Paper No.: 03-2136

Title: **Prediction of Expected Red-Light-Running Frequency at Urban Intersections**

Author: **James A. Bonneson, P.E.**
Research Engineer
(979) 845-9906
fax: (979) 845-6254
j-bonneson@tamu.edu

Ho Jun Son
Graduate Research Assistant
h-son@tamu.edu

Texas Transportation Institute
The Texas A&M University System
3135 TAMU
College Station, TX 77843-3135

Submitted for Consideration of Presentation and Publication at:
Transportation Research Board
82st Annual Meeting
January 2003
Washington, D.C.

October 17, 2002

Word count: 5,482 words + 8 figures * 250 = 7,482 equivalent words

ABSTRACT

Statistics consistently indicate that red-light-running has become a significant safety problem throughout the United States. Comprehensive guidelines for treating red-light-running at problem intersections have been developed. Unfortunately, these guidelines do not include a tool or technique for quantitatively determining if a problem exists and if a countermeasure is truly effective. The objective of this paper is to describe the development and calibration of this type of tool.

The calibrated prediction model developed for this research indicates that red-light-running increases with flow rate, speed, and dense platoons arriving at the end of the phase. It was also found that red-light-running decreases with increasing cycle length, cross street width, and when back plates are used on the signal heads. Uses for the calibrated model are described.

INTRODUCTION

Background

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. Studies by Retting et al. (*1*) have shown that both enforcement and engineering countermeasures are effective in reducing the frequency of red-light-running. However, some individuals (*3*) have disputed the effectiveness of enforcement and the manner in which intersections are targeted for enforcement activities.

To allay some concerns with the use of enforcement, Milazzo et al. (*4*) have developed comprehensive guidelines for treating red-light-running at problem intersections. Their guidelines consist of a series of steps; the first of which is to confirm that a problem exists. Next, the engineer is encouraged to consider engineering countermeasures. If engineering countermeasures are not effective, then officer enforcement would be tried. Automated enforcement would only be considered as a last resort. Unfortunately, these guidelines do not include a tool or technique for quantitatively determining if a problem exists and if a countermeasure is truly effective.

Objective

The guidelines developed by Milazzo et al. (*4*) represent an excellent tool to facilitate the uniform treatment of problem intersections. However, the guidelines' effectiveness could be improved if a tool was available that could be used to compute the expected red-light-running frequency for a given intersection. This tool could be used to: (1) identify the most problematic intersections, (2) evaluate the likely effectiveness of some engineering countermeasures; and (3) quantify the effectiveness of the countermeasure used. The objective of this paper is to describe the development and calibration of this type of tool.

Scope

A red-light-running event can be characterized by traffic movement type, entry time of the red-light-running vehicle, and the motivation underlying the driver's decision to run the red. "Traffic movement type" reflects the different expectations and experiences of the left-turn versus the through driver. Relative to the through driver, the left-turn driver is forced (by geometry) to travel through the intersection at a slow rate of speed and is also more likely to experience lengthy delays.

"Entry time of the red-light-running driver" relates to the time that the driver enters the intersection after the onset of red. When a driver enters late into the red, it may be an indication of deficiencies in signal visibility or driver sight-distance along the intersection approach. It may also be an indicator of driver indifference to the traffic laws regarding the red indication. Intuitively, crash potential is higher when a red-light-runner enters several seconds after red onset. 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 crashes due to late entries is relatively low.

"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 interests to run the red. In contrast, an "unavoidable" event is committed by a driver who either (1) believes that is impossible to safely stop and consciously decides to run the red, or (2) is unaware of the need to stop.

This paper focuses on the unavoidable red-light-running by through drivers that takes place during the first few seconds after the onset of red. Red-light-running events having these characteristics occur frequently and are most treatable by engineering countermeasures. Efforts to reduce this type of red-light-running are likely to have the greatest return in terms of a reduced number of crashes.

FACTORS ASSOCIATED WITH RED-LIGHT-RUNNING

Bonneson et al. (*6*) identified the following factors as being the most likely to influence the frequency of red-light-running during the first few seconds after yellow onset:

- flow rate on the subject approach (exposure factor),
- number of signal cycles (exposure factor),
- frequency of phase termination by extension to the maximum green limit (exposure factor),
- probability of stopping (contributory factor), and
- yellow interval duration (contributory factor).

"Exposure factors" represent the basic events that must occur or be present for a red light to be run. These factors are not necessarily considered to be "causes" of red-light-running. In contrast, contributory factors represent conditions or behaviors that cause or facilitate red-light-running. The last two contributory factors listed are described in the next section.

Phase termination by extension to the maximum green limit (i.e., max-out) represents an exposure measure for actuated signal phases when advance detection is used. If the phase is pretimed, or if it is actuated but uses only stop-line detection, then max-out frequency is not an exposure measure. When advance detection is available, the controller attempts to end the phase when the approach is clear of vehicles. Phase termination with a clear approach ensures there will be no red-light-running. However, if max-out occurs, then the approach is not clear at yellow onset and one or more drivers are exposed to a potential red-light-running situation.

Probability of Stopping

Many researchers have studied the decision to stop in response to the yellow indication (*7, 8, 9*). In each instance, they found that the probability of stopping (at the onset of yellow) increases with the driver's distance from the intersection. This probability has also been analyzed in terms of the driver's travel time to the intersection. A review of the literature by Bonneson et al. (*6*) indicated that several factors may influence the probability of stopping. These factors include: short headways associated with platoon flow, control mode (i.e., actuated or pretimed), approach grade, yellow interval duration, threat of crash, threat of citation, and expected delay.

Yellow Interval Duration

The yellow interval duration is generally recognized as a key factor that affects the frequency of red-light-running. This recognition has led several researchers to recommend setting the yellow interval duration based on the probability of stopping (*7*). These researchers suggest that the yellow interval should be based on the 85^{th} (or 90^{th}) percentile driver's travel time to the stop line.

MODEL DEVELOPMENT

This section describes the development of a model for predicting the frequency of red-light-running. The model is based on the probability of a driver stopping (following the onset of the red indication) when he or she is *t* seconds travel time from the stop line. This probability can be used to predict the expected number of red-light-runners per *cycle*. When it is multiplied by the number of cycles per hour, the result is the expected number of red-light-runners per *hour*.

Different probability distributions have been used to represent the probability-of-stopping relationship. Sheffi and Mahmassani (*9*) used the normal distribution. Bonneson et al. (*8*) used the logistic distribution. The logistic distribution is attractive because its cumulative form exists as a closed-form equation. It is represented by the following equation:

$$p_{stop}(t) = \frac{1}{1 + e^{(\alpha - t)/\beta}} \qquad \textbf{(1)}$$

where:

$p_{stop}(t)$ = probability of stopping in response to the yellow indication when at travel time *t*;
t = travel time to the stop line at the onset of yellow, s;
α = shift parameter (equals the travel time at which the probability of stopping is 0.5), s; and
β = shape parameter, s^{-1}.

The complement to the probability of stopping is the "probability of going." This latter probability can be computed as:

$$p_{go}(t) = 1 - p_{stop}(t) \qquad \textbf{(2)}$$

where, $p_{go}(t)$ = probability of going in response to a yellow indication when at travel time *t*.

The probability-of-going can be used to develop an equation for predicting the expected number of red-light-runners per cycle. It is developed by integrating the product of the vehicle flow rate and the probability of going over all travel times in excess of the yellow duration. This formulation is based on the assumption that each driver, in a given lane, decides to go (or stop) independently of any other driver. This assumption is relatively strong when the headway between vehicles in the same lane exceeds 4 s. More complicated formulations would be required to address the joint probability of there being two or more drivers within 2 and 6 s travel time of the intersection at the onset of yellow and their respective decisions to stop or go.

It was noted in the previous paragraph that the integration should be over all travel times in excess of the yellow duration. However, if advance detection is used on the subject intersection approach *and* the approach phase does not terminate by max-out, then the area monitored by the advance detectors is insured to be free of vehicles at the onset of yellow. In this case, the interval of integration would include only those travel times in excess of the quantity D/v where D is the distance between stop line and the most distant upstream detector and v is vehicle speed.

Based on the preceding discussion, the basic form of the red-light-running model is:

$$E[R] = m \int_{v=0}^{\infty} \int_{t=T}^{\infty} p(v)\ p_{go}(t)\ q(t)\ dt\ dv \tag{3}$$

with,

$$T = p_x Y + (1 - p_x) \max\!: \left[Y, \frac{D}{v} \right] \tag{4}$$

where:

$E[R]$ = expected red-light-running frequency, veh/h;
m = number of signal cycles per hour (= 3,600/C), cycles/hr;
v = vehicle speed on the intersection approach; ft/s;
C = cycle length, s;
T = travel time before red-light-running can occur, s;
$p(v)$ = probability of speed v;
$q(t)$ = flow rate t seconds travel time from the stop line at the onset of yellow, veh/s;
p_x = probability of phase termination by max-out (= 1.0 if movement is pretimed or if it is actuated but does not have advance detection);
Y = yellow interval duration, s;
max [a,b] = the larger of variables a and b; and
D = distance between stop line and the most distant upstream detector, ft.

To simplify the mathematics of Equations 3 and 4, it can be assumed that the effect of speed variation is negligible and that the average speed V can be used to represent the entire traffic stream. This simplification eliminates the first integration and leaves the following model form:

$$E[R] = m \int_{t=T}^{\infty} p_{go}(t)\ q(t)\ dt \tag{5}$$

with,

$$T = p_x Y + (1 - p_x) \max\!: \left[Y, \frac{D}{V} \right] \tag{6}$$

where, V = average running speed; ft/s. If the subject intersection approach is pretimed, then $p_x = 1.0$ and the integral in Equation 5 is bound to the interval from $t = Y$ to $t = \infty$. If the subject approach is actuated and Y is larger than the travel time D/V, then the integral in Equation 5 is also bound to the interval from $t = Y$ to $t = \infty$. Values of D/V for stop-line-only detection are typically less than 2.0 s; values for approaches with advance detection are typically between 5 and 6 s.

The integral in Equation 5 computes the expected number of vehicles running the red at the end of a signal phase for a given intersection approach. The product "$q(t)\ dt$" in the integral represents the count of vehicles during a given time dt. The term $p_{go}(t)$ represents the probability of these vehicles "going" if they are t seconds from the stop line. The integral sums all such possible events for the approach (i.e., for all lanes). For the typical range of yellow interval durations, it can be assumed that $q(t)$ is equal to the average approach flow rate q (i.e., $q(t) = q$).

Equations 1, 2, and 5 can be combined and integrated to yield the following generalized form of the red-light-running model:

$$E[R] = \frac{Q}{C} \frac{1}{b_1} \ln\left[1 + e^{(b_0 - b_1 T + b_2 x_2 + \ldots + b_n x_n)}\right] \qquad \textbf{(7)}$$

where,
$E[R]$ = expected red-light-running frequency, veh/h;
Q = approach flow rate (= $q \times 3600$), veh/h;
$\ln[x]$ = natural log of x;
x_i = variables describing selected traffic and geometric characteristics; and
b_i = regression coefficients, $i = 0, 1, 2, \ldots, n$.

Regression constants have been substituted in Equation 7 for the shift and shape parameters from Equation 1 (i.e., $\alpha = (b_0 + b_2 x_2 + \ldots + b_n x_n) \times \beta$ and $\beta = 1/b_1$).

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 1.

The five cities included in the study collectively represent a wide range in population. This characteristic facilitated the examination of "small town" versus "big city" driver behavior. The city of Driscoll (near Corpus Christi) has a population of 811 persons while city of Richardson is in the Dallas/Fort Worth metropolitan area which has a population of about three million persons.

Data Collection

The objective of the research was to evaluate the effect of select countermeasures on the frequency of red-light-running. To achieve this objective, a "before-after" study design process was used. Countermeasures included a small increase in yellow interval duration, a change from bulb to LED yellow indications, and the addition of back plates to the signal head. Each "before" study and each "after" study included the collection of six hours of traffic flow data on each intersection approach. Details of the study design are described by Bonneson et al. (*6*).

TABLE 1 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 15^{th} and 85^{th} percentile values observed at the site on one day.

The field study of each site included the collection of geometric, traffic flow, traffic control, and operational characteristics. These data were collected using a variety of methods including videotape recorders, laser speed guns, and site surveys. The data collected during each field study included approach cross section and grade, movement flow rates, heavy vehicle percentage, speed limit, signal phase sequence, yellow and all-red interval durations, running speed, frequency of max-out for those intersections with advance detection, and the count of red-light-runners.

Observations during the field studies indicated that, at some intersections, traffic platoons would often arrive near the end of the phase. When this occurred, the propensity for red-light-running appeared to be higher than at intersections of similar volume but with random arrivals or with platoons arriving nearer to the start of green. To facilitate an examination of the effect of platoon arrival on red-light-running, the flow rate at the end of the phase was included in the database. It was estimated by counting the vehicles arriving to the intersection during the last 8.0 s of the phase's green indication.

Characteristics of the intersection approaches studied are listed in Table 2. The data in this table indicate that the study sites collectively offer a reasonable range of speeds, grades, all-red interval durations, and signal types.

TABLE 2 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]
Mexia	EB Milam St.	35	2	-2.8	3.9	1.0	Red: LED
	WB Milam St.	35	2	+2.8	4.0	1.0	Red: LED
	EB S.H. 171	30	1	-0.5	4.0	1.0	bulb
	WB S.H. 171	30	1	0.0	4.0	1.0	bulb
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
Corpus Christi	EB S.H. 44	50	2	0.0	4.2 (4.7)	2.0	Green:LED
	WB S.H. 44	50	2	0.0	4.2 (4.7)	2.0	Green:LED
	NB U.S. 77	40	2	+0.3	4.0	2.1	Red:LED
	SB U.S. 77	40	2	0.0	4.0	2.1	Red:LED
Laredo	NB Loop 20	40	2	-1.8	4.5 (3.8)	1.0	bulb
	SB Loop 20	40	2	+0.9	4.5 (4.0)	1.0	bulb
	NB U.S. 83	55	2	+1.5	5.1 (5.0)	2.0	bulb
	SB U.S. 83	55	2	-1.3	5.1 (4.9)	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 the "before" and the "after" study.
3 - Signal head type: all indications use bulb lighting, except as noted in the table.

EVALUATION OF FACTORS ASSOCIATED WITH RED-LIGHT-RUNNING

This section describes the findings from an investigation of the factors that are associated with frequent red-light-running. Initially, the database content is summarized. Then, the data are graphically examined to identify basic cause-and-effect relationships. Next, the red-light-running model (described previously) is calibrated. Finally, this section concludes with a sensitivity analysis of the calibrated model.

Database Summary

Summary statistics describing the variables in the database are provided in Table 3. The data in this table indicate that more than 10,018 signal cycles were observed at 20 intersection approaches. During these cycles, 586 vehicles entered the intersection after the change in signal indication from yellow to red. The red-light-running rate for each site, in red-light-running events per 1000 vehicles is listed in Column 6 of Table 3. The above average rates are shown in bold type.

A second red-light-running rate is listed in Column 7 of Table 3. This rate represents the number of red-light-running events per 10,000 veh-cycles where, "cycles" represents the *average* number of cycles per hour during the period for which vehicles are counted. This rate is less intuitive than some rates found in the literature; however, it is more accurate because it reflects both events that "expose" the driver to potential red-light-running. The use of "vehicle-cycles" is supported by the ratio Q/C that appears in Equation 7. The average rate for the intersections studied is 1.0 red-light-runners per 10,000 veh-cycles. The above average rates are shown in bold type. A comparison of Columns 6 and 7 indicates some differences. In most instances, this difference is because the rates in Column 6 do not reflect the large number of cycles that were observed at the corresponding site. The rates in Column 7 rightly accounts for this difference.

The last three columns in Table 3 compare the yellow interval observed at each site with that computed using an equation described by Kell and Fullerton (*10*). Differences between the observed and computed yellow intervals ranged from -1.3 s to 1.0 s (difference = $Y_{observed}$ - $Y_{computed}$).

Analysis of Factors Affecting Red-Light-Running

This section describes an analysis of the relationship between red-light-running frequency and selected variables in the database. The analysis considered a wide range of variables. They include: approach flow rate, cycle length, yellow interval duration, heavy-vehicle percentage, running speed, clearance path length, platoon ratio, approach grade, number of approach lanes, LED signal indications, use of signal head back plates, use of advance detection, and signal head mounting. The findings described in this section focus on the three variables that show the most significant cause-and-effect relationship: flow rate, cycle length, and yellow interval duration.

Each variable included in the data base represents the total events observed during a one hour period. Given that there were six hours of data for each of 20 approaches and two study periods, there are a total of 240 observations in the data base.

Figure 1 presents a comparison of the relationship between approach flow-rate-to-cycle-length ratio and the frequency of red-light-running. The trend in this figure suggests that red-light-running frequency increases with increasing flow rate or shorter cycle lengths. The pattern in the data indicate that the relationship is somewhat linear and that there is negligible red-light-running when there is negligible flow or extremely long cycle lengths.

TABLE 3 Red-Light-Running Rate and Yellow Interval at Each Study Site

Study Site	Study Period	Total Observations / 6 hr			RLR per 1000 veh	RLR per[1] 10,000 veh-cycles	85^{th} % Speed, mph	Yellow Interval,[2] s		
		Vehicles	Cycles	RLR				Obs.	Computed	Difference
EB Milam St.	Before	2526	285	13	**5.1**	**1.1**	39.0	4.0	4.1	-0.1
	After	2477	384	9	3.6	0.6	39.0	4.0	4.1	-0.1
WB Milam St.	Before	2728	288	9	3.3	0.7	37.0	4.0	3.5	0.5
	After	2276	377	14	**6.2**	1.0	35.2	4.0	3.4	0.6
EB S.H. 171	Before	509	281	0	0.0	0.0	37.0	4.0	3.8	0.2
	After	572	405	3	**5.2**	0.8	38.4	4.0	3.9	0.1
WB S.H. 171	Before	1073	386	1	0.9	0.1	35.8	4.0	3.6	0.4
	After	1132	407	4	3.5	0.5	36.0	4.0	3.6	0.4
NB Texas Ave.	Before	6801	195	24	**3.5**	**1.1**	45.2	3.5	4.3	-0.8
	After	7530	179	7	0.9	0.3	42.0	5.0	4.1	0.9
SB Texas Ave.	Before	6372	191	10	1.6	0.5	43.0	3.5	4.2	-0.7
	After	7808	179	35	**4.5**	**1.5**	47.0	3.5	4.5	-1.0
EB University Dr.	Before	5732	194	33	**5.8**	**1.8**	37.0	3.2	3.7	-0.5
	After	7070	189	12	1.7	0.5	37.0	4.0	3.7	0.3
WB University Dr.	Before	5546	195	60	**10.8**	**3.3**	39.0	3.2	3.8	-0.6
	After	6630	190	35	**5.3**	**1.7**	40.0	4.1	3.9	0.2
SB Plano Road	Before	4673	231	4	0.9	0.2	45.0	4.4	4.3	0.2
	After	5341	208	4	0.7	0.2	42.0	5.0	4.0	1.0
EB Belt Line Road	Before	3382	232	6	1.8	0.5	42.0	4.0	4.1	-0.1
	After	4540	210	1	0.2	0.1	38.2	4.6	3.8	0.8
SB Greenville Ave.	Before	1764	234	3	1.7	0.4	36.0	3.6	3.6	0.0
	After	1478	250	2	1.4	0.3	39.0	4.2	3.8	0.4
EB Main Street	Before	5179	243	25	**4.8**	**1.2**	32.0	3.7	3.4	0.4
	After	4711	250	15	3.2	0.8	32.0	3.7	3.4	0.4
EB S.H. 44	Before	3683	193	16	**4.3**	**1.4**	53.0	4.2	4.9	-0.7
	After	3359	162	7	2.1	0.8	53.0	4.7	4.9	-0.2
WB S.H. 44	Before	3768	192	11	2.9	0.9	56.0	4.2	5.1	-0.9
	After	3899	148	10	2.6	1.0	55.0	4.7	5.0	-0.3
NB U.S. 77	Before	2484	326	15	**6.0**	**1.1**	42.0	4.0	4.1	-0.1
	After	2603	255	21	**8.1**	**1.9**	41.0	4.0	4.0	0.0
SB U.S. 77	Before	2314	339	13	**5.6**	1.0	42.0	4.0	4.1	-0.1
	After	2353	250	15	**6.4**	**1.5**	44.0	4.0	4.2	-0.2
NB Loop 20	Before	2625	234	14	**5.3**	**1.4**	50.2	4.5	4.9	-0.4
	After	2787	205	22	**7.9**	**2.3**	52.0	3.8	5.1	-1.3
SB Loop 20	Before	2946	235	9	3.1	0.8	50.0	4.5	4.6	-0.1
	After	2748	197	29	**10.6**	**3.2**	51.2	4.0	4.7	-0.7
NB U.S. 83	Before	2209	299	20	**9.1**	**1.8**	60.2	5.1	5.2	-0.1
	After	2461	275	23	**9.3**	**2.0**	58.2	5.0	5.1	-0.1
SB U.S. 83	Before	2135	266	9	**4.2**	1.0	57.0	5.1	5.4	-0.3
	After	2578	259	23	**8.9**	**2.1**	58.0	4.9	5.4	-0.5
Total Obs. & Average Rate:		142,802	10,018	586	4.1	1.0				

Notes:
1 - RLR per 10,000 veh-cycles = RLR / Vehicles x (6 hours / Cycles) x 10,000.
2 - "Computed": Based on the equation described by Kell and Fullerton (*10*): $Y = t + V/(2\,a + 64\,G)$ where, Y = yellow interval, t = driver perception-reaction time (= 1.0 s), a = deceleration rate (10 ft/s^2), and G = approach grade (ft/ft).

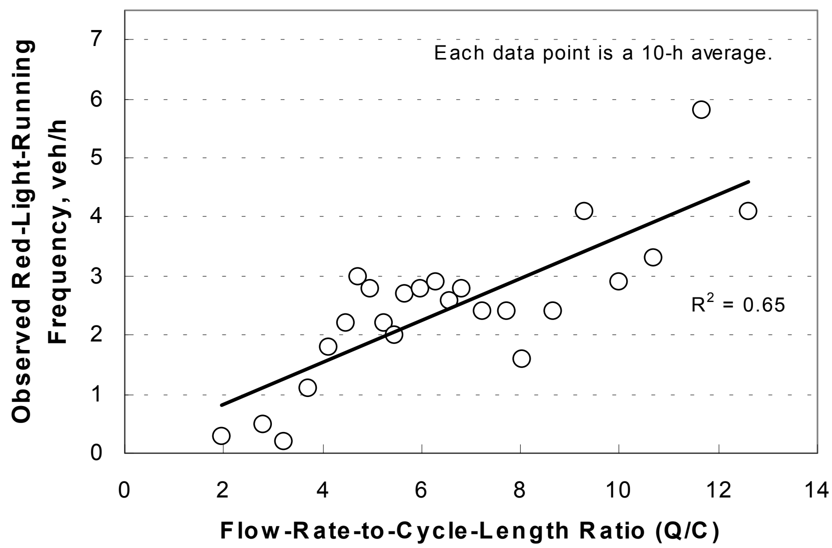

FIGURE 1 Red-light-running frequency as a function of flow-rate-to-cycle-length ratio.

There are only 24 data points shown in Figure 1. In fact, each data point in this figure (and in subsequent figures in this section) represents an average over 10 hours. This aggregation was needed because plots with 240 data points tended to obscure the portrayal of trends in the data. To overcome this problem, the hourly data were sorted by the independent variable (e.g., *Q/C* ratio), placed in sequential groups of 10, and averaged for both the independent and dependent variables. This procedure was only used for graphical presentation; the 240 hour-based data points were used for all statistical analyses.

Figure 2 illustrates the relationship between yellow interval duration and red-light-running frequency. The best-fit trend line shown suggests a curved relationship where the frequency of red-light-running is at relatively low values for yellow intervals between 3.8 and 5.0 s. Red-light-running increases significantly for yellow intervals less than 3.5 s. This trend is consistent with that reported by Van der Horst and Wilmink (*7*). The trend line shown also suggests that the frequency of red-light-running increases slightly for yellow interval durations larger than 4.5 s. However, further investigation of the data indicates that this increase is associated with other factor influences.

The relationship between red-light-running and the "yellow interval difference" listed in Table 3 was also evaluated. The results of this examination are shown in Figure 3. It should be noted that each data point in this figure represents one intersection approach.

The data shown in Figure 3 indicate that there is a trend toward more red-light-running when the observed yellow duration is shorter than the computed duration. A yellow interval difference of 0.0 s is associated with about 2.0 red-light-runners per hour. A regression analysis of the relationship between yellow interval difference and red-light-running rate indicated that the relationship is statistically significant (i.e., $p = 0.001$). A similar finding was previously reported by Retting and Green (*12*) in an examination of red-light-running at several intersections.

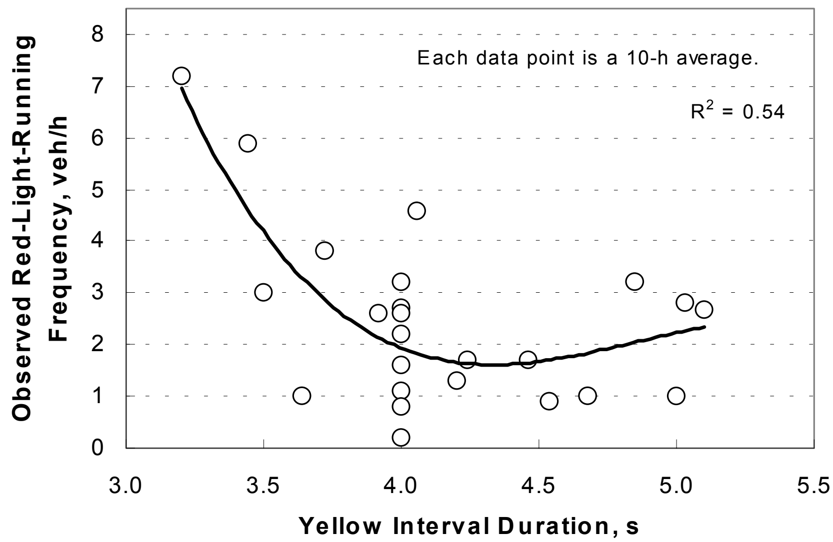

FIGURE 2 Red-light-running frequency as a function of yellow interval duration.

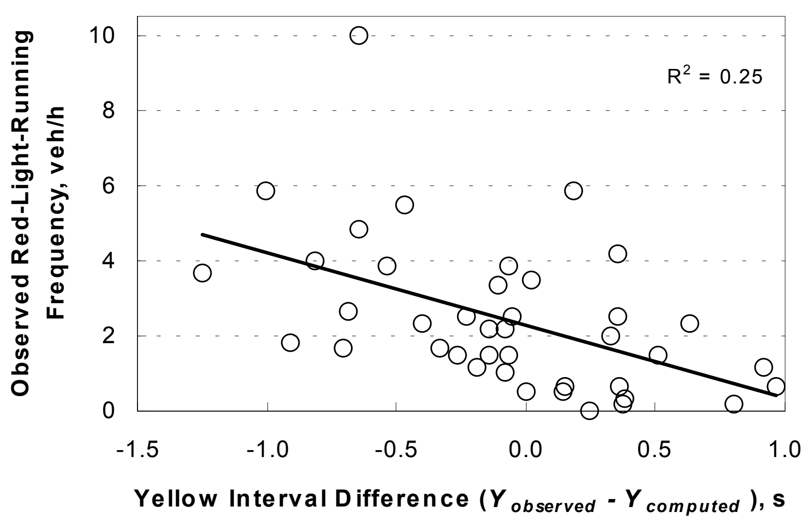

FIGURE 3 Red-light-running frequency as a function of yellow interval difference.

Statistical Approach for Model Calibration

A preliminary examination of the red-light-running data indicated that it is neither normally distributed nor of constant variance, as is assumed when using traditional least-squares regression. Under these conditions, the generalized linear modeling technique, described by McCullagh and Nelder (*13*), is appropriate because it accommodates the explicit specification of an error distribution using maximum-likelihood methods for coefficient estimation.

The distribution of red-light-running frequency can be described by the family of compound Poisson distributions. In this context, there are two different sources of variability underlying the distribution. One source of variability stems from the differences in the mean red-running frequency *m* among the otherwise "similar" intersection approaches. The other source stems from the randomness in red-light-running frequency at any given site, which likely follows the Poisson distribution.

Abbess et al. (*14*) have shown that if event occurrence at a particular location is Poisson distributed then the distribution of events of a group of locations can be described by the negative binomial distribution. The variance of this distribution is:

$$V(x) = E(m) + \frac{E(m)^2}{k} \qquad \textbf{(8)}$$

where, x is the observed red-light-running frequency for a given approach having an expected frequency of $E(m)$ and dispersion parameter k.

The Nonlinear Regression procedure (NLIN)in the SAS software (*15*) was used to estimate the red-light-running model coefficients. It was necessary to use this procedure because of the nonlinear form of the model. The "loss" function associated with NLIN was specified to equal the scaled deviance for the negative binomial distribution. The procedure was set up to estimate model coefficients based on maximum-likelihood methods.

The disadvantage of using NLIN is that k must be specified, yet its value has to be computed from the variability in the distribution of residuals. This requirement was overcome through an iterative procedure. Initially, NLIN was used, with k set to equal 1.0, to tentatively calibrate the model and compute a predicted red-light-running frequency for each observation. Then, the Generalized Modeling procedure (GENMOD) in SAS was used to obtain a better estimate of k. Specifically, GENMOD was used to regress the relationship between the predicted and observed red-light-running frequencies (the natural log of the predicted values was specified as an offset variable and the "log" link function was used). GENMOD automates the k-estimation process using maximum likelihood methods. This new estimate of k from GENMOD was then used in a second application of NLIN and the process repeated until convergence was achieved between the k value used in NLIN and that obtained from GENMOD. Convergence was typically achieved in two iterations.

Model Calibration

The regression analysis revealed that mathematic relationships existed between red-light-running frequency and yellow interval duration, use of signal head back plates, speed, clearance path length, and platoon ratio. The regression coefficient associated with each factor was found to be significant at a level of confidence that exceeded 95 percent. As a result of this analysis, the linear regression terms in Equation 7 were specified as:

$$E[R] = \frac{Q}{C} \frac{1}{b_1} \ln\left[1 + e^{(b_0 - b_1 T + b_2 Bp + b_3 V + b_4 L_p + b_5 R_p)}\right] e^{(b_6 I_C + b_7 I_L)} \qquad \textbf{(9)}$$

with,

$$T = p_x Y + (1 - p_x) \max\!: \left[Y, \frac{D}{V}\right] \qquad \textbf{(10)}$$

The platoon ratio R_p used in Equation 9 represents the ratio of the flow rate at the end of the phase to the approach flow rate. This ratio can be computed as:

$$R_p = \frac{Q_e}{Q} \qquad \textbf{(11)}$$

where:

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;
I_C = indicator variable for City of Corpus Christi, (1 if data applies to this city, 0 otherwise);
I_L = indicator variable for City of Laredo, (1 if data applies to this city, 0 otherwise); and
Q_e = phase-end flow rate, veh/h.

The regression analysis indicated that the calibrated model could not account for all of the red-light-running observed in two of the five cities included in the study. This finding is likely due to different levels of enforcement and variation in driver behavior among cities. Two indicator variables were added to the model to account for these differences.

The statistics related to the calibrated red-light-running model are shown in Table 4. The calibrated coefficient values can be used with Equations 9, 10, and 11 to predict the hourly red-light-running frequency for a given intersection approach. A dispersion parameter k of 9.0 was found to yield a scaled Pearson χ^2 of 1.04. The Pearson χ^2 statistic for the model is 239 and the degrees of freedom are 231 (= n-p-1 =239-7-1). As this statistic is less than $\chi^2_{0.05,\,231}$ (= 267), the hypothesis that the model fits the data cannot be rejected. The R^2 for the model is 0.49. An alternative measure of model fit that is better-suited to negative binomial error distributions is R_K^2, as developed by Miaou (*16*). R_K^2 for the calibrated model is 0.83.

TABLE 4 Calibrated Red-Light-Running Model Statistical Description

Model Statistics		Value		
	R^2 (R_K^2):	0.49 (0.83)		
	Scaled Pearson χ^2:	1.04		
	Pearson χ^2:	239 ($\chi^2_{0.05,\,231}$ = 267)		
	Dispersion Parameter *k*:	9.0		
	Observations:	239 hours		
	Standard Error:	±1.8 veh/h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
Q	Approach flow rate	veh/h	75	1551
C	Cycle length	s	47	161
Y	Yellow interval duration	s	3.2	5.1
V	Average running speed	mph	28	52
L_p	Clearance path length	ft	63	145
R_p	Platoon ratio	--	0.5	5.4
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Std. Dev.**	**t-statistic**
b_0	Intercept	2.30	0.74	3.1
b_1	Effect of travel time	0.927	0.155	6.0
b_2	Effect of back plates on signal heads	-0.334	0.150	-2.2
b_3	Effect of running speed	0.0435	0.0155	2.8
b_4	Effect of clearance path length	-0.0180	0.0048	-3.8
b_5	Effect of platoon ratio	0.220	0.100	2.2
b_6	Added effect of City of Corpus Christi	0.745	0.193	3.9
b_7	Added effect of City of Laredo	0.996	0.192	5.2

The regression coefficients for the model are listed in the last rows of Table 4. The *t*-statistic shown indicates that all coefficients are significant at a 95 percent level of confidence or higher. A negative coefficient indicates that red-light-running decreases with an increase in the associated variable value. Thus, approaches with higher speeds are likely to have a higher frequency of red-light-running. Red-light-running is also more frequent on approaches with platoons concentrated near the end of the phase. In contrast, red-light-running is less frequent at intersections with wider cross streets or at those with back plates on the signal heads. Red-light-running is 2.1 and 2.7 (= $e^{0.745}$ and = $e^{0.996}$) times more frequent in the cities of Corpus Christi and Laredo than it is in the other cities. This trend may be due to a lower level of enforcement of red-light-running in the cities of Corpus Christi and Laredo.

The calibrated model can be rewritten to yield the following form:

$$E[R] = \frac{Q}{C} \frac{1}{0.927} \ln\left[1 + e^{(2.30 - 0.927T - 0.334Bp + 0.0435V - 0.0180L_p + 0.220R_p)}\right] \quad \textbf{(12)}$$

Computation of the platoon ratio requires knowledge of the phase-end flow rate Q_e. This flow rate can be directly measured by counting the vehicles crossing the stop line in the last 5 to 10 s before the onset of the yellow indication. Alternatively, the platoon ratio can be approximated using guidance in Chapters 10 and 16 of the *Highway Capacity Manual* (*17*) (i.e., Exhibits 10-18 and 16-11, respectively). The information in these tables indicates that R_p has values ranging from 0.33 to 2.0 for very poor to exceptionally good progression, respectively. A value of 1.0 is recommended for isolated intersection approaches.

Given that enforcement levels and driver behavior may vary among cities, it may be necessary to calibrate Equation 12 to local conditions. This calibration can be accomplished by observing the hourly count of red-light-running x on a few intersection approaches. These approaches should be selected because they have a "typical" level of red-light-running. Equation 12 would then be used to estimate $E[R]$ for each approach. A calibration factor C_f is then be computed as the ratio of the total count of red-light-runners to the total expected red-light-running frequency (i.e., $C_f = \Sigma x / \Sigma E[R]$) for all approaches. Thereafter, any value obtained from Equation 12 would be multiplied by C_f to predict the expected red-light-running frequency for a given approach.

Sensitivity Analysis

Figure 4 illustrates the effect of yellow interval duration and 85th percentile speed on the frequency of red-light running. The 85th percentile speed was estimated as being 12 percent larger than the average running speed. The trends in this figure indicate that, for the same yellow duration, the number of red-light-running events is higher on higher speed approaches.

The black dots in Figure 4 indicate the yellow interval duration computed using the equation provided by Kell and Fullerton (*10*) for the corresponding speed. The location of the dots suggests that use of this equation yields about 2.0 red-light-runners per hour (or 0.8 red-light-runners per 10,000 veh-cycles) for the "typical" conditions represented in the figure.

APPLICATION EXTENSIONS

The model developed in the preceding section can be used in several ways to treat the red-light-running problem. Specifically, it can be used to: (1) quantify the expected red-light-running frequency on an intersection approach, (2) evaluate the likely effectiveness of some engineering countermeasures, (3) identify problem intersections, and (4) quantify the effectiveness of the countermeasure used at a specific location.

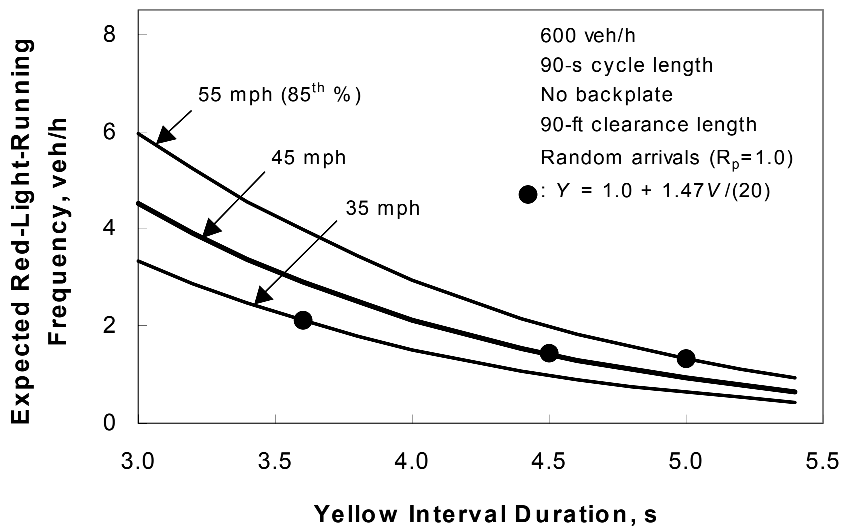

FIGURE 4 Predicted effect of yellow duration and speed on red-light-running frequency.

Equation 12 can be used to compute the expected red-light-running frequency for the "typical" intersection approach. The model can also be used to estimate the relative effectiveness of several engineering countermeasures such as: increase cycle length, increase yellow interval duration, add advance detection, add back plates, change speed limit, and adjust platoon arrival time and concentration. These countermeasures can be evaluated for specified flow rates and intersection widths.

If a specific approach is to be evaluated, then the following equation should be used:

$$E[R|x] = E[R] \times weight + \frac{x}{H} \times (1 - weight) \qquad \textbf{(13)}$$

with,

$$weight = \left(1 + \frac{E[R]\, H}{k} \right)^{-1} \qquad \textbf{(14)}$$

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 at the problem intersection, veh;
H = time interval during which x was observed, h; and
$weight$ = relative weight given to the prediction of expected red-light-running frequency.

Equation 13 is based on the empirical Bayes approach of Hauer (*18*) and is used to minimize the misleading effects of regression-to-the-mean when estimating a site's average red-light-running frequency. Its use requires the first-hand observation of red-light-running for one or more hours at the subject intersection approach.

Problem locations can be identified by computing and ranking the following "index" value for the intersection approaches being considered:

$$Index = \frac{E[R|x] - E[R]}{\sqrt{\frac{E[R]^2}{k} + \sigma_m^2}} \quad \textbf{(15)}$$

with,

$$\sigma_m^2 = (1 - weight)\ E[R|x] \quad \textbf{(16)}$$

where σ_m^2 is the variance of the expected red-light-running frequency $E[R|x]$, as described by Hauer (*18*). Sites with larger index values would be identified as being most likely to benefit from some type of treatment.

Finally, the model can be used to evaluate the effectiveness of one or more countermeasures used at a specific intersection approach. This evaluation would follow the techniques described by Persaud et al. (*19*) and by Hauer (*18*) for observational before-after studies. Specifically, the model can be used to estimate the expected red-light-running frequency that would have occurred in the "after" period of study had a countermeasure not been implemented.

CONCLUSIONS

Based on the analysis conducted for this research, several conclusions are reached regarding the factors associated with (perhaps causing) red-light-running. Flow rate and cycle length are considered to be "exposure" factors in that they represent the basic events that must occur or be present for a red light to be run. From this, it is concluded that the most appropriate red-light-running rate statistic is "red-light-running events per 10,000 veh-cycles." An average rate of 1.0 red-light-runners per 10,000 veh-cycles was found for the sites studied for this research.

The frequency of red-light-running is higher when the yellow interval duration is shorter than the value computed with the equation offered by Kell and Fullerton (*10*). Moreover, there tends to be about 2.0 red-light-runners per hour (or 0.8 red-light-runners per 10,000 veh-cycles) on intersection approaches that have yellow intervals equal to those computed by this equation.

The red-light-running model is able to explain most of the systematic variation in red-light-running in three Texas cities. Model predictions had to be inflated to account for local conditions (reflecting a possible lower level of enforcement) at two cities. This finding suggests that the model may need to be calibrated for use in cities with a relatively high level of red-light-running.

The model coefficients indicate that approaches with higher speeds are likely to have a higher frequency of red-light-running. Red-light-running is also more frequent on approaches with platoons concentrated near the end of the phase. In contrast, red-light-running is less frequent at intersections with wider cross streets or at those with back plates on the signal heads.

ACKNOWLEDGMENT

This work was sponsored by the Texas Department of Transportation (TxDOT) and was conducted for TxDOT's Research and Technology Implementation Office. The materials and methods presented were developed as part of TxDOT Project 0-4027, "Signalization Countermeasures to Reduce Red-Light-Running." The authors would like to recognize the project director, Mr. Wade Odell, for his support and guidance throughout the duration of this project.

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