tiple detectors did not significantly reduce accident rates at intersections that have approach speeds less than 50 mph. A test installation of the EC-DC design in the Atlanta area has a median approach speed of 48 mph. The EC-DC scheme was found to reduce abrupt stops from 5 to none over the observation period (6). "Brake before clearing" maneuvers were reduced from 8 to none. Total conflicts were reduced 69 percent from 29 to 9. Overall, the authors rated the design superior to either the density scheme or the extended-call detector system. These observed reductions in erratic maneuvers suggest the potential for a reduction in accidents.

Zegeer (5) gathered accident data in addition to conflict rates. He found that his green-extension systems brought about a 54 percent reduction in total accidents, and rear-end collisions were reduced by 75 percent. At least two of the three locations studied appear to have average speeds of only 45 mph.

The authors found that the Beirele, Winston-Salem, and SSITE detector placement methods produced about the same delay in their computer simulations. This is an unexpected finding, as the allowable gaps vary over a wide range (4-7 s) and it is well established (16,17) that delay is sensitive to the allowable gap. Morris and Pak-Poy (16) found by computer simulation that delay can increase by as much as 45-105 percent if the allowable gap is increased from 4 to 7 s. Similarly, Tarnoff and Parsonson (17, p. 14) found by computer simulation that delay can increase by as much as 50 to 70 percent if the allowable gap is increased from 4 to 7 s.

Possibly the authors used a low setting of the maximum interval, thereby causing the green to change to yellow before gap-out could take place.

It is worth emphasizing that a long allowable gap is objectionable not primarily because of delay but because only moderate volumes can extend the green to the maximum interval. In that case, a vehicle may well be caught in the zone of indecision. A computer simulation could be very helpful in the preparation of guidelines for the maximum volumes that can be tolerated by designs of various allowable gaps.

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Driver Use of All-Red Signal Interval

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The purpose of this study was to investigate the theory that drivers use the red signal interval more frequently at intersections that have all-red intervals (i.e., all approaches to an intersection have a red indication) than at intersections that do not have all-red intervals. Data were collected at 10 intersections in four New England cities, during both peak and off-peak periods. Some 2764 signal cycles were observed, during which 1115 vehicles entered the intersection after the start of the red interval. The data were subjected to statistical analyses that yielded the following conclusions: (a) more drivers ran the red light at intersections that had all-red intervals than at intersections that had no all-red intervals; (b) the length of the all-red interval appeared to be cor-

related with driver use of the red interval (there were, however, four other predictor variables, each of which was more closely correlated with driver use of the red interval than was the length of the all-red interval); and (c) apparently drivers did not run the red light longer after the start of the red interval at intersections that had all-red intervals than at intersections that had no all-red intervals. The results of this study must be viewed with caution because the number of observed locations was relatively small, and some factors that influence driver use of the red interval may not have been studied during this project. However, the results indicate that a problem may exist and that more research should be done in this area.

The purpose of this study was to investigate driver use of the red signal interval, especially the all-red signal interval. An all-red signal interval is a period of time during a signal cycle during which all approaches to an intersection have a red indication, and all pedestrian signals show a steady DON'T WALK indication. All-red intervals (ARIs) have been in use for at least 20 years, and quite possibly longer. However, no uniform criteria may be applied in the decision to use or not to use an ARI in a particular situation. The Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) (1) states, "The yellow vehicle change interval may be followed by a short all-way red clearance interval, of sufficient duration to permit the intersection to clear before cross traffic is released."

In addition, the Institute of Traffic Engineers' Transportation and Traffic Engineering Handbook (2) states, "When y_2 (the nondilemma yellow interval) exceeds the value selected for the yellow interval and when hazardous conflict is likely, an all-red clearance interval could be used for 2-3 s between the yellow interval and the start of green for opposing traffic."

Thus, an ARI is called for in a situation when more clearance time is needed but when it is not desirable to extend the amber interval.

Many drivers use the first few seconds of the red interval as an extension of the amber interval. The presence of an ARI might serve to encourage such behavior. Little information on this topic is available in the literature. Thus, research was undertaken to determine whether or not more drivers ran the red light at intersections that had ARIs than at intersections that had no ARIs.

Specifically, this research was directed toward answering three questions:

1. Do more drivers run the red light at intersections that have ARIs than at intersections that have no ARIs?
2. Is the length of the ARI correlated with driver use of the red interval? and
3. Do drivers run the red light longer after the start of the red interval at intersections that have ARIs than at intersections that have no ARIs?

FIELD METHODOLOGY

Decision Zone

When a vehicle approaches an intersection and the signal indication changes from green to amber, the vehicle must be in one of the following positions:

1. The vehicle is so close to the intersection that it is virtually impossible to stop before entering the intersection,
2. The vehicle is so far away from the intersection that it is impossible to enter the intersection until long after the start of the red interval, or
3. The vehicle is somewhere in between the two positions described above.

A vehicle in this in-between zone when the signal turns amber is said to be in the decision zone. The driver of the vehicle is forced to make a decision between stopping before entering the intersection or continuing through the intersection.

In order for a vehicle to stop safely before entering the intersection, it must be far enough upstream to allow the driver to react to the amber light and decelerate safely to a stop. As shown by Gazis, Herman, and Maradudin (3), this minimum distance is given by

$$x_c = v_o t_2 + (v_o^2/2d_m) \tag{1}$$

where

- x_c = minimum distance from the front of the vehicle to the stop line when the amber interval starts,
- v_o = initial velocity of the vehicle,
- t_2 = perception-reaction time of the driver for braking, and
- d_m = maximum deceleration rate.

Thus, for a given approach speed, the downstream boundary of the decision zone is defined by Equation 1 and may be found by using appropriate values for t_2 and d_m. By using the mean value of t_2 found by Gazis, Herman, and Maradudin (3) and an assumed maximum deceleration of 16 ft/s², Equation 1 reduces to

$$x_d = 1.14v_o + (v_o^2/32) \tag{2}$$

where x_d is the distance upstream from the intersection line (the curb line extended) at which the downstream boundary of the decision zone is located (ft) and v_o is measured in feet per second.

The upstream boundary of the decision zone is given by

$$x_u = v_o t_m + [a(t_m)^2/2] \tag{3}$$

where

- x_u = distance upstream from the intersection line at which the upstream boundary of the decision zone is located,
- t_m = longest time after the start of the amber interval that a driver will enter the intersection, and
- a = acceleration rate.

The longest amber interval at the observed intersections was 3.5 s, and 99 percent of the drivers who ran the red light entered the intersection 5.0 s or less after the start of the red interval. Thus, a reasonable value of t_m for these data is 8.5 s If we assume a maximum value for a of 5.0 ft/s², Equation 3 reduces to

$$x_u = 8.5v_o + 184.9 \tag{4}$$

where x_u is measured in feet and v_o is measured in feet per second. Thus, if a vehicle is located x ft upstream of the intersection line when the signal changes to amber and $x_d < x < x_u$, the vehicle is in the decision zone.

As the foregoing discussion indicates, the size and location of the decision zone for an individual vehicle are primarily a function of the approach velocity. Note, however, that t_m and d_m vary from driver to driver, and probably vary for an individual driver, depending on mood, influence of drugs or alcohol, or similar human factors. Therefore, the size and location of the decision zone will also be affected by individual driver characteristics.

Only one observer studied the intersections; therefore, it was not possible to observe the speeds of the individual vehicles and determine if they were in the decision zone when the signal turned amber. Instead, the observer was required to make a subjective judgment as to whether or not any vehicles were in the decision zone when the signal changed to amber.

Signal cycles during which at least one vehicle was in the decision zone when the signal turned amber were regarded as decision cycles. Signal cycles during which no vehicles were in the decision zone when the signal turned amber were regarded as nondecision cycles. Whenever there was any doubt as to whether a cycle was a decision cycle or a nondecision cycle, the cycle was regarded as being a decision cycle.

Data Collection

Each of the intersections chosen for this study was a four-legged, signal-controlled intersection in an urban area. At each intersection, each approach was perpendicular to the adjacent approaches or as close to perpendicular as possible. Nine of the 10 intersections were located in the central business district (CBD) of the city, and the 10th was in an urbanized section of the city a short distance from the CBD. Four of the intersections had ARIs; six did not.

At nine of the 10 intersections, data were collected on two days. At the 10th intersection data were collected on only one day. Each day, both the afternoon off-peak and the evening peak periods were observed. Afternoon off-peak data were collected between 12:30 and 3:00 p.m. The evening peak data were collected between 3:45 and 5:45 p.m. The observation periods were either 1.5- or 2-h long. Thus, each of the intersections observed on two days was observed for a minimum of 6 h and a maximum of 8 h. All data were collected on Monday, Tuesday, Wednesday, or Thursday.

At each intersection, the observer recorded the volume on the approach under consideration. The observer also recorded the direction taken by each of the vehicles as it left the intersection.

When the signal indication turned from amber to red for the approach under consideration, the observer started two hand-held stopwatches. If a vehicle crossed the intersection line (curb line extended) after the start of the red interval, one of the stopwatches was stopped when the vehicle's frontmost axle crossed the intersection line. If a second vehicle ran the red light, the second stopwatch was stopped by using the same criterion. The direction taken by each runner as he or she left the intersection was also recorded.

Note that the intersection line, rather than the stop line, was used as a reference line. This was done in order to maintain a constant reference line at all of the intersections. The distance from the stop line to the intersection line varied from 0 ft at one intersection to 40 ft at another, and drivers frequently stopped in the region between the two lines. Thus, many vehicles crossed the stop line after the start of the red interval but did not go through the intersection until the following green interval. However, virtually every time a vehicle crossed the intersection line during the red interval, it continued through the intersection. Thus, the intersection line was a better reference line.

Every 30 min the volume on the approach during the preceding 30 min was recorded, and the time was marked on the data-collection sheets. This made it possible to analyze all of the data in half-hour intervals. Table 1 shows the number of half-hour intervals observed and the number of runners observed at each intersection.

DATA ANALYSIS

All observed signal cycles were divided into two groups: decision cycles and nondecision cycles. A decision cycle is a signal cycle during which at least one vehicle is in the decision zone at the start of the amber interval. A nondecision cycle is a signal cycle during which no vehicles are in the decision zone at the start of the amber interval. During a nondecision cycle no driver has a chance to decide whether to stop or to continue through the intersection when the signal turns amber. Thus, a nondecision cycle is useless in an examination of how often drivers decide to use the red interval. For this reason, the nondecision cycles were eliminated from the data base before any analysis was performed.

In order to compare driver use of the red interval at the various intersections, the following equation was used:

$$P_r = (C_r/C_d) \times 100 \tag{5}$$

where

- P_r = percentage of decision cycles during which at least one vehicle crossed the intersection line after the start of the red interval,
- C_r = number of cycles during which at least one vehicle crossed the intersection line after the start of the red interval, and
- C_d = number of decision cycles.

The values of C_d, C_r, and P_r for each intersection may be found in Table 2.

t-Test: P_r at Intersections That Have ARIs Versus P_r at Intersections That Do Not Have ARIs

The concept that the presence of an ARI is correlated with increased driver use of the red interval was tested. The observed P_r values, in 30-min intervals, were divided into two groups. The first group was comprised of the observations made at intersections that had ARIs, and the second group was comprised of the observations made at intersections that had no ARIs. The mean P_r values of the two groups were then compared by means of the t-test.

The variances of the two samples are significantly different at $\alpha = 0.01$, so it was necessary to use the modified t-test. The results of the modified test, given in the table below, reveal that the difference is significant at $\alpha = 0.01$ between the two groups. Thus, the presence of an ARI is correlated with increased driver use of the red interval.

Intersections	No. of Half-Hour Intervals	Mean P_r	SD
Have ARIs	47	37.2	22.53
Do not have ARIs	84	27.6	13.76

Regression Analysis

A regression analysis was performed to determine the factors that are important in driver use of the red interval. Only geometric features of the intersections and traffic control factors were considered;

Table 1. Intersections observed and data collected.

City	Intersection	Approach	No. of Half-Hour Intervals Observed			No. of Runners
			Off-Peak	Peak	Total	
Hartford, CT	Farmington-Sigourney	Farmington eastbound	8	8	16	122
	Main-Gold	Main northbound[a]	8	7	15	94
	Ann-Asylum	Asylum westbound[a]	4	4	8	74
New Haven, CT	College-Elm	Elm eastbound	7	8	15	149
	Church-George	George eastbound[a]	6	6	12	53
	Church-Elm	Elm eastbound	8	6	14	128
	Chapel-Church	Church northbound[a]	6	6	12	216
Providence, RI	Dorrance-Weybosset	Weybosset eastbound	6	6	12	87
	Empire-Washington	Washington westbound	6	6	12	118
Worcester, MA	Main-Pearl-Mechanic	Main southbound	8	7	15	74
Total			67	64	131	1115

[a]Approach has ARI.

Table 2. Driver use of the red interval.

City	Intersection	Approach	No. of Decision Cycles, C_d	No. of Cycles Run, C_r	Percentage of Decision Cycles, P_r
Hartford, CT	Farmington-Sigourney	Farmington eastbound	330	98	29.7
	Main-Gold	Main northbound[a]	181	57	31.5
	Ann-Asylum	Asylum westbound[a]	147	62	42.2
New Haven, CT	College-Elm	Elm eastbound	289	106	36.7
	Church-George	George eastbound[a]	210	46	21.9
	Church-Elm	Elm eastbound	255	97	38.0
	Chapel-Church	Church northbound[a]	246	155	63.0
Providence, RI	Dorrance-Weybosset	Weybosset eastbound	368	81	22.0
	Empire-Washington	Washington westbound	413	105	25.4
Worcester, MA	Main-Pearl-Mechanic	Main southbound	325	62	19.1
Total			2764	869	31.4

[a]Approach has ARI.

factors that vary from vehicle to vehicle, such as vehicle speed, number of occupants, and sex of the driver were not considered.

A priori, seven variables were selected that could have some significant effect on driver use of the red interval:

1. Length of the ARI,
2. Volume on the approach under consideration,
3. Width of the approach under consideration,
4. Width of the crossing roadway,
5. Volume-to-capacity ratio for the approach under consideration,
6. Percentage of signals in that particular city that have an ARI, and
7. Distance from the stop line to the intersection line.

In order to determine the correlation between each of the predictor variables and P_r, and also to determine the correlations among the supposedly independent predictor variables, a correlation matrix was constructed. The matrix is shown in Table 3. Examination of the matrix reveals that the correlation between P_r and the width of the crossing roadway is statistically insignificant at α = 0.05, and so is the correlation between P_r and the percentage of signals in the city that have an ARI. The correlation between P_r and the length of the ARI is significant at α = 0.05 but not at α = 0.01. The remainder of the correlations between P_r and the predictor variables are significant at α = 0.01.

The best linear representation of the data is given by

$$P_r = -18.3 + 0.56W_a + (38.02V/C) \quad (6)$$

where W_a is the width of the approach under consideration (ft) and V/C is the volume-to-capacity ratio on the approach under consideration. An analysis of the partial regression coefficients is given below.

Variable	Partial Regression Coefficient	Confidence Interval at α = 0.05
W_a	0.56	0.228
V/C	38.02	22.695

Equation 6 leaves much of the variance unexplained and also has a considerable standard error. Thus, the equation should not be expected to accurately predict driver use of the red interval at a specific intersection. In addition, note that the data collected covered the ranges of the predictor variables as given in Table 4 and that extension of the equation beyond these limits is of questionable value.

Conspicuous by its absence from Equation 6 is the length of the ARI. As stated earlier, there is a significant correlation at α = 0.05 but not at α = 0.01 between P_r and the length of the ARI. This is solid, but not overpowering, evidence to suggest that the length of the ARI influences driver use of the red interval. However, in terms of predictive ability, the approach width and the volume-to-capacity ratio seem to be far superior to the length of the ARI.

In light of the results of the multiple linear regression, we thought that a nonlinear equation might give a better indication of the relation

Table 3. Correlation matrix.

Item	A	B	C	D	E	F	G	H
A	1.000	−0.1334	0.3394	0.3116	0.3509	0.2283	0.2550	0.1912
B		1.000	0.1090	0.5348	−0.0637	0.5244	−0.4967	0.4303
C			1.000	0.5152	−0.0245	−0.0702	−0.5010	0.0275
D				1.000	0.0756	0.3187	−0.5288	0.4676
E					1.000	0.4367	0.6243	0.2695
F						1.000	0.0727	0.3847
G							1.000	−0.0507
H								1.000

Notes: A = length of ARIs, B = volume on the approach under consideration (vehicles/h), C = width of the crossing roadway (ft), D = width of the approach under consideration (ft), E = distance from the stop line to the intersection line (ft), F = volume-to-capacity ratio, G = percentage of signals in the city that have an ARI, and H = P_r.

Table 4. Range of observed values of independent variables.

Variable	Range	Variable	Range
Length of ARI (s)	0.0-3.0	Volume-to-capacity ratio	0.43-0.98
Volume on approach (vehicles/h)	428-1738	Percentage of signals in the city that have an ARI	0-50
Width of approach (ft)	19-59		
Width of crossing roadway (ft)	34-62	Distance from stop line to intersection line (ft)	0-40

between P_r and the predictor variables. The following equation was used to test this concept:

$$P_r = a_0 x_1^{a_1} x_2^{a_2} x_3^{a_3} \ldots x_n^{a_n} \quad (7)$$

Equation 7 was then transformed by taking the logarithm of each side of the equation. Thus,

$$\log_{10} P_r = \log_{10} a_0 + a_1 \log_{10} x_1 + \ldots + a_n \log_{10} x_n \quad (8)$$

The multiple linear regression on the transformed data resulted in a poorer representation of the data than was found in the regression described by Equation 6. Therefore, the results of the regression on the transformed data are not included here.

t-Test: Off-Peak P_r Versus Evening Peak P_r

As mentioned earlier, each intersection was observed during off-peak conditions and also during evening peak conditions. The purpose of this part of the data analysis was to determine whether time of day affects the frequency of driver use of the red interval at a given intersection. The concept was tested by comparing the off-peak mean P_r at a given intersection to the evening peak mean P_r at the same intersection. The data, as before, were examined in 30-min intervals. The null hypothesis was tested by means of the t-test. The results of the test may be found in Table 5.

Examination of Table 5 reveals that, for each intersection, the variances are homogeneous at α = 0.05. At 7 of the 10 intersections, there is no significant difference between means at α = 0.05. At the remaining three intersections, the difference is significant at α = 0.05 but not at α = 0.01. Interestingly, at two of these three intersections, more drivers used the red interval during the peak period than during the off-peak period; however, at the third intersection, more drivers used the red interval during the off-peak period than during the peak period.

t-Test: Mean Timing at Intersections That Have ARIs Versus Mean Timing at Intersections That Do Not Have ARIs

A t-test was conducted to determine if the presence of an ARI coincides with drivers entering the intersection at a later time than they would if there was no ARI. Because driver use of the red interval was greater at intersections that had ARIs, we thought that the mean timing of the runners might be greater at intersections that had ARIs than at intersections that did not have ARIs. This concept was tested by means of the t-test.

The results of the test may be found in the table below. Examination of the table reveals that the variances are significantly different at α = 0.01, and that the modified t-test value is insignificant at α = 0.05.

Intersections	No. of Runners	Mean Timing (s)	SD
Have ARIs	357	1.20	0.71
Do not have ARIs	604	1.24	0.85

Thus, despite the evidence that the presence of an ARI coincides with increased driver use of the red interval, it apparently does not coincide with drivers entering the intersection at a later time after the start of the red interval.

t-Test: Comparison of Mean Timing by Direction and Conflict Level

The mean timing by direction and conflict level was tested to determine if there is a significant difference in mean timings between directions and between two classifications of conflict for left turns. The entire set of 961 runners was divided into four groups. One of the groups was comprised of the right-turn runners and a second group was comprised of the straight-through runners. Left-turn runners were stratified into two groups; the left turn without conflict group was comprised of runners who turned left from a one-way street onto a one-way street (and thus encountered no more conflict than did a runner making an ordinary right turn) and the left turn with conflict group was comprised of the remainder of the left-turn runners.

The mean timing for each of these groups was then compared with the mean timing of the other three groups. These comparisons were made by means of the t-test.

The results of the tests may be found in Table 6. Table 6 reveals that there is a significant difference at α = 0.01 between the mean timing for the through runners and the mean timing for each of the other groups. The difference between the mean timing for left runners without conflict and the mean timing for right runners is significant at α = 0.05 but not at α = 0.01. The difference between the mean timings for the left runners with conflict and the mean timing for right runners is not significant at α = 0.05.

Further examination of Table 6 reveals that through runners have the lowest mean timing and are

Table 5. Variation in P_r with time of day.

Intersection	Period	No.	Mean P_r	SD	SE	F	t-Test	Result
Farmington-Sigourney	Off-peak	8	17.2	11.27	3.98	2.31	2.37	Significant at $\alpha = 0.05$
	Peak	8	34.4	17.13	6.06			
Main-Gold	Off-peak	8	26.8	14.05	4.97	2.82	0.05	Insignificant at $\alpha = 0.05$
	Peak	7	26.3	23.62	8.93			
Ann-Asylum	Off-peak	4	34.1	17.95	8.97	2.98	1.66	Insignificant at $\alpha = 0.05$
	Peak	4	51.3	10.40	5.20			
College-Elm	Off-peak	7	45.2	15.84	5.99	3.76	2.86	Significant at $\alpha = 0.05$
	Peak	8	27.0	8.17	2.89			
Church-George	Off-peak	6	23.8	12.75	5.20	1.17	0.71	Insignificant at $\alpha = 0.05$
	Peak	6	18.8	11.80	4.82			
Church-Elm	Off-peak	8	36.6	8.26	2.92	1.39	0.25	Insignificant at $\alpha = 0.05$
	Peak	6	37.8	9.73	3.97			
Chapel-Church	Off-peak	6	61.4	18.34	7.49	2.71	0.32	Insignificant at $\alpha = 0.05$
	Peak	6	64.2	11.14	4.55			
Dorrance-Weybosset	Off-peak	6	24.4	5.98	2.44	1.97	1.19	Insignificant at $\alpha = 0.05$
	Peak	6	19.4	8.39	3.42			
Empire-Washington	Off-peak	6	22.8	12.16	4.96	3.38	0.88	Insignificant at $\alpha = 0.05$
	Peak	6	27.8	6.61	2.70			
Main-Pearl-Mechanic	Off-peak	8	13.4	8.30	2.93	2.30	2.23	Significant at $\alpha = 0.05$
	Peak	7	25.5	12.60	4.75			

Table 6. Comparison of mean timings by direction and conflict level.

Direction Conflict Level	No.	Mean Timing (s)	SD	SE	F	t-Test	Modified t-Test		Result
							θ (°)	d	
Left turn without conflict	163	1.31	0.789	0.062	1.81		50	0.19	Insignificant at
Left turn with conflict	146	1.33	1.061	0.088					$\alpha = 0.05$
Left turn without conflict	163	1.31	0.789	0.062	1.56		56	3.36	Significant at
Straight through	487	1.08	0.645	0.029					$\alpha = 0.01$
Left turn without conflict	163	1.31	0.789	0.062	1.22	2.15			Significant at
Right turn	165	1.50	0.871	0.068					$\alpha = 0.05$
Left turn with conflict	146	1.33	1.061	0.088	2.71		60	2.70	Significant at
Straight through	487	1.08	0.645	0.029					$\alpha = 0.05$
Left turn with conflict	146	1.33	1.061	0.088	1.48		49	1.53	Insignificant at
Right turn	165	1.50	0.871	0.068					$\alpha = 0.05$
Straight through	487	1.08	0.645	0.029	1.83		57	5.68	Significant at
Right turn	165	1.50	0.871	0.068					$\alpha = 0.01$

followed in ascending order by left runners without conflict, left runners with conflict, and right runners.

CONCLUSIONS

The results of the analyses of the field data may be summarized as follows. In answer to the three questions posed earlier,

1. More drivers ran the red light at intersections that had ARIs than at intersections that had no ARIs. At the intersections studied, the difference is significant in the frequency of driver use of the red interval between intersections that had ARIs and intersections that had no ARIs. This difference is found to be significant, by means of the modified t-test, at $\alpha = 0.01$.
2. The length of the ARI appeared to be correlated with driver use of the red interval. The simple correlation between the length of the ARI and the frequency of driver use of the red interval is significant at $\alpha = 0.05$ but not at $\alpha = 0.01$. (The simple correlation between frequency of driver use of the red interval and each of four other predictor variables, however, was significant at $\alpha = 0.01$).
3. Apparently drivers did not run the red light longer after the start of the red interval at intersections that had ARIs than at intersections that have no ARIs. At the intersections studied, the difference in the mean timings between intersections that had ARIs and intersections that had no ARIs is not significant at $\alpha = 0.05$. In fact, the mean timing at intersections that had no ARIs is slightly higher than the mean timing at intersections that had ARIs.

These conclusions must be viewed with caution, however, for the following reasons. Only 10 intersections in four different cities were studied. Some factors that influence driver's use of the red interval might not have been studied during this project. For example, the type of phase following the observed phase (such as a pedestrian phase or the crossing street green phase) may very well influence driver use of the red interval. Also, at intersections that had ARIs, drivers may have used the red interval as frequently before the implementation of the ARI as afterward. In fact, it is possible that use of the red interval by drivers was the reason that the ARI was implemented in the first place.

These results raise some interesting questions. If it is indeed true that people treat the ARI merely as an extension of the amber, two potentially serious problems present themselves:

1. If a driver gets accustomed to having ARIs, and to taking advantage of them, he or she may try to take advantage of the ARI at an intersection where no ARI exists.

2. If a driver gets accustomed to being able to safely enter an intersection after the start of the red interval, at least a portion of the traffic signal's authority is diminished for that driver.

The implications of the second potential problem are somewhat less tangible but are just as serious as the implications of the first potential problem. Each driver on a street risks his or her life on the assumptions that all other drivers obey the signs and traffic signals used to control traffic and that all other drivers accept those signs and signals as the absolute authority over their travel.

If the authority of these signs and signals is reduced in some way (such as suggested above), and some drivers begin to treat the signs and signals contemptuously, the law-abiding driver takes a bigger risk each time he or she enters an intersection.

The effects of this potential problem would be difficult, if not impossible, to quantify, and the use of the ARI may do more good than harm. Indeed, many traffic engineers can quickly cite instances in which use of an ARI at a particular intersection has led to reductions in accident levels. Nonetheless, the potential problems listed here should be considered.

In conclusion, these results should not indicate to the reader that the use of ARIs should be abolished or even limited. The number of intersections studied is simply not large enough to make such a sweeping conclusion. However, these results indicate that a problem may exist and that more research should be done in this area.

In addition to the major findings of this report, the following results were also obtained from the data analyses. There is no evidence to suggest that driver use of the red interval is greater during peak hours than during off-peak hours. In fact, at 4 of the 10 intersections studied, driver use of the red interval was greater during off-peak hours than during peak hours. Right-turn runners had the highest mean timing. They were followed, in descending order, by left-turn-with-conflict runners, left-turn-without-conflict runners, and straight-through runners.

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Discussion

Peter S. Parsonson

Worldwide concern is mounting that drivers may be becoming increasingly disobedient of the red signal (1). The authors have addressed an important and timely topic. The first conclusion of the paper is that more drivers ran the red light at intersections that had ARIs than at intersections that had no ARIs. The authors concluded that, if their 10 intersections are indicative of all signalized locations, then a potentially serious problem presents itself.

One difficulty with these results is that the paper does not report the length of the yellow interval at any of the intersections; neither are the approach speeds stated. So, for all the reader is told, the yellow intervals could have been shorter at those intersections that use all-red, and that could be the reason that more drivers ran the red signal at those intersections.

Ryan has said in response to queries that he did not know whether the yellow intervals were identical at the 10 intersections and in fact had not measured them. However, the paper states that "the longest amber interval at the observed intersections was 3.6 s," so it appears that the yellow intervals are in fact known.

As the paper stands, it is hard to see how the interested reader can find any assistance whatever with a problem in timing the intergreen period, as the British call it. It would be helpful if the authors would state the yellow times and compare them with the minimum calculated as

$$y = t + (V/2a \pm 64.4g) \quad (9)$$

where

- y = minimum yellow time (s);
- t = perception-reaction time of driver (s); the standard value is 1 s;
- v = approach speed (ft/s);
- a = deceleration rate (ft/s²), currently taken to be 10 (2,3); and
- g = percent of grade divided by 100 (added for upgrade and subtracted for downgrade).

This equation was proposed by the discussant previously (2) as the minimum yellow to ensure that drivers need not enter on the red.

Authors' Closure

In this discussion, Parsonson raises several valid points. Certainly, the length of the amber interval at each intersection is important, and a computation of the adequacy of the amber interval would also be of interest.

The length of the amber interval was observed at each intersection. Table 7 shows the length of the amber interval, the length of the ARI, and P_r for each intersection. The length of the amber interval and the length of the ARI are average values; some variation in the lengths of these intervals was observed at several of the intersections.

Casual examination of Table 7 does not appear to indicate a relation between P_r and length of the amber interval. Statistical analysis might, of course, yield a different result.

Further examination of Table 7 reveals that the longest amber interval observed was 3.5 s, instead of the 3.6 s reported earlier. The text has been corrected in regard to this point. Since this value was not used in any of the statistical analyses, none of the results are affected by this correction.

Unfortunately, we could not obtain speed data along with the driver behavior data, because only one observer studied each intersection. Because of this, we cannot use the equation suggested by Parsonson to check the adequacy of the amber interval.

Parsonson is correct when he states that the paper does nothing to assist the reader with timing of the intergreen period. However, it was not the intent of this research to investigate the timing of that period. Rather, it was to investigate driver use of the ARI, and specifically to investigate the three questions stated in the paper's introduction.

Table 7. Driver use of the red intervals.

City	Intersection	Approach	Length of Amber Interval (s)	Length of ARI (s)	Percentage of Driver Use, P_r
Hartford, CT	Farmington-Sigourney	Farmington eastbound	3.0	0.0	29.7
	Main-Gold	Main northbound	2.6	1.6	31.5
	Ann-Asylum	Asylum westbound	3.0	3.0	42.2
New Haven, CT	College-Elm	Elm eastbound	3.4	0.0	36.7
	Church-George	George eastbound	3.5	2.8	21.9
	Church-Elm	Elm eastbound	3.4	0.0	38.0
	Chapel-Church	Church northbound	3.2	1.8	63.0
Providence, RI	Dorrance-Weybosset	Weybosset eastbound	2.7	0.0	22.0
	Empire-Washington	Washington westbound	3.0	0.0	25.4
Worcester, MA	Main-Pearl-Mechanic	Main southbound	3.4	0.0	19.1

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Comparison of Signs and Markings for Passing and No-Passing Zones

RICHARD W. LYLES

An experiment was undertaken to examine the relative effectiveness of five pavement marking and signing sequences for informing motorists of passing and no-passing zones on rural two-lane, two-way rural roads. Treatments included (a) standard pavement markings, (b) pavement markings plus standard regulatory signing, (c) pavement markings plus no-passing pennants, and (d) and (e) two combinations of regulatory signs and pennants. Data were collected on overtaking and passing vehicles by two observers in a staged vehicle that traveled over a measured length of roadway. The principal findings were that the addition of any sign sequence to pavement markings resulted in motorists being appreciably more observant of the passing and no-passing zones and spending less time in the passing (opposing) lane. Less conclusive evidence was presented in support of the more emphatic and informative sequences that resulted in progressively more compliance with the marked zones.

Overtaking and passing maneuvers are two of the most common sources of conflict between two or more vehicles on two-lane, two-way rural roads. Numerous possibilities exist for collision, including rear-end, sideswipe, and, most dangerous, head-on. Drivers, in overtaking and passing another vehicle, depend on a number of visual cues to ascertain whether such maneuvers can be completed safely. In addition to checking for oncoming traffic and gauging the speed of both any oncoming vehicles within sight and the vehicle to be overtaken and passed, the driver also uses the information provided by pavement markings and roadside signs to ascertain the advisability of the maneuver--Is he or she in a marked passing zone, how much of the passing zone remains, and so forth. Signs and marking can clearly provide considerable guidance to the motorist in making judgments about the relative safety of passing maneuvers. Despite the presumed importance of the signs and markings for passing and no-passing zones, there appears to be a considerable range in how such devices are, or should be, used in practice [see, for example, Nickerson, (1) and Weaver and others (2)].

In the context described above, the basic objective of the research described herein was to evaluate several alternatives for roadside signing, relative to traditional pavement markings, for indicating passing and no-passing zones.

STUDY METHODOLOGY

Many traffic situations lend themselves to straightforward examination; for example, vehicles approaching a specified intersection or other potentially hazardous situation can be observed or tracked by using sensors on the road surface and appropriate electronic equipment (3) with the acquired data being used to calculate vehicle speeds at certain points on the approach to the hazard. The result is that fairly extensive sets of data can be obtained in a relatively short time, even in low-volume situations. By contrast, overtaking and passing maneuvers are dynamic in nature and, hence, more difficult to document relative to where certain events took place. Alternative methods for documenting such maneuvers include the use of film or videotape, isolation of one specific passing or no-passing zone, or use of some sort of mobile data-collection device.

For a variety of reasons, including equipment availability and the explicit capability to use several different zones, a mobile data-collection device was selected in this instance. The basic approach was to have a staged vehicle (Jeep Wag-