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DRIVER RESPONSE TO THE AMBER PHASE OF TRAFFIC SIGNALS

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Observations of motorist response to the amber phase of traffic signals obtained at five intersections, representing three speed zones, are presented. The data from these observations give an estimate of the probability of stopping for vehicles as a function of their distance from the intersection at the onset of the amber phase of the traffic signal. The results lend no support to a popular hypothesis, i.e., that drivers tend to 'take advantage' of a long amber phase by treating it as an extension of the green. The results of the study are compared with other investigations pertaining to amber phase lengths and implications of this work for the design of amber phases is discussed.

IN AN interesting paper, GAZIS, HERMAN, AND MARADUDIN[1] discuss, in considerable detail, a problem associated with the amber signal light in traffic flow. This problem arises when a driver, confronted with an improperly timed amber light phase, finds himself in the position of being too close to the intersection to stop safely and too far from the intersection to proceed and pass through it completely before the red phase commences. By means of a theoretical discussion and observational data, Gazis, et al. present criteria for the design of the amber light phase which would eliminate such 'dilemma zones,' e.g., they derive the following formula for $\tau_{\min}$, the minimum amber phase duration:

$$\tau_{\min}=\delta_2+V_0/2a_2^*+(\mathrm{W}+\mathrm{L})/V_0, \tag{1}$$

where δ_2 is the reaction and decision-making time of the driver, V_0 is the approach speed of the vehicle, W and L are the intersection width and vehicle length respectively, and a_2^* is the constant rate of deceleration for the case when the vehicle attempts to stop in front of the intersection. In practice this constant deceleration represents the maximum average deceleration to which it is desirable or practical to subject drivers. In order to use equation (1), assumptions must be made concerning this deceleration as well as the reaction-decision time of drivers. Despite the uncertainties regarding these parameters, $\tau_{\min}$ undoubtedly provides a reasonable approximation of an adequate amber phase duration. When it is used as a criterion, comparison of observed and calculated amber phase duration indicates that many light cycles are improperly designed even for fairly high decelerations ($\sim$16 ft/sec^2), and for reasonable reaction times ($\sim$1.0 sec).

It would appear then that there is a very real problem involving amber signal duration and this problem could probably be resolved by extending the duration of the amber phase so that it was at least $\tau_{\min}$. One major difficulty seems to stand in the way of adopting this procedure. It is the contention of many traffic engineers that drivers tend to regard long amber phases as extensions of the green. The inference from this contention is that drivers further from the intersection may be tempted to continue where otherwise they would have stopped. Because of this, a greater error may be introduced in their judgments, increasing the probability of their being caught in the intersection during the red phase of the light cycle. Of course, even if this contention is valid, it still does not constitute an adequate reason for presenting drivers with an insoluble problem during amber cycles, particularly if the vehicle code is not compatible with physical reality. In light of this contention the authors were stimulated to investigate the behavior of vehicle operators at normal intersections, making observations on those drivers caught near the intersection at the moment the amber phase commences. In particular, we wished to determine whether the behavior of motorists in this situation actually does change with significantly different amber phase durations.

TABLE I

PROBABILITY OF CARS STOPPING AS A FUNCTION OF THEIR SPEED AND DISTANCE FROM SIGNAL AT ONSET OF AMBER(a)

Speed (mph)	Probability of stopping, feet		
	0.50	0.80	0.95
30	100	120	135
40	160	190	210
50	225	275	300

(a) Data from Webster[2]

It should be mentioned that another study related to this problem has been made by F. V. WEBSTER.[2] In this experiment drivers approached a mock-up light signal at specific speeds. As the vehicle approached the light which was set on the green phase, the vehicle itself, at fixed distances from the stop line, triggered the light to the amber phase. From this admittedly artificial situation, Webster was able to construct a table giving the probability of stopping at different speeds for particular vehicle distances from the intersection when the amber phase commenced. These data are reproduced in Table I. From these data one obtains one probability of stopping curve for each speed as a function of the distance from the intersection.

If the contention that long amber phases are regarded as extensions of the green is correct, then instead of one probability of stopping curve (P_s) for a given speed of approach, there should in reality be a family of curves, one for each significantly different amber phase duration.

In light of the preceding discussion it would seem to be important to determine whether driver behavior does change as a function of altered amber phase lengths. One way in which this problem might be investigated is to determine the probability of stopping as a function of the distance from a particular intersection for two different amber phase settings. However, since it would require some time, perhaps a very long time, for individuals to become aware of a change of the amber phase and alter their response (if they ever do), an alternate procedure was used. This technique involved comparison of *pairs* of intersections as similar as possible in their physical characteristics but differing appreciably in amber phase durations. This latter approach has one disadvantage in that if the two resultant curves differ, we can not legitimately maintain that it is due to the amber phase.

PROCEDURE

Two ITEMS of information were necessary in order to obtain the desired P_s curves: first, the distance of the vehicles from the intersection at the beginning of the amber phase, and second, whether each vehicle stopped or proceeded through the intersection. It is assumed that the speed distribution for a given speed zone does not differ appreciably from one intersection to another. The position of the vehicles was recorded photographically by setting a 35 mm camera to cover an area some distance back from the intersection and manually tripping the shutter as the light turned to amber. For the purpose of consistency the reference point along the road being studied, from which the measurements of vehicle position originated, was always taken from a point on a line with the paved edge of the intersected road. Simultaneously, a written record was made of the vehicles that were in this region, whether they stopped or not, and identifying them as to make or other obvious characteristics. Cars that turned or were moving conspicuously slower than the bulk of the traffic were not considered. If the behavior of a driver was in any obvious way influenced by other drivers, his vehicle was also eliminated. Thus, for example, if a car stopped, all others behind it were not recorded, even if there was an opportunity to change lanes. Only free running, relatively open traffic was considered.

Recordings were made generally in the afternoon, sometimes in the

TABLE II

FREQUENCY OF OCCURRENCE OF DIFFERENT SPEEDS DURING FIVE-SECOND TIME BLOCKS OF A GREEN PHASE

Miles per hour	n	Five-second intervals during green phase				
		0–5	6–10	11–15	16–20	21–25
56.8	8			2	4	2
48.7	37		8	15	10	4
42.6	106	3	12	33	37	21
37.9	115	5	11	22	30	47
34.1	115	2	13	20	35	45
31.0	42		9	7	6	20
28.4	11		3	3	4	1
26.0	2			1		1
24.3	6	1		4		1
22.7	1					1
21.3	2			1	1	
20.0	1				1	
n	446	11	56	108	128	143
Mean speed		37.3	38.0	39.0	38.8	36.7

TABLE III

COMPARISON OF CHARACTERISTICS OF TWO INTERSECTIONS POSTED AT 40 MPH

Comparisons	Mound at 11 Mile	Stephenson at Lincoln
Amber phase	4.15 sec	2.90 sec
Cross street width	28 feet	36 feet
Mean speed	38.0 mph	36.4 mph
$\tau_{\min}$(a) $a_2^* = 12$ ft/sec^2 $\delta_2 = 0.75$ sec	5.07 sec	5.41 sec
$\tau_{\min}$ $a_2^* = 12$ ft/sec^2 $\delta_2 = 1.0$ sec	5.32 sec	5.66 sec
$\tau_{\min}$ $a_2^* = 16$ ft/sec^2 $\delta_2 = 0.75$ sec	4.00 sec	4.25 sec
$\tau_{\min}$ $a_2^* = 16$ ft/sec^2 $\delta_2 = 1.0$ sec	4.25 sec	4.50 sec

(a) The calculations for $\tau_{\min}$ are based on a speed of 40 mph.

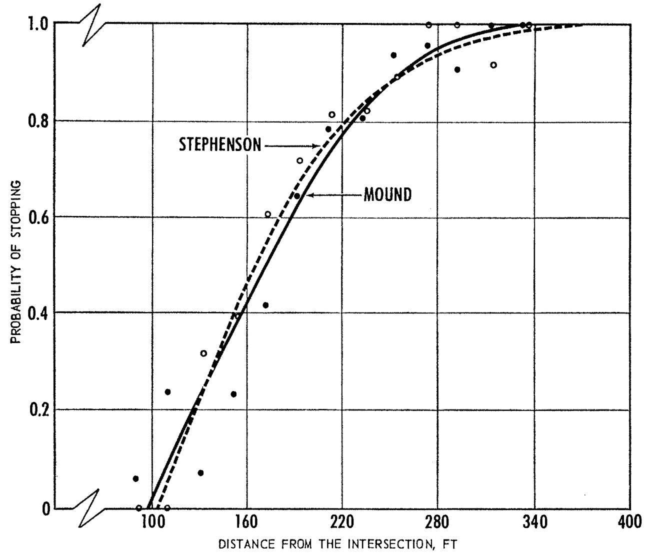

Fig. 1. Comparison of the probability of stopping for two intersections posted at 40 mph. The circles are the points for Stephenson and the solid dots are for the Mound intersection. The smooth curves are a visual fit to the data.

TABLE IV

Probability of Stopping Data for Two 40 mph Intersections

Mound				Stephenson			
Distance	Number stop	Number not stop	P_s	Distance	Number stop	Number not stop	P_s
92′	1	15	0.06	94′	0	17	0.00
112′	5	16	0.24	114′	0	20	0.00
132′	2	26	0.07	134′	7	15	0.32
152′	5	16	0.24	154′	8	13	0.38
172′	8	11	0.42	174′	11	7	0.61
192′	13	7	0.65	194′	18	7	0.72
212′	19	5	0.79	214′	23	5	0.82
232′	13	3	0.81	234′	20	4	0.83
252′	16	1	0.94	254′	27	3	0.90
272′	23	1	0.96	274′	29	0	1.00
292′	20	2	0.91	294′	21	0	1.00
312′	23	0	1.00	314′	12	1	0.92
332′	11	0	1.00	334′	18	0	1.00

morning, covering all periods of the day except rush hours, when the density of traffic was usually such that queues were created that would not clear during the green phase.

At each of the several intersections studied, about 300 usable measurements were obtained. These were distributed among eight to fourteen twenty-foot intervals back from the intersection. On the basis of the fractional number of vehicles that stopped in each of these intervals it was possible to plot the desired P_s curves, using the midpoint of each interval as the reference distance. The data in this form are displaced toward the intersection by an amount equal to the distance covered by the vehicles during the time required for the camera operator to react to the amber onset. Accordingly, a correction was made by shifting the curves back from the intersection by a distance equal to the product of the mean speed in ft/sec and a reasonable reaction time. The value used for this reaction time was 0.15 sec as given by WOODWORTH AND SCHLOSBERG[3] for this type of stimulus.

TABLE V

COMPARISON OF CHARACTERISTICS OF TWO INTERSECTIONS POSTED AT 25 MPH

Comparisons	Gratiot at Robertson	Gratiot at Church
Amber phase	4.75 sec	3.00 sec
Cross street width	30 feet	30 feet
Mean speed	32.9 mph	31.0 mph
$\tau_{\min}$(a) $a_2^* = 12$ ft/sec^2 $\delta = 0.75$ sec	3.65 sec	3.65 sec
$\tau_{\min}$ $a_2^* = 12$ ft/sec^2 $\delta = 1.0$ sec	3.90 sec	3.90 sec
$\tau_{\min}$ $a_2^* = 16$ ft/sec^2 $\delta = 0.75$ sec	3.20 sec	3.20 sec
$\tau_{\min}$ $a_2^* = 16$ ft/sec^2 $\delta = 1.0$ sec	3.45 sec	3.45 sec

(a) The calculations for $\tau_{\min}$ are based on a speed of 30 mph.

Three speed zones were investigated: 25, 40, and 55 mph. In order to ascertain whether the traffic was moving at comparable speeds at the intersections to be paired, speed checks were made at each by means of a Simplex time productograph, recording the time required for a vehicle to move through a trap of a known length. Only freely moving vehicles that did

TABLE VI

Probability of Stopping Data for Two 25 mph Intersections

Distance, feet	Robertson			Church		
	Number stop	Number not stop	P_s	Number stop	Number not stop	P_s
77	0	36	0.00	0	15	0.00
97	2	36	0.05	2	34	0.06
117	9	18	0.33	19	16	0.54
137	10	16	0.38	22	7	0.76
157	25	15	0.63	27	6	0.82
177	23	5	0.82	34	2	0.94
197	51	2	0.96	34	1	0.97
217	85	1	0.99	18	0	1.00
237				26	0	1.00
257				17	0	1.00

not stop or turn were considered. Because it seemed reasonable that traffic would be moving at different speeds past the trap at different phases of the green cycle the speed data at the first intersection were classified according to time during the green cycle in five-second intervals. These data are reproduced in Table II. The small differences in the different

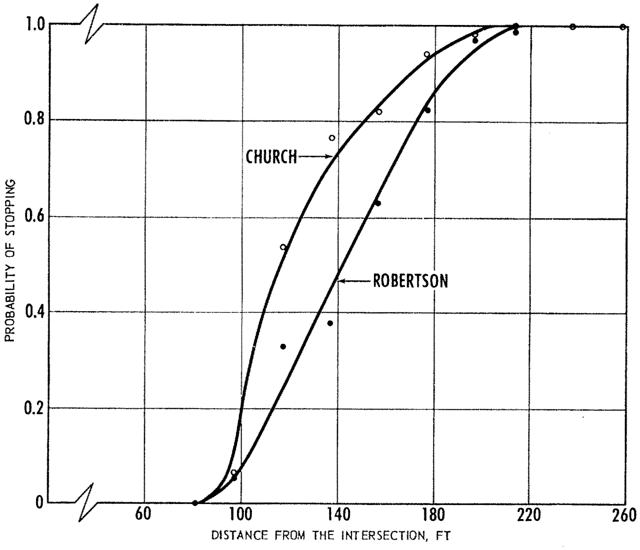

Fig. 2. Comparison of the probability of stopping for two intersections having mean speeds of approximately 30 mph.

TABLE VII

CHARACTERISTICS OF AN INTERSECTION POSTED AT 55 MPH

Characteristic	Value
Amber phase	4.20 sec
Cross street width	38 feet
Mean speed	48.0 mph
$\tau_{\min}$(a) $a_2^* = 12$ ft/sec^2 $\delta_2 = 0.75$ sec	6.09 sec
$\tau_{\min}$ $a_2^* = 12$ ft/sec^2 $\delta_2 = 1.0$ sec	6.34 sec
$\tau_{\min}$ $a_2^* = 16$ ft/sec^2 $\delta_2 = 0.75$ sec	4.95 sec
$\tau_{\min}$ $a_2^* = 16$ ft/sec^2 $\delta_2 = 1.0$ sec	5.20 sec

(a) The calculations for $\tau_{\min}$ are based on a speed of 50 mph.

classes were far short of significance as tested by the extension of the Median test described by SIEGEL.[4] Because of this only the mean speeds were considered in subsequent cases.

RESULTS

THE FIRST comparison was made between two intersections on thoroughfares whose speed limits were posted at 40 mph. In each case the mean

TABLE VIII

PROBABILITY OF STOPPING DATA FOR A 50 MPH INTERSECTION

Distance, feet	Number stop	Number not stop	P_s
221	6	58	0.09
241	13	26	0.33
261	13	21	0.38
281	17	20	0.46
301	25	15	0.63
321	31	10	0.76
341	25	5	0.83
361	24	9	0.73
381	21	2	0.91

speed was fairly close to the posted speed limit, being 38.0 mph in one case and 36.4 mph in the other. The differences between these two mean speeds is really quite small. For example, using equation (1), they would have a $\tau_{\min}$ differing by approximately 0.1 sec.

At the time the measurements were taken both amber phases had been unchanged for more than a year. Both roads were four lanes wide with grassy medians over one-hundred feet wide. Table III lists the significant parameters; amber phase duration, intersection width, speed limit, and observed mean speeds together with the theoretical $\tau_{\min}$ as calculated by equation (1) for the approach speed of 40 mph assuming maximum desirable decelerations of 12 ft/sec^2 and 16 ft/sec^2 and reaction times of 0.75 and 1.0 sec. A car length is taken as 17 feet.

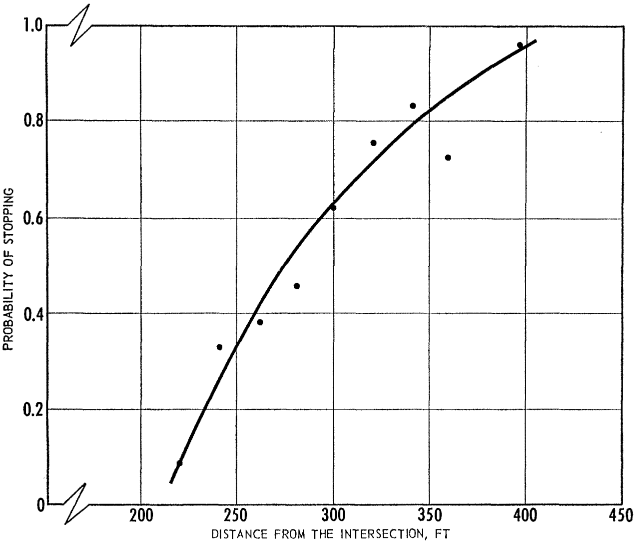

Fig. 3. Probability of stopping for an intersection where the mean speed is approximately 50 mph.

It can be seen from Table III that neither amber is adequate for reasonable decelerations or reaction times, but the longer of the two is close to being satisfactory. In Table IV the data are presented for these two intersections, showing the number and per cent of cars that stopped in each 20 foot interval. From these data the probability of stopping points were computed. These curves for both intersections are shown in Fig. 1. The smooth curves represent a visual fit to the data.

It is apparent that at no point along the P_s scale do the curves differ by much more than a car length and at the higher percentiles, there is an overlap.

A second comparison was made between two intersections on thoroughfares whose speed limits were posted at 25 mph. At the time the study was made these signals had remained unchanged for more than four years. In this case both intersections were on the same four lane street, approximately one-half mile apart. Table V lists the significant parameters of the two intersections. It should be noted in this case that the actual mean speeds at both intersections are in excess of the posted limit. Because of this the data should be considered as a better approximation of what would be expected for an approach speed of 30 mph rather than 25 mph.

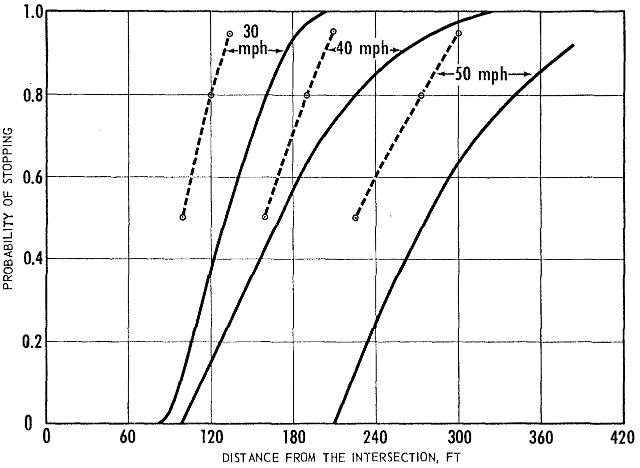

Fig. 4. Representative curves for the probability of stopping for three speed zones. The dotted curves are that of the Webster data given in Table I.

As can be seen in Table V, not only is there a significant difference between the two amber phases but the longer one is longer than would be recommended on a basis of an application of equation (1). In Table VI the data are reproduced for these intersections and in Fig. 2 the P_s curves are shown.

The results of the first two comparative phases of this study provided strong reason to believe that driver behavior does not change significantly when faced with longer amber phases. For this reason the investigation of the higher speed zone was done at only one intersection, with no effort being made to pair it with another. Table VII lists the significant parameters of the intersection and Table VIII lists the stopping data. The P_s curve appears in Fig. 3. In Fig. 4 representative P_s curves have been drawn for the 30 and 40 mph speed zones as well as the curve for the 50 mph intersection.

DISCUSSION AND CONCLUSIONS

From Figs. 1 and 2, comparing two sets of intersections, it would appear that there is no significant behavioral change in drivers associated with different amber cycle lengths. If the contention that drivers regard amber phases as extensions of the green were true, we would expect the P_s curve to be displaced a distance approximately equal to the difference in cycle length multiplied by the mean velocity of the traffic on the thoroughfare considered. For example, in the first comparison, a vehicle traveling at the posted speed limit of 40 mph would travel approximately 80 ft in the 1.25 sec time difference between the two amber phase durations. Obviously, the two curves of Fig. 1 are displaced but a fraction of this distance. Similarly, in the second comparison a vehicle traveling at the observed mean speed of 30 mph would travel a distance of 77 ft in the 1.75 sec time difference between these two amber phase durations. Again, the curves of Fig. 2 are displaced but a fraction of this distance. It is true that in this case there occurs a maximum displacement of approximately 25 feet. However, it is noted that the correspondence of the curves is particularly striking at the extremes. One would expect that the higher percentile performance would be displaced were the hypothesis of differential response to amber phases true. Furthermore, if these kinds of data are to be used as criteria for amber phase design as will be discussed, only the high percentile performance is of interest.

In comparing the representative curves of the three different speed zones of Fig. 4, one notices that they are displaced from each other significantly for the different speed zones. The distance is approximately 40 ft at the fiftieth percentile point between the curves for the 30 and 40 mph speeds and approximately 105 ft between the curves for the 40 and 50 mph speeds, again at the fiftieth percentile point. In this figure Webster's data have also been plotted for comparison. It can be seen that for a given speed and distance his probability of stopping is considerably greater than for the same values in this investigation. For example, for an approach speed of 50 mph, Webster's stopping distance at the fiftieth percentile point is given as 225 ft. This would require an average deceleration of 17.7 ft/sec^2 for drivers having a reaction time of 1.0 sec and would require an average deceleration of 15.8 ft/sec^2 for drivers having a reaction time of 0.75 sec. These rather high decelerations can probably be attributed to the motivation and orientation of Webster's subjects.

In Fig. 4 it can be seen that the stopping curve for the 50 mph zone is displaced from the stopping curves of the second comparison by approximately 105 ft at the fiftieth percentile level. From this displacement the apparent *average* deceleration to which drivers are willing to subject themselves is calculated to be 12.9 ft/sec^2 (assuming a 0.75 sec reaction time) at this level. Thus, the results seem to indicate that drivers allow themselves an added stopping distance for higher speeds so that they can stop comfortably with a deceleration in the range of 12 to 14 ft/sec^2.

The data in Tables IV and VI make possible an interesting comparison. By multiplying the length of the amber phase by the mean speed, and subtracting the width of the intersection and the length of a typical vehicle, it is possible to calculate the average maximum possible distance a car, traveling at the mean speed, can be from the intersection at the beginning of the amber phase and still clear the intersection without accelerating. For example, using the data in Table III, cars approximately 200 ft or more back from the intersection having the longer amber (Mound) could not have cleared in time. In the case of the shorter amber (Stephenson) cars approximately 100 ft or further from the intersection could not have cleared. Of the cars beyond this cut-off distance, 9 per cent did not stop at the intersection having the long amber, and 28 per cent failed to stop at the shorter amber. It is noted that in the case of the shorter amber light the dilemma zone is of considerable length. Indeed, if one assumes a reasonable desirable deceleration of 12 ft/sec^2 and a fair reaction time of 1.0 sec, then the dilemma zone is of the order of 100 ft. In comparison, the longer amber has a dilemma zone of the order of 10 ft. It seems significant that of the 28 per cent who did not stop at the shorter amber and who could not have cleared the intersection, 82 per cent were in this 100 ft dilemma zone. One might conjecture that, if the shorter amber at Stephenson was extended to 4.2 sec there would be approximately a 82 per cent decrease in the number of vehicles that would not clear the intersection before the red phase. Furthermore, the fractional number of motorists who did not stop and who could not have cleared the intersection would then be essentially the same for these two intersections.

If driver behavior does not change as a function of amber phase durations, it should be possible to establish realistic amber phase settings on the basis of actual driver behavior. Thus one might decide that an amber phase should be of such a length that no more than say, perhaps 5 per cent of the vehicle operators who do not stop when faced with the amber light do not clear the intersection before the red phase. Thus one could refer to a P_s curve for the appropriate speed, determine how far back from the intersection the 95th percentile point is, and use the following modification of equation (1):

$$\tau_{\min}=(A+W+L)/V_0, \qquad (2)$$

where A is the distance from the intersection at which the desired percentile cut-off occurs and W, L, and V_0 retain the same definitions as in equation (1). For example, if the 95th percentile cut-off is used, the prescribed $\tau_{\min}$

for the lower speed intersection (calculated at the actual mean speed of 32 mph) would be 5.25 secs, $\tau_{\min}$ for the mid-speed intersections (calculated at the actual mean speed of 38 mph) would be 5.39 secs, and the $\tau_{\min}$ for the high speed intersection (calculated at the actual speed of 48 mph) would be 5.57 secs. The small differences between these recommendations is worthy of note. It might well be feasible to use an essentially constant amber phase length for a large range of speed limits, making small changes only for unusually large cross street widths.

This investigation of the behavior of motorists faced with the onset of an amber signal light has been a continuation of the theoretical analysis and observations reported by Gazis, et al.[1] This study was made to seek possible behavioral trends in this decision-making problem that all too frequently occurs in every day traffic. We realize, of course, that the data are limited. This is mainly due to the extended effort required to obtain the kind of information necessary to make the comparisons presented. However, it is felt that from this data the following meaningful conclusions can be drawn:

1. Driver behavior does not seem to change as a function of different amber phase durations.

2. The amber phases observed are too short as measured either by a criterion of driver behavior or a dilemma zone.

3. A constant amber phase of about 5.5 secs would be practical for a wide range of speed zones, with possible variations made to allow for extra wide cross streets.

That drivers seem to react about the same to ambers of different duration is perhaps a result of confusion resulting from the fact that the average motorist simply does not know how long the typical amber phase is, a situation which is further confounded by the fact that there is no standard method of setting the length of the amber duration. Thus, the motorist, under these conditions may not try to react differently, though the possibility exists that he would were ambers lengthened and standardized. Unless there exists a locale unknown to the authors where amber phases are characteristically longer than what appears to be 'normal,' this possibility cannot be checked out. What really needs to be done in this area is to have an operating staff in a given locality set the amber phases for an adequate duration and study the results. The authors hope that this paper will stimulate this kind of investigation.

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