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Title: **Effect of Yellow Interval Timing on Red-Light Violation Frequency at Urban Intersections**

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ABSTRACT

Statistics indicate that red-light-running has become a significant safety problem throughout the United States. It is estimated that about 200,000 red-light-running-related collisions occur at signalized intersections in the U.S. each year. There is a wide range of potential countermeasures to the red-light-running problem. The objective of this research is to quantify the effectiveness of an increase in yellow interval duration as an engineering countermeasure to red-light violations.

A before-after study is described and the resulting data used to quantify the effect of increasing the yellow interval on the frequency of red-light violations. Based on this research, it was concluded that: (1) an increase of 0.5 to 1.5 s in yellow duration (such that it does not exceed 5.5 s) will decrease the frequency of red-light-running by at least 50 percent; (2) drivers do adapt to the increase in yellow duration; however, this adaptation does *not* undo the benefit of an increase in yellow duration; and (3) increasing a yellow interval that is shorter than that obtained from a proposed recommended practice published by the Institute of Transportation Engineers (ITE) is likely to yield the greatest return (in terms of a reduced number of red-light violations) relative to the cost of re-timing a yellow interval in the field.

INTRODUCTION

Statistics indicate that red-light-running has become a significant safety problem throughout the United States. Retting et al. (*1*) report that about one million collisions occur at signalized intersections in the U.S. each year. Of these collisions, Mohamedshah et al. (*2*) estimate that at least 16 to 20 percent can be attributed directly to red-light-running. Retting et al. also report that motorists involved in red-light-running-related crashes are more likely to be injured than those in other crashes.

There is a wide range of potential countermeasures to the red-light-running problem. These countermeasures are generally divided into two broad categories: engineering countermeasures and enforcement countermeasures. Enforcement countermeasures are intended to encourage drivers to adhere to the traffic laws through the threat of citation and possible fine. In contrast, engineering countermeasures (which include any modification, extension, or adjustment to an existing traffic control device) are intended to reduce the chances of a driver being in a position where he or she must decide whether or not to run the red indication. Studies by Retting et al. (*1*) have shown that countermeasures in both categories are effective in reducing the frequency of red-light-running. However, most of the research conducted to date has focused on the effectiveness of enforcement; less is known about the effectiveness of many engineering countermeasures.

The objective of this research is to quantify the effectiveness of an increase in yellow interval duration as an engineering countermeasure to red-light violations. Initially, this paper examines the characteristics of a red-light violation. Then, the role of yellow duration as an engineering countermeasure is discussed. Next, a before-after study is described and the resulting data used to quantify the effect of increasing the yellow interval on the frequency of red-light violations. Finally, some conclusions are offered regarding (1) the conditions where a change in yellow duration should be considered and (2) the appropriate value of this interval.

BACKGROUND

Characterizations of a Red-Light Violation

A red-light violation can be characterized by "driver decision type," "driver intent," and by "entry time of the red-light-running driver." The relationship between these characteristics is shown in Table 1. The characterizations are based on discussions by Milazzo et al. (*3*) and by Bonneson et al. (*4*).

Driver Decision Type describes the basis for the driver's decision to run the red indication. An "avoidable" red-running event is committed by a driver who believes that it is possible to safely stop but decides it is in his or her best interest to run the red indication. In contrast, an "unavoidable" event is committed by a driver who either (1) believes that he or she is unable to safely stop and consciously decides to run the red, or (2) is unaware of the need to stop. Frequent "avoidable" red-light violations may be an indication of excessive delay or a degradation in driver respect for traffic laws.

TABLE 1 Characterization of a Red-Light Violation

Driver Decision Type	Possible Scenario	Driver Intent Regarding Violation [1, 2]	
		Intentional	**Unintentional**
"Avoidable"	Congested, Cycle overflow	Frequent cause of RLR, especially in the first few seconds of red.	n.a.
"Unavoidable"	Incapable of stop, Inattentive	Frequent cause of RLR, especially in the first few seconds of red.	Occasional Cause of RLR; occurs at any time.
Common Crash Consequences:		Left-turn-related crash <u>if</u> left-turns are not provided a protected phase.	Right-angle crash.
Percent of RLR-Related Crashes:[3]		20 %	80 %

Notes:
1 - n.a. - not applicable.
2 - RLR: red-light running.
3 - Based on crash data reported by Milazzo et al. (*3*, p. 33)

Driver Intent regarding the red-light violation subdivides the "unavoidable" driver decision category into two types: "intentional" and "unintentional." An unavoidable, intentional red-light violation occurs if the driver sees the signal indication (as yellow or red) but determines that it is impossible to stop safely before reaching the intersection. In contrast, an unavoidable, unintentional violation occurs when the driver is inattentive and does not see the signal. Unavoidable, intentional red-light violations may be an indication of an inadequate yellow interval duration or excessive speed. Unavoidable, unintentional red-light violations may be an indication of poor signal visibility.

Entry Time (of the red-light-running driver) relates to the time that the driver enters the intersection after the onset of the red indication. When drivers enter late into the red, it may be an indication of deficiencies in signal visibility or driver sight-distance along the intersection approach. When drivers enter in the first few seconds of red, it may be an indication of frustration due to excessive delay, an inadequate yellow interval duration, or excessive speed. It may also be an indicator of driver indifference to the traffic laws regarding the red indication.

Entry Time is also correlated with crash frequency and type. Milazzo et al. (*3*) found that red-light-related crashes are more frequent when the red-light-runner enters several seconds after the end of the yellow interval. Fortunately, about 85 percent of all red-light-runners enter the intersection within the first 1.5 s of red (*5*) so the frequency of red-light-related crashes is relatively low. Milazzo et al. (*3*) have also found that the few red-light-related crashes that do occur within the first few seconds of red are almost always between left-turning vehicles and opposing through vehicles (i.e., left-turn-related crashes). In these situations, the left-turning driver is attempting to clear the intersection at the end of the adjacent through phase and an opposing through driver runs the red indication (this scenario exists when protected-only left-turn phasing is not provided).

Yellow Interval Duration

A commonly used equation for calculating the duration of the yellow interval is that proposed by the Institute of Transportation Engineers' (ITE) Technical Committee 4A-16 as a recommended practice (*6*). This equation is:

$$Y(v) = T_{pr} + \frac{V_a}{2\,d_r + 2\,g\,G_r} \tag{1}$$

where:
$Y(v)$ = yellow interval evaluated at speed $V_a = v$, s;
d_r = deceleration rate, use 10 ft/s^2;
g = gravitational acceleration, use 32.2 ft/s^2;
G_r = approach grade, ft/ft;
T_{pr} = driver perception-reaction time, use 1.0 s; and
V_a = speed of vehicle approaching the intersection (typically the 85th percentile speed), ft/s.

For level intersection approaches, this equation yields yellow interval durations that range from 3.2 s at 30 mph to 5.0 s at 55 mph.

The yellow interval duration is generally recognized as being highly correlated with the frequency of red-light violations that occur during the first seconds of red. Van der Horst and Wilmink (*7*) have found that a 1-s increase in yellow (i.e., from 3 to 4 s in urban areas and 4 to 5 s in rural areas) reduced red-light violations by 50 percent. In a more recent study of red-light violations at 10 intersections, Retting and Green (*8*, p. 6)) also found that "...red-light compliance can be increased by lengthening yellow signals...".

Several researchers have suggested that yellow interval duration should be based on the probability of stopping (*7, 9*) rather than Equation 1. These researchers recommend that the yellow interval should be based on the 85th (or 90th) percentile driver's travel time to the stop line. This approach is illustrated in Figure 1 where the trends shown suggest that a yellow interval of 4.2 s is sufficient for 85 percent of drivers. Only 15 percent of drivers would choose to run the red indication if they are more than 4.2-s travel time from the stop line at the onset of yellow and are in the "first-to-stop-position" as they approach the intersection.

Van der Horst and Wilmink (*7*) have noted that long yellow intervals can lead to bad behavior because the last-to-stop drivers are not "rewarded" with a red indication as they arrive at the stop line. Instead, the yellow remains lit as they roll up to the stop line. These drivers may be more inclined not to stop the next time they approach the intersection. Several researchers have found that drivers adjust their stopping behavior to offset the effect of longer change intervals (*7, 8*). This behavior is illustrated in Figure 2 and is based on the data reported by Van der Horst and Wilmink (*7*).

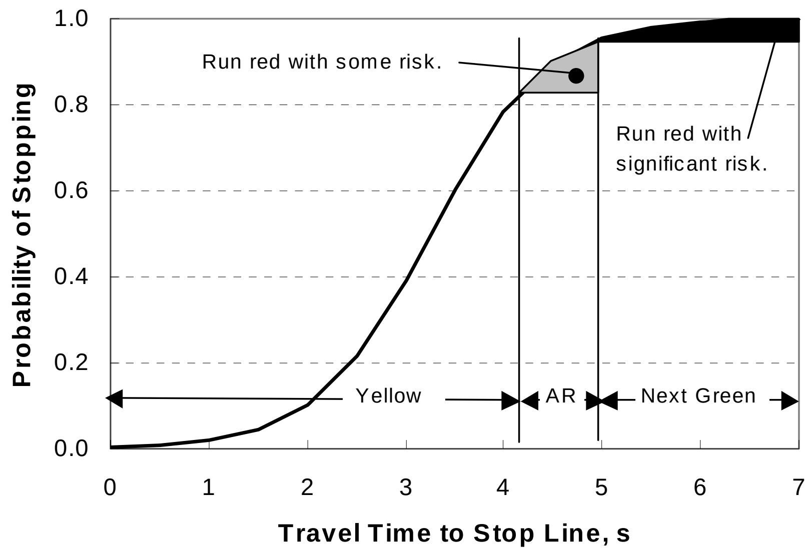

FIGURE 1 Relationship between probability of stopping and yellow interval duration.

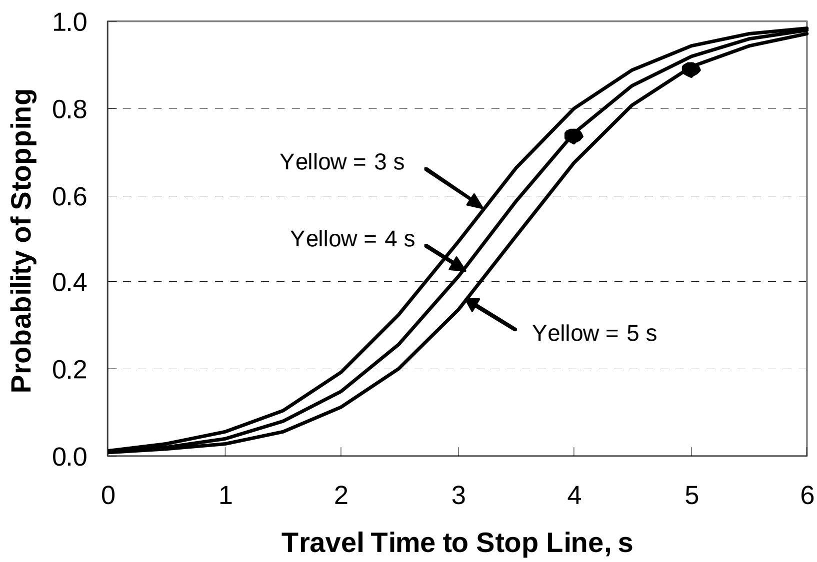

FIGURE 2 Probability of stopping as a function of travel time and yellow duration.

Figure 2 indicates that the probability of stopping curve shifts about 0.2 s to the right for a 1.0-s increase in yellow interval duration. This shift correlates to a reduction in the probability of stopping for a given travel time. However, in spite of this driver adjustment (or shift), the curves indicate that there is still a benefit from an increase in yellow duration. Specifically, the curves suggest that 25 percent of drivers would choose to run the red indication if they are more than 4.0-s travel time from the stop line at the onset of a 4.0-s yellow interval. In contrast, only 10 percent of drivers would run the red if they are 5.0 s from the stop line at the onset of a 5.0-s yellow interval.

ENGINEERING COUNTERMEASURES

A range of engineering countermeasures are available to address red-light violations and related crashes. A fairly thorough synthesis of the effectiveness of many countermeasures is provided in Reference 10. This document categorizes countermeasures in terms of whether they improve signal visibility, improve signal conspicuity, increase the likelihood of stopping, address intentional violations, or eliminate the need to stop. Increasing the yellow change interval is one countermeasure that addresses intentional violations. It is the subject of this paper.

Clues to Countermeasure Selection

The information in Table 1 can be used to guide the selection of countermeasures. For example, an avoidable red-running event is likely committed by a driver who is frustrated by excessive delay or congested flow conditions. This driver may also be indifferent to traffic laws. Short of major resource investments to increase capacity, enforcement countermeasures are likely to be the most effective means of curbing this driver's inclination to run the red indication.

An unavoidable event is likely to be committed by a driver who is incapable of stopping (e.g., due to a poorly judged downgrade or relatively high speed) or just inattentive (i.e., does not see the traffic signal). This event may also be precipitated when the yellow interval is not sufficiently long as to give drivers time to reach the intersection when they are at a distance within which they can not comfortably stop. Engineering countermeasures, such as a longer yellow interval or a more visible signal indication, are likely to be the most effective means of helping these drivers avoid red-light-running.

The information in Table 1 suggests that efforts to improve driver attention (such that unintentional red-light violations are reduced) are likely to be more effective at reducing red-light-related crashes. In contrast, efforts to increase yellow interval duration or to reduce driver speed are very likely to be effective at reducing red-light violations (*7, 8)*; however, they are likely to have a more modest effect on red-light-related crashes. This latter effect was recently confirmed by Retting et al. (*11*). They found that an increase in change interval (i.e., yellow and all-red intervals combined) reduced reportable crashes by about 8 percent (based on a study of 40 intersections).

Countermeasures to Be Evaluated

Based on a review of available countermeasures and discussions with traffic engineers, it was determined that the effectiveness of several countermeasures should be evaluated with field data. The study of one of these countermeasures, "increase the yellow interval duration," is the subject of this paper. Other countermeasures evaluated include: improve signal coordination, improve signal operation, improve visibility of signal through use of back plates, and improve conspicuity of signal through use of LED indications. Findings from the study of these countermeasures is provided by Bonneson et al. (*4*)

FIELD STUDY PLAN

Study Site Characteristics

The selection of study sites (one intersection approach is a "site") was based on a search for typical intersections that were not previously identified as having a problem with red-light-running. Twenty sites were selected representing ten intersections in five Texas cities. The characteristics of each intersection are listed in Table 2. The eight sites in the cities of Richardson and College Station were selected for the before-after study of yellow interval duration.

Data Collection

One objective of the research was to evaluate the effect of a increase in yellow interval duration on the frequency of red-light-running. To achieve this objective, a before-after study design process was used. Each "before" study and each "after" study included the collection of six hours of traffic flow data on each intersection approach. At each site, the "after" study was conducted six months after the yellow increase was implemented. Details of the study design are described by Bonneson et al. (*4*).

TABLE 2 Intersection Characteristics

City	Intersection[1]	Characteristic		
		Study Sites[2] (Approach)	Cycle Length[3], s	Advance Detection
Mexia	Bailey St. (F.M. 1365) & Milam St (U.S. 84)	EB, WB	75	No
	S.H. 14 & Tehuacana Hwy (S.H. 171)	EB, WB	37-66	No
College Station	Texas Ave. (S.H. 6) & G. Bush Dr. (F.M. 2347)	NB, SB	89-131	No
	College Main & University Dr. (F.M. 60)	EB, WB	110	No
Richardson	Plano Road & Belt Line Road	SB, EB	75-108	No
	Greenville Ave. & Main Street	SB, EB	69-111	No
Corpus Christi	F.M. 2292 & S.H. 44	EB, WB	57-156	Yes
	U.S. 77 & F.M. 665 (City of Driscoll)	NB, SB	42-86	Yes
Laredo	Loop 20 & Los Presidentes	NB, SB	90	No
	U.S. 83 & Prada Machin	NB, SB	53-90	Yes

Notes:
1 - North-south street is listed first.
2 - A "site" is defined as one intersection approach. NB: northbound; SB: southbound; EB: eastbound; WB: westbound.
3 - Cycle length range represents the 15th and 85th percentile values observed at the site on one day.

Characteristics of the intersection approaches studied are listed in Table 3. The data in this table indicate that the study sites collectively offer a reasonable range of speeds, grades, and all-red interval durations.

TABLE 3 Study Site Characteristics

City	Study Site	Characteristics					
		Speed Limit, mph	Approach Lanes	Grade, [1] %	Yellow Interval [2], s	All-Red Interval, s	Signal Head Type [3]
College Station	NB Texas Ave.	40	3	0.0	3.5 (5.0)	1.0	bulb
	SB Texas Ave.	40	3	-0.5	3.5	2.0	bulb
	EB University Dr.	35	3	+0.5	3.2 (4.0)	1.0	bulb
	WB University Dr.	35	3	+0.2	3.2 (4.1)	1.0	bulb
Richardson	SB Plano Road	40	3	+0.5	4.4 (5.0)	2.0	bulb
	EB Belt Line Road	35	3	0.0	4.0 (4.6)	2.5	bulb
	SB Greenville Ave.	30	3	+0.5	3.6 (4.2)	2.0	bulb
	EB Main Street	30	2	0.0	3.7	2.0	bulb

Notes:
1 - Grade: plus (+) grades are upgrades in a travel direction toward the intersection.
2 - Where pairs of values are listed, the first corresponds to the "before" period and that in parentheses corresponds to the "after" study. Where a single value is listed, the value was used for both the "before" and the "after" study.
3 - Signal head type: all indications studied use incandescent bulb lighting.

The information in column 6 of Table 3 indicates the extent of the increase in yellow interval duration at each study site. The increases ranged from 0.6 s to 1.5 s, with the average increase being 0.8 s. The yellow interval at one site in each city was not changed. This site served as a comparison site. The amount by which the yellow interval was increased was not based on an examination of the adequacy of the site's existing yellow interval duration. Rather, the increase was guided by a desire not to disrupt signal coordination and not to have any yellow interval exceed 5.5 s.

DATA ANALYSIS

Database Summary

The database assembled for the study of yellow interval duration included traffic events observed during 3370 signal cycles at eight intersection approaches. During these cycles, 276 vehicles entered the intersection after the change in signal indication from yellow to red. The average violation rate for the intersections studied is 0.9 red-light violations per 10,000 veh-cycles. No crashes were observed during 240 hours of observation. A detailed summary of the database is provided by Bonneson et al. (*4*).

Entry Time of the Red-Light-Running Driver

Entry Time Distribution

The time after the end of the yellow interval at which the red-light-runner enters the intersection is logically correlated with the potential for a right-angle collision. As this "time into red" increases, crash frequency is also likely to increase. The extent to which a red-light-runner enters after the end of the yellow interval is shown in Figure 3. Also shown is the extent to which a red-light-runner enters after the end of all-red. The data shown in this figure represent observations at all 20 study sites (not just the eight sites for which yellow interval duration were studied).

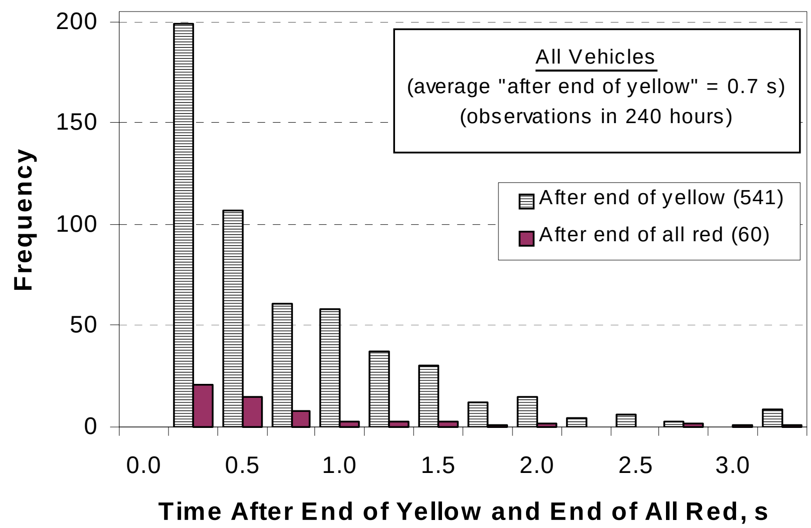

FIGURE 3 Frequency of red-light-running as a function of time into red.

The trends in Figure 3 indicate that more than one-half of the red-light-running occurred in the first 0.5 s of red. The average red-running driver entered about 0.7 s after the end of the yellow interval. About 80 percent of the drivers entered within 1.0 s after the end of the yellow, which is consistent with the trend reported by Farraher et al. (*5*). Also shown in this figure is the frequency of red-light violations based on the time after the end of the all-red interval. About 80 percent of these drivers entered within 1.0 s after the end of the all-red interval. The most flagrant driver entered 14 s after the all-red interval ended.

Driver Adaptation to Yellow Duration

There is speculation among engineers that lengthy yellow intervals may be abused by some drivers (*7, 8*). Specifically, it is believed that drivers adapt to an increase in the yellow duration and continue to run the red indication with the same frequency as before the increase. This issue was examined by comparing the distributions of entry time before and after the yellow interval increase. The results of this examination are shown in Figure 4.

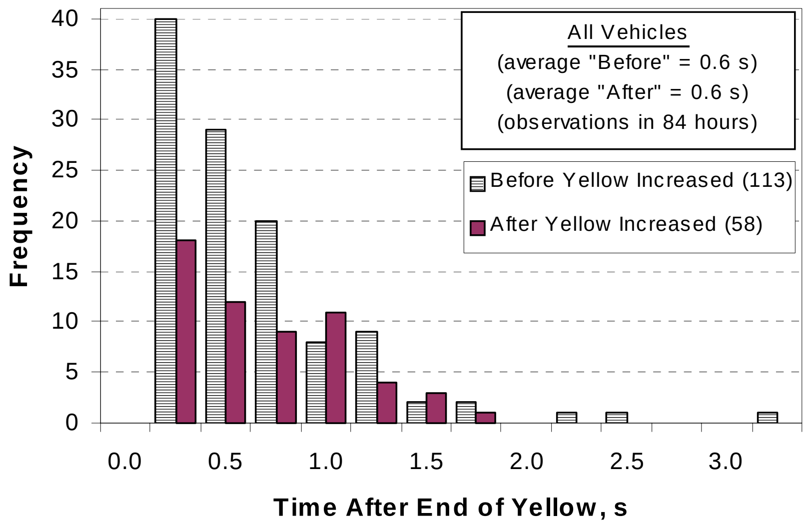

FIGURE 4 Effect of an increase in yellow interval duration on the frequency of red-light-running.

The trends in Figure 4 indicate that the increase in yellow duration had the desired effect of decreasing the frequency of red-light-running (from 113 red-runners during the "before" study to 58 red-runners during the "after" study). The average time of entry into the red is the same (0.6 s) for both study periods.

The data in Figure 4 were examined more closely to explore the effect of an increase in yellow duration on driver behavior. An examination of the "before" data suggested that only 18 vehicles would have run the red had the longer yellows been implemented during the "before" study. Thus, longer yellow intervals should reduce red-light violations by 84 percent (= 100 - 18/113 ×100). However, examination of the "after" data revealed that: (1) the number of vehicle-cycles of exposure had increased by 7.2 percent in the "after" period, and (2) 58 violations were actually observed in the after period (not 18). After conversion of the 113 violations to an equivalent "after" count, the actual reduction due to the increased yellow interval was 52 percent (= 100 −58/113 ×100/1.072).

The fact that 58 violations occurred in the "after" period when only 19 (=18/1.072) should have occurred indicates that drivers do adapt to an increase in yellow duration. However, the yellow increases at the study sites still reduced overall red-light violations by about 50 percent.

Examination of a Common Yellow Interval Equation

This section examines the relationship between red-light-running and the yellow interval duration computed using Equation 1. The results of this examination are shown in Figure 5. The data shown in this figure represent observations at all 20 study sites (not just the eight sites for which yellow interval duration were studied).

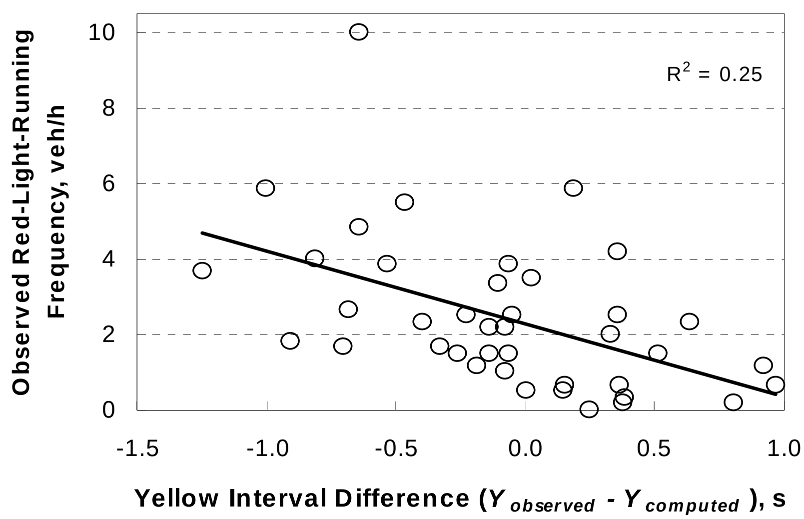

FIGURE 5 Red-light-running frequency as a function of yellow interval difference.

The data in Figure 5 indicate that there is a trend toward more red-light-running when the observed yellow duration is shorter than the computed duration. A regression analysis of the relationship between yellow interval difference and red-light-running frequency indicated that the relationship is statistically significant (i.e., p = 0.001). A similar relationship was previously reported by Retting and Greene (*8*) in an examination of red-light violations at 10 intersections.

The trend line shown in Figure 5 indicates that there is a benefit to insuring that yellow intervals are at least as long as that obtained from Equation 1. It would appear that the yellow duration obtained from Equation 1 is likely to yield a nominal 2.0 red-light violations per hour. There may be some additional benefit to yellow intervals that are slightly longer than that computed using Equation 1. It is likely that the drivers benefitting from this “extra” yellow are those that have an exceptionally long reaction time, speeds in excess of the 85th percentile speed, or low toleration for high deceleration rates.

Evaluation of Increased Yellow Duration

This section describes a formal statistical analysis of the before-after data. Initially, the statistical analysis methods are described. Then, the statistical tests for comparing red-light-running frequencies during the "before" and "after" periods is described. Finally, the effects of the yellow interval increase are quantified and the findings discussed.

Statistical Analysis Method

Hauer (*12*) and others have observed that intersections selected for safety improvements are often in a class of "high-crash" locations. As a consequence of this selection process, these intersections tend to exhibit significant crash reductions after specific improvements are implemented. While the observed reduction is factual, it is not typical of the benefit that could be derived from the improvement if it were applied to other locations. Hauer advocates the use of the empirical Bayes method to more accurately quantify the true crash reduction potential of a specific improvement or countermeasure.

The empirical Bayes method is extended in this research to the analysis of red-light-running frequency. This method provides an unbiased estimate of the red-light-running frequency in the "before" period. This estimate is based on a weighted combination of the observed frequency of red-light-running during the "before" period x and the predicted red-light-running frequency $E[R]$. The estimate obtained in this manner $E[R|x]$ is a more accurate estimate of the expected red-light-running frequency at the subject approach than either of the individual values (i.e., $E[R]$ or x). The following equations were used to compute $E[R|x]$:

$$E[R|x] = E[R] \times weight + \frac{x}{H} \times (1 - weight) \qquad \textbf{(2)}$$

with,

$$weight = \left(1 + \frac{E[R]\, H}{9.0} \right)^{-1} \qquad \textbf{(3)}$$

where,
$E[R|x]$ = expected red-light-running frequency given that x were observed in H hours, veh/h;
x = observed red-light-running frequency in the "before" period, veh;
H = time interval during which x was observed, h; and
weight = relative weight given to the prediction of expected red-light-running frequency.

The predicted red-light-running frequency $E[R]$ was obtained from the following equation:

$$E[R] = \frac{Q}{C} \frac{1}{0.927} \ln\left[1 + e^{(2.30 - 0.927Y - 0.334Bp + 0.0435V - 0.0180L_p + 0.220R_p)}\right] \qquad \textbf{(4)}$$

where:
$E[R]$ = expected red-light-running frequency, veh/h;
Q = approach flow rate, veh/h;
C = cycle length, s;

Y = yellow interval duration, s;
Bp = presence of back plates on the signal heads, (1 if present, 0 if not present);
V = average running speed, mph;
L_p = clearance path length, ft;
R_p = platoon ratio (= Q_e / Q); and
Q_e = phase-end flow rate (flow rate during last 8 s of green), veh/h.

The development and calibration of this equation is described by Bonneson et al. (*4*).

Table 4 illustrates the application of Equations 2, 3, and 4 to the "before" data. Column 3 lists the count of red-light-runners during the 6-hour study period at each site. Column 4 represents the expected red-light-running frequency *E[R]* obtained from Equation 4. Specifically, this equation was used to estimate *E[R]* for each of the six study hours at a given site. The value in column 4 represents an average of the six hourly estimates. The values in columns 5 and 6 are based on the direct application of Equations 3 and 2, respectively.

TABLE 4 Expected Red-Light-Running during the "Before" and "After" Periods

City	Study Site	RLR, veh/6 hours	*E[R]* veh/h	*weight*	*E[R|x]* veh/h	*E[R]** veh/h	RLR* veh/6 hours
College Station	NB Texas Ave.	24	4.0	0.27	4.0	3.8	22.7
	SB Texas Ave.	10	2.9	0.34	2.1	4.3	18.3
	EB University Dr.	33	6.1	0.20	5.6	8.1	45.1
	WB University Dr.	60	7.1	0.17	9.5	8.7	69.5
Richardson	SB Plano Road	4	1.6	0.49	1.1	1.4	5.8
	EB Belt Line Road	6	0.8	0.66	0.8	0.9	5.9
	SB Greenville Ave.	3	1.2	0.55	0.9	1.4	6.2
	EB Main Street	25	1.9	0.45	3.1	1.9	19.4

The estimate *E[R|x]* is an unbiased estimate of the red-light-running frequency for the "before" study. However, it is still "biased" if compared directly to the observed count of red-light-runners during the "after" period. This bias stems from the fact that conditions (e.g., flow rate, speed, etc.) typically change during the interim between the two studies. In this case, six months lapsed between the two studies. To remove this bias, *E[R|x]* was multiplied by a ratio (= *E[R]*/E[R]*) that accounts for the change in conditions that have occurred since the "before" study. This computation is illustrated in the following equation:

$$RLR^* = E[R|x] \times \frac{E[R]^*}{E[R]} \times 6.0 \tag{5}$$

The ratio used in Equation 5 follows the recommendation of Hauer (*12*). The terms include the expected red-light-running frequency in the "before" period *E[R]* and that in the "after" period had no countermeasure been implemented *E[R]**. This ratio is multiplied by the quantity "6.0" to facilitate the before-after comparison of red-light-running during a 6-hour time period. The value obtained from Equation 5 (*RLR**) represents the expected number of red-light-runners that would have occurred in the "after" period had the countermeasure not been applied. This value is listed in the last column of Table 4.

Each value of *E[R]** listed in Table 4 was derived by using Equation 4 six times–once for each of the six "after" study hours at a given site. With one exception, the flow rate, speed, and other conditions present during each hour of the "after" study were used in Equation 4. The only exception was the variable associated with the yellow interval duration. This variable was unchanged from its condition in the "before" period. The value of *E[R]** listed in column 7 represents an average of the six hourly estimates obtained for each site.

Evaluation

The effectiveness of the yellow interval increase was evaluated using a "log-odds ratio" test, as described by Griffin and Flowers (*13*). This test compares the ratio of the red-light-running frequency of the "after" study period to that of the "before" period. This ratio is computed for both the sites receiving a countermeasure (i.e., the treated sites) and those not receiving a countermeasure (i.e., the comparison sites). The ratio of these two ratios represents the "relative change" due to the countermeasure with respect to any change found at the comparison sites. To determine if this relative change is significant, it can be used to compute a "z-statistic" that follows the standard normal distribution. This statistic can be used to identify the probability of falsely rejecting the null hypothesis (i.e., that there is no change). The results of the analysis are listed in Table 5.

TABLE 5 Effect of an Increase in Yellow Interval Duration

City	Treatment	Observed Hours [1]	RLR Frequency [2]		After/Before Ratio (R) [3]	Relative Change [4] (RC)	z-statistic (z) [p-value] [5, 6, 7]
			"Before" Study	"After" Study			
College Station	Increase yellow	36	137.3	54	0.39	-79	**4.79 [0.00]**
	Control	12	18.3	35	1.91		
Richardson	Increase yellow	36	17.9	7	0.39	-49	1.21 [0.23]
	Control	12	19.4	15	0.77		
College Sta. Richardson	Increase yellow	72	155.2	61	0.39	-70	**4.62 [0.00]**
	Control	24	37.7	50	1.33		

Notes:
1 - Hours listed are evenly distributed among the "before" and the "after" studies.
2 - RLR Frequency: red-light-running events during a 6-hour period.
3 - $R = RLR_{after} / RLR_{before}$.
4 - $RC = (R_{treatment}/R_{comparison} - 1) \times 100$. Negative values of RC indicate a reduction in RLR frequency.
5 - $z = L / L_{se}$ where, $L = \ln(R_{treatment}/R_{comparison})$; "ln($x$)" = natural log of x; and
$L_{se} = (1/RLR_{after,\,treatment} + 1/RLR_{before,\,treatment} + 1/RLR_{after,\,comparison} + 1/RLR_{before,\,comparison})^{0.5}$.
6 - p-value: probability that the null hypothesis (i.e, no change, $RC = 0.0$) is erroneously rejected.
7 - Underlined values identify changes that are statistically significant (with less than 5 percent chance of error).

The last column in Table 5 indicates that the increase in yellow duration at the College Station and Richardson sites is associated with a decrease in red-light-running. Specifically, the 0.6 s increase in yellow duration in Richardson led to a 49 percent reduction in violations. The average 1.1-s increase in yellow duration in College Station led to a 79 percent reduction in violations. Overall, the average 0.8 s increase in yellow duration resulted in a 70 percent reduction in red-light-violations.

The violation reduction percentages listed in column 7 of Table 5 compare with the 52 percent reduction previously noted for the entry time analysis. Moreover, an examination of Equation 4 (which is calibrated for all 20 sites) revealed that a 1.0 s increase is most likely to equate to a 53 percent reduction in violations. Lastly, these percentages are very consistent with that of Van der Horst and Wilmink (*7*). As noted previously, they found that a 1.0 s increase in yellow duration reduced red-light violations by 50 percent.

CONCLUSIONS

The following conclusions are reached as a result of an examination of the data collected and analyzed for this research:

- Efforts to increase yellow interval duration or to reduce driver speed are very likely to be effective at reducing red-light violations; however, they are likely to have a more modest effect on red-light-related crashes (only crashes that are left-turn related are likely to be reduced). In contrast, efforts to improve driver attention (such that unintentional red-light violations are reduced) are likely to be more effective at reducing red-light-related crash frequency.

- The yellow duration obtained using ITE's proposed recommended practice (i.e., Equation 1) is likely to yield a nominal 2.0 red-light violations per hour (which equates to 0.8 red-light violations per 10,000 veh-cycles for typical intersections).

- In general, an increase of 0.5 to 1.5 s in yellow duration (such that it does not exceed 5.5 s) will decrease the frequency of red-light-running by about 50 percent.

- The before-after study of driver response to an increase in yellow interval duration confirms that drivers do adapt to the increase in yellow duration. This adaptation results in a slightly lower probability of stopping for a given travel time to the intersection at yellow onset. However, this adaptation does *not* undo the benefit of an increase in yellow duration.

- When expressed in terms of violation frequency, increasing a yellow interval that is shorter than that obtained from Equation 1 is likely to yield the greatest return (in terms of a reduced number of red-light violations) relative to the cost of re-timing a yellow interval. Therefore, it is recommended that agencies consider timing the yellow interval such that it at least equals the value obtained from Equation 1.

! There may be some additional benefit to having a yellow interval that is slightly longer than that computed using Equation 1 (but does not exceed 5.5 s). It is likely that the drivers benefitting from this "extra" yellow are those that have an exceptionally long reaction time, speeds in excess of the 85th percentile speed, or low toleration for high deceleration rates.

! An increase in the yellow interval duration is one of several viable countermeasure to red-light-running. However, countermeasure selection to address a problem location should be based on a comprehensive engineering analysis of traffic conditions, control device visibility, and intersection sight distance.

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