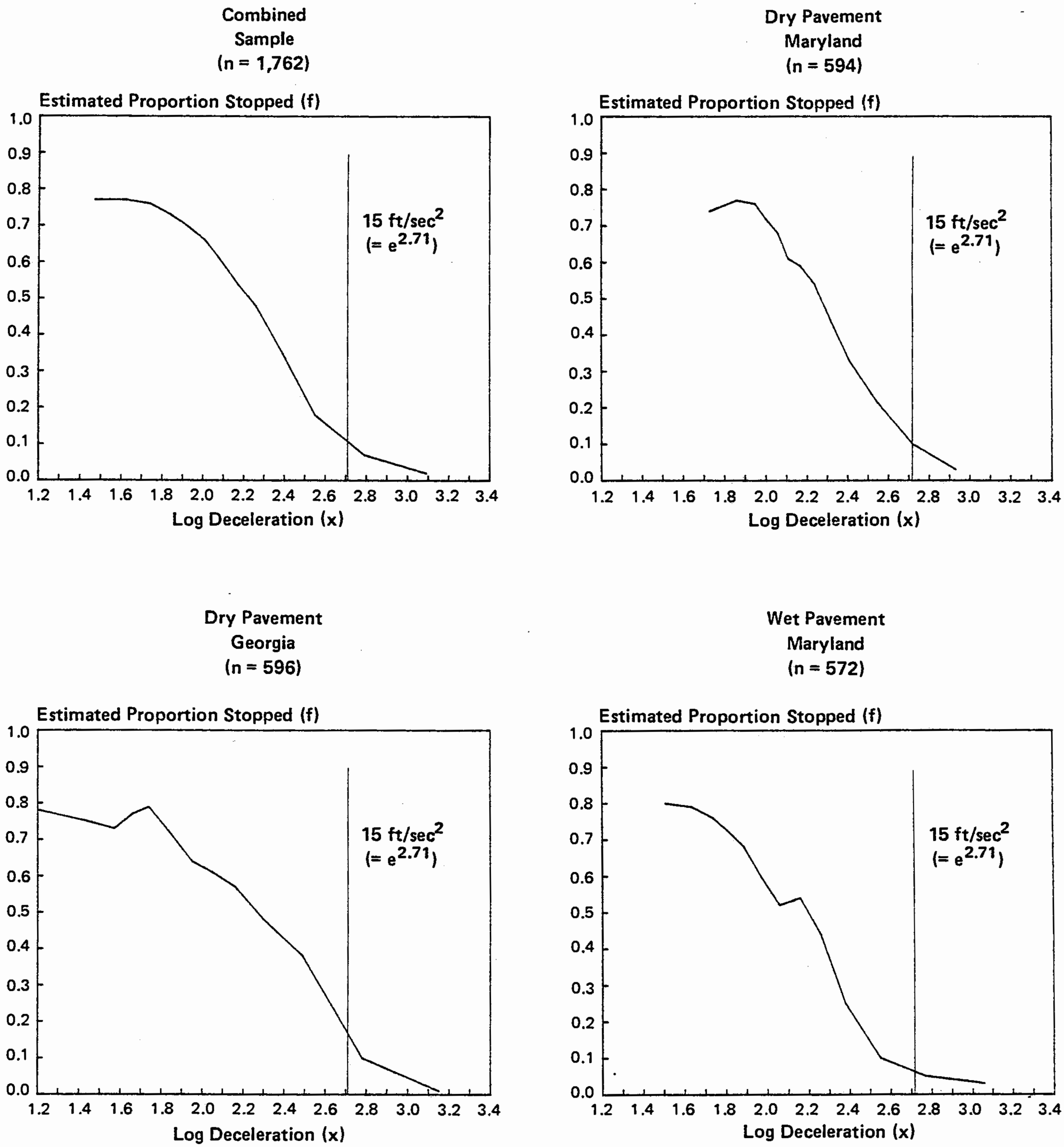
Estimated [1] Probability of Stopping (f_i) by Decision Vehicles Upon Yellow Onset for Vehicles at the Maryland and Georgia Sites for the Combined Sample and by Site and Pavement Condition as a Function of Deceleration (e^{x_i}) Needed for Stopping.

	Combined Sample (n=1,762)		Dry Pavement Maryland (n=594)		Wet Pavement Maryland (n=572)		Dry Pavement Georgia (n=596)	
i	x_i	f_i	x_i	f_i	x_i	f_i	x_i	f_i
1	1.47	0.77	1.73	0.74	1.51	0.80	1.21	0.78
2	1.62	0.77	1.86	0.77	1.64	0.79	1.44	0.75
3	1.74	0.76	1.95	0.76	1.74	0.76	1.57	0.73
4	1.84	0.73	2.00	0.72	1.82	0.72	1.66	0.77
5	1.92	0.70	2.06	0.68	1.89	0.68	1.74	0.79
6	2.01	0.66	2.11	0.61	1.97	0.60	1.84	0.72
7	2.08	0.61	2.17	0.59	2.06	0.52	1.95	0.64
8	2.17	0.54	2.24	0.54	2.16	0.54	2.05	0.61
9	2.26	0.48	2.32	0.44	2.26	0.44	2.16	0.57
10	2.39	0.35	2.41	0.33	2.38	0.25	2.30	0.48
11	2.55	0.18	2.54	0.22	2.55	0.10	2.49	0.38
12	2.79	0.07	2.72	0.10	2.77	0.05	2.78	0.10
13	3.09	0.02	2.93	0.03	3.06	0.03	3.15	0.01

(1) Probabilities were smoothed by equation (2). (See text)

FIGURE 1

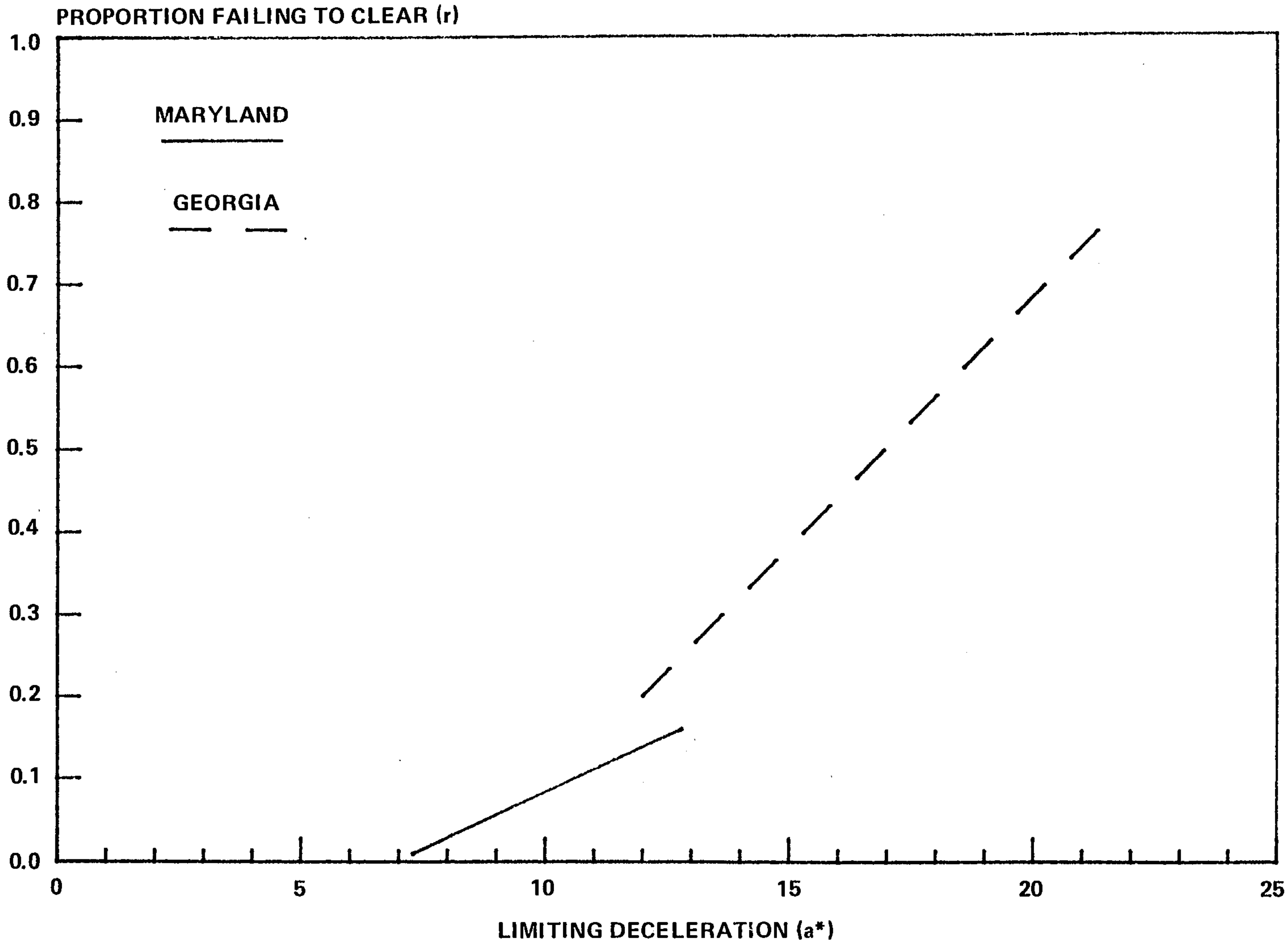
ESTIMATED [1] PROBABILITY OF STOPPING (f) BY DECISION VEHICLES UPON YELLOW ONSET BY SITE AND PAVEMENT CONDITION AS A FUNCTION OF DECELERATION (e^{x}) NEEDED FOR STOPPING.



(1) Probabilities were smoothed by equation (2). (See text.)

FIGURE 2

PROPORTION (r) OF LAST-TO-CROSS VEHICLES CLEARING INTERSECTION AT LEAST 0.2 SECONDS AFTER CROSS-STREET GREEN AS A FUNCTION OF LIMITING DECELERATION VALUE (a*) USED IN YELLOW TIMING FORMULA[(1)]



[(1)] Yellow time = t + 0.5 v/a* + (W + L)/v, when t = 1, v = approach speed limit, W = cross street width, and L = vehicle length (= 20 ft). [(1) p. 815.]

Acknowledgments

The author wishes to express his appreciation to Dr. Ron Karpf and Mr. Brian O'Neill of the Insurance Institute for Highway Safety, Dr. Santanu Basu of Allan Voorhees and Associates and Dr. Shalom Hakkert of the Technian Haifa, who was on sabbatical at the IIHS during the concluding months of this work for assistance on data analysis and helpful suggestions.

References

[1] "Transportation and Traffic Engineering Handbook," Institute of Traffic Engineers, Prentice Hall, Inc., New Jersey, 1976.

[2] "Manual on Uniform Traffic Control Devices for Streets and Highways," U.S. Department of Transportation, Federal Highway Administration, 1971.

[3] May, A. D., "Clearance Interval at Traffic Signals," Highway Research Record 221, 1968.

[4] Olson, P. L. and Rothery, R. W., "Driver Response to the Amber Phase of Traffic Signals," Traffic Engineering, pp. 17-29, February 1962.

[5] Huber, M. J. and Tracy, J. L., "Effects of Illumination on Operating Characteristics of Freeways," National Cooperative Highway Research Program Report 60, 1968.

[6] Bleyl, R. L., "Traffic Analysis of Time-Lapse Photographs Without Employing a Perspective Grid," Traffic Engineering, pp. 29-31, August 1972.

[7] Stimpson, W. H., Zador, P. L., and Tarnoff, P. J., "The Influence of the Time Duration of Yellow Traffic Signals on Driver Response," Institute of Traffic Engineer's Journal, In Press.