Evaluation of Right-of-Way Transitions at Signalized Intersections

Implications of Driver Behavior for Conflicting Through Movements

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To improve traffic safety at signalized intersections, driver behavior associated with right-of-way transitions at signalized intersections must be quantified carefully. Video data from five intersections across Oregon were collected and transcribed; a total of 149 h corresponded to 3,474 vehicles responding to a circular yellow (CY) indication and 731 vehicles responding to a circular red (CR) indication. A mixed logit model was used to evaluate driver responses to CY and CR indications. Multiple linear regression was used to analyze the characteristics of red light runners (RLRs). Sufficiency of the red clearance interval was evaluated by considering the interactions of RLRs with vehicles on the conflicting approach. Developed models indicated that a 1-s increase in red time per cycle decreased the probability that a car would stop in response to a CY indication (by 41.4%) or a CR indication (by 9.0%). However, an increase in red time decreased the required duration of the red clearance interval. A 1-s red clearance interval generally was adequate for passenger cars, light trucks, and trucks at intersections up to 80 ft wide and at intersections with a red time of at least 60 s per cycle but rarely was sufficient for semitrailers in wider intersections with shorter red times. This observation is critical because semitrailers were more likely to be RLRs than were other vehicle types.

One of the most challenging decisions made by drivers approaching a signalized intersection occurs when they encounter the onset of a circular yellow (CY) indication. The correct driver response to the CY depends on the yellow law governing that particular state. Laws pertaining to driver reaction to the yellow change interval in each state can be classified as three types:

- Type 1. Vehicles can enter the intersection at any point during the yellow change interval; a vehicle may legally be in the intersection during a red if it entered the intersection during a yellow.
- Type 2. Vehicles cannot enter or be in the intersection on red.
- Type 3. Vehicles should stop during the yellow indication, but they may proceed with caution through the intersection if it is not possible to stop safely (*1*).

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Previous work has called Type 1 a "permissive yellow" law. Types 2 and 3 are referred to as "restrictive yellow" laws, such as found in Oregon (*2*).

According to national statistics, incorrect stop-or-go decisions and associated acceleration or deceleration in response to the onset of CY indications cause catastrophic numbers of fatalities and serious property damage. In 2013, the NHTSA Fatality Analysis Reporting System reported 697 crash deaths caused by red light runners (RLRs) (*3*). Similarly, in 2014, NHTSA estimated that motor vehicle crashes at intersections constitute 27% of all fatal crashes reported in the United States (*4*). An estimated 127,000 people are injured each year as a result of red light running (*5*).

To improve traffic safety at signalized intersections, driver behavior associated with right-of-way transitions at signalized intersections must be carefully quantified. This study evaluated driver responses to CY and circular red (CR) indications on the major approach and to the onset of the circular green (CG) indication on the minor approach at signalized intersections. The red clearance interval was evaluated by considering the interaction of RLRs on the major approach with conflicting vehicles on the minor approach.

LITERATURE REVIEW

An important first step in the analysis of driver behavior in response to right-of-way transitions is the identification of influencing factors. Bonneson et al. (*6*) proposed two categories of factors that contribute to red light running: exposure and contributory factors. A third category, conflict factors, was proposed specifically for RLRs.

Exposure factors are precursor events that expose drivers to a situation in which they must decide whether to stop or proceed through an intersection. Some exposure factors that affect RLR rates include

- Flow rate of the subject's approach,
- Number of cycles,
- Phase termination by max-out, and
- Flow rate of the conflicting approach.

Three studies reported sufficient data to support an increase in RLR frequency as the approach flow rate increases (*7–9*). Longer cycle lengths decrease the frequency per unit of time that a CY indication is presented; Bonneson et al. (*6*) recommended that red light running statistics be normalized by cycle frequency. Green light extension systems are used to extend the green interval if the approach is occupied in an attempt to reduce the number of vehicles that are presented with a CY indication because CY exposure can lead to red light running (*10, 11*), and the *Traffic Signal Timing Manual* defines max-out as "a type of actuated operation for a given phase where the phase terminates due to reaching the designated maximum green time for the phase" (*11*). Mohamedshah et al. found that the probability of RLR crashes on the major street increased with increasing volume on the minor street (*9*).

Unlike exposure factors, which create opportunities for red light running, contributory factors directly influence red light running events. The literature identifies several contributory factors:

- Probability of stopping,
- Duration of yellow change interval, and
- Leading and following positions.

A driver's probability of stopping in response to a CY indication depends on many factors, including travel time to the stop line at the onset of CY, headway between vehicles ahead and behind, signal coordination, signal actuation, approach grade, and speed (*6, 12–14*). An improperly timed yellow change interval—specifically, one timed too short—can contribute to red light running (*15*); long yellow change intervals can lead to disobedience because drivers are tempted to enter the intersection later in the CY (*16*) when they are not "rewarded" with a CR if they stop at the stop line (*6*). A vehicle following a leading vehicle going through the intersection at the onset of a CY is more likely to be an RLR (*17*).

A conflict may occur if a driver makes an incorrect decision during the yellow change interval and runs the red light. Two factors related to this conflict include

- Duration of the red clearance interval and
- Entry time of the conflicting driver.

Use and duration of red clearance intervals vary by jurisdiction because the *Manual on Uniform Traffic Control Devices* allows engineering judgement to dictate the inclusion of a red clearance interval (*18*). Improper timing can lead to a conflict if a vehicle entering at the end of the yellow change interval cannot clear the intersection before the end of the red clearance interval (*6*). The entry time of a conflicting driver (i.e., the time it takes for a vehicle on a minor approach to enter intersection) after onset of the CG indication can lead to conflict with an RLR, which can be compounded by unique intersection geometries. If the RLR is still clearing the intersection at the onset of the CG indication for conflicting traffic and the conflicting driver reaches the conflict zone before the RLR clears it, then a conflict will occur (*6*).

In analyzing the effects of exposure, contributory, and conflict factors, past studies have focused mainly on stop-or-go decisions, brake response times, and acceleration rates associated with driver behavior in response to signal changes (*17, 19, 20*). These evaluations were primarily based on descriptive statistics and probabilistic techniques or small sample sizes. To account for the heterogeneity of factors that influence the behavior of individual drivers (*21*), the present study considered a comparatively large sample size with an econometric method for developing a stop-or-go model.

DATA COLLECTION

With guidance from the literature review, a field study was developed to investigate factors contributing to driver responses to signal changes. Table 1 summarizes the factors for site selection.

TABLE 1 Site Selection Factors (*1*, pp. 22–23)

Factor	Categories
Speed limit	≤ 40 mph, 45 mph, or ≥ 50 mph
Area type	Urban (downtown), suburban, or rural (outside of incorporated area)
Intersection clearing width (from stop line to far curb)	≤ 48 ft, 48–72 ft, 72–96 ft, 96–120 ft, or ≥ 120 ft
Proximity to upstream signal	No upstream signal within 0.5 mi or upstream signal within 0.5 mi
Cycle length	< 90 s, 90–120 s, 120–180 s, or > 180 s
Yellow change interval duration	≤ 4.0 s, 4.1–4.5 s, 4.6–5.0 s, or ≥ 5.1 s
Red clearance interval duration	None, < 1.0–2.0 s, 2.1–3.0 s, or > 3.0 s
Opposing left-turn signalization	Protected only, permissive only, protected–permissive (leading left turn), permissive–protected (lagging left turn), or none or prohibited
Approach grade	Level (between −3% and +3%), upgrade (greater than +3%), or downgrade (greater than −3%)
Existence of red-light camera enforcement	Camera enforcement at the intersection, or no camera enforcement program within jurisdiction
Time of day for sampling	Weekday peak (7–9 a.m., 4–6 p.m.), weekday lunch (11 a.m.–1 p.m.), weekday off-peak (all other weekday times), or weekend periods
Vehicle type	Passenger vehicle, motorcycle, bus, recreational vehicle, single-unit truck, or multiunit truck

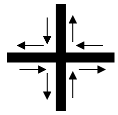
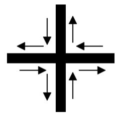
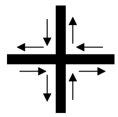
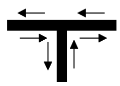
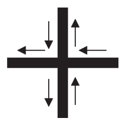
From a review of the history of crashes related to red light running, the presence of red light cameras, and the use of red clearance extension systems, 11 possible sites selected for consideration. Site characteristics were analyzed to determine the best sites for data collection. Additional data were collected, consistent with the recommendations of McGee et al. (*1*). Finally, five distinct sites with one intersection per site were selected for field data collection (Table 2).

Sites were located in various geographic areas to collect driver behavior from across Oregon. Sites with pretimed signals were not selected because previous literature has shown differences in driver behavior at pretimed and actuated intersections (i.e., drivers approaching an actuated intersection are less likely to stop) (*22*). Site A in Corvallis, Oregon, was selected as the beta test site; its proximity to Oregon State University simplified the logistics of testing alternative implementation plans.

Video data were collected at each test site for 1 week during the first quarter of 2015; digital cameras typically were installed on telescoping poles at the site on Monday and removed on Friday. Intersection operations were collected between 7:00 a.m. and 7:00 p.m. on Tuesday, Wednesday, and Thursday. Mondays and Fridays were excluded to avoid bias from weekend travel, because weekend and weekday travel behavior and traffic characteristics were expected to be different (*23*).

Various tools were evaluated robustly for video data collection, and the CountCam Duo 40 was selected. Video footage was saved to SD cards, which later were uploaded to a computer for data reduction and analysis. At two of the five intersections, CountCam systems were installed at two opposing corners of the intersection. At the remaining three intersections, only one CountCam system was installed because

TABLE 2 Summary of Selected Sites in Oregon

Site	Intersection Location	Geometry	Red Light Camera	RCE System	Area Type	Speed Limit (mph)	Coordination
A (Beta)	OR-99W at Circle Blvd. Corvallis, Oregon		No	No	Urban	50	Yes
B	OR-99E at Broadway Salem, Oregon		No	No	Urban	45	No
C	OR-99E at Mt. Hood Woodburn, Oregon		Yes	No	Suburban	35	Yes
D	US-30 at Cornelius Pass Rd. Unincorporated Multnomah County, Oregon		No	Yes	Rural	55	No
E	US-26WB at 185th Beaverton, Oregon		No	No	Suburban	45	Yes

NOTE: RCE = red clearance extension.

of site geometry (e.g., horizontal curve, T-intersection, or one-way ramp). In addition, a measuring wheel was used to measure distances on major and minor approaches of each intersection. Distance measurements were captured on video to aid the processes of video reduction and transcription.

DATA REDUCTION

Distance measurements on the major and minor approaches made in the field were overlaid on video data. Satellite images and intersection plan drawings were used to verify field measurements. Paint.net, free image-editing software, was used to make "transparent" images used as distance overlays in video reduction. Data reduction was completed with VirtualDub, a free video-capture and -processing utility that allows captured video data to be viewed frame by frame, with a video time stamp displayed to the millisecond. CountCams were set to record at a rate of 10 frames per second (i.e., accuracy of 0.1 s). The Image Overlay Utility program was used to display transparent images with distance markings over the video files. Figure 1 summarizes the process of setting up the raw video footage to be transcribed.

In total, 252 h of video data were collected across all five intersections. File errors and equipment tampering reduced this total to 234 h of usable data. Seven students were trained on the software and the transcription process during one 2-h training session. Microsoft Excel templates were created as an outline for transcribed data. Video data transcriptions were divided into the following categories from the major approaches:

- Time stamps at onset of CG, CY, and CR indications;
- Vehicle location at onset of CY and CR indication;
- Driver decision (stop or go);
- Number of RLRs; and
- Vehicle classification.

Video data transcriptions were divided into the following data from the minor approaches:

- Time stamps at onset of CG indication,
- Time stamp of first vehicle per lane to reach the stop line and each conflict zone boundary, and
- Vehicle classification.

The lead graduate student randomly spot checked 5 minutes of every transcribed hour. If any inconsistencies were identified, then the entire hour was transcribed again. Table 3 summarizes the collected and transcribed data. Because the camera field of view was required to include intersection approaches and the conflict zone, some mainline vehicles were occluded from view, resulting in a greater amount of minor street vehicles.

The study was limited because of the type of data collected. The effects of factors including driver demographics (e.g., age, gender, and experience) and ambient characteristics (e.g., traffic volume, weather, light, and pavement conditions) on the stop-or-go decisions of drivers could not be considered because these data were not collected.

ANALYSIS

Driver Response to Signal Change on Major Approach

To investigate driver response to signal changes, a mixed logit model (or random parameter logit model) was used to determine the probability that a vehicle will stop or go through the intersection at the

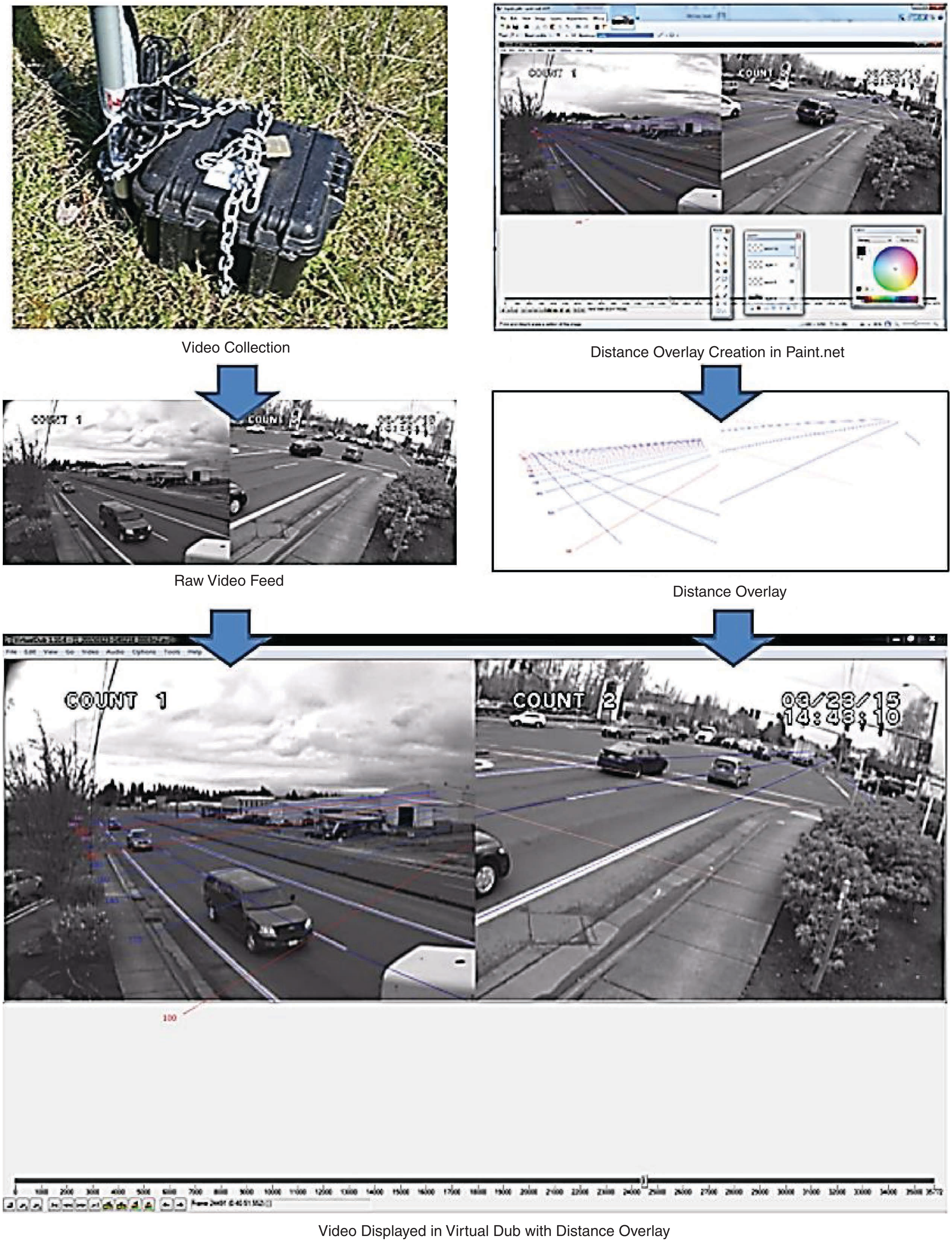


FIGURE 1 Data transcription process.

TABLE 3 Summary of Collected Data

Site	Hours: Recorded	Hours: Usable	Hours: Transcribed	Vehicles/Day: Major Approach	Vehicles/Day: Minor Approach	Cycles/Day	RLR Events/Day
A	72	71	47	N: 844 S: 640	NW: 925 SE: 1,035	390	N: 3 S: 3
B	36	36	23	1,141	697	372	0
C	72	72	36	N: 625 S: 571	NW: 401 SE: 779	403	N: 1 S: 0
D	36	36	24	984	1,439	844	24
E	36	19	19	1,350	2,180	501	5
Total	252	234	149	6,155	7,456	2,510	36

NOTE: N = north, S = south, NW = northwesterly, and SE = southeasterly; all indicate vehicle direction.

onset of a CY or a CR indication. This probability was coded as a 0 or 1 outcome (0 = stop, 1 = go), resulting in a binary structure for analysis. The mixed logit model accounts for potential observed and unobserved heterogeneities in the data. Heterogeneity across driver responses might result from the unique characteristics of each intersection, unobserved heterogeneity due to traffic conditions, and driver and vehicle characteristics. Accordingly, the influence of variables that affect stop-or-go decisions may vary across intersections or vehicle types. A mixed logit model explicitly accounts for these variations.

In a mixed logit model, parameter estimates for variables follow a stochastic distribution to account for observed and unobserved heterogeneities. A binary mixed logit formulation is

$$P_n^m(i) = \int \frac{1}{1 + \text{EXP}[-\beta_i X_{in}]} f(\beta|\varphi)d\beta \quad (1)$$

where

$P_n^m(i)$ = probability of observation n having discrete outcome i in a mixing distribution m,

X_{in} = vector of explanatory variables corresponding to outcome i for observation n,

β_i = vector of estimable parameters conditioned on outcome i, and

$f(\beta|\varphi)$ = density function of parameter β given a vector of the density function parameters φ (*21*).

Separate models were developed to investigate driver responses to CY and CR indications. The entire data set (4,048 observations) was used to model responses to CY. After missing data were removed, the original data set was reduced to 3,474 observations (676 stopping vehicles and 2,798 go decisions). The limited number of RLRs at four intersections meant that combining all of the data would not be statistically sound. Observations from Site D, which had the highest rate of RLRs, were considered when modeling driver responses to CR indications. Usable observations of driver responses to CR indications included 707 stop decisions and 24 go decisions (731 total observations) available for model development.

A backward stepwise procedure was used to select significant variables and exclude insignificant variables from the final models. Specifically, the presence of a red light camera, time of day (morning or evening peak), and duration of yellow change interval were not statistically significant and therefore were removed from the final models. The definitions and descriptive statistics [means and standard deviations (SDs)] for the final variables in the models are listed in Table 4. Time to stop line (TTSL) at the onset of a signal change provided a generally consistent measure of a vehicle's upstream position and therefore was used instead of distance and approach speed.

NLOGIT3 econometric software was used to develop the mixed logit models. Random parameters were obtained from 1,000 random draws using standard Halton-sequence intelligent draws. With considerations of normal, lognormal, triangular, and uniform distributions,

TABLE 4 Variable Definitions and Descriptive Statistics

Variable	Description	Response to CY Indication: Mean	Response to CY Indication: SD	Response to CR Indication: Mean	Response to CR Indication: SD
RED	Average red time in each cycle per hour (s)	51.55	18.20	21.32	3.57
TTSL	Time to stop line at onset of signal change (s)	1.77	1.41	2.10	0.95
NOC	Number of cycles per hour	39.56	14.52	68.82	7.16
PC	Vehicle type (1 if passenger car, 0 otherwise)	0.73	0.44	0.72	0.45
LT	Vehicle type (1 if light truck, 0 otherwise)	0.20	0.40	na	na
ST	Vehicle type (1 if semitrailer, 0 otherwise)	na	na	0.04	0.20
Rural	Area type (1 if rural, 0 otherwise)	0.18	0.38	na	na
ALA	Adjacent lane action (1 if go, 0 stop)	0.16	0.37	na	na
LVG	Lead vehicle goes through intersection (1 if yes, 0 if no)	0.19	0.39	na	na

NOTE: na = not applicable.

TABLE 5 Analysis of Driver Responses to Signal Changes

	Response to CY Indication					Response to CR Indication				
Variable	Mean	*t*-Stat.	SD	*t*-Stat.	Marginal Effect	Mean	*t*-Stat.	SD	*t*-Stat.	Marginal Effect
Constant	−2.313	−1.402	na	na	na	7.238	1.279	na	na	na
RED	−0.026	−2.412	na	na	−0.414	−0.177	−1.652	na	na	−0.090
TTSL	2.027	16.520	na	na	1.363	3.932	3.952	na	na	0.074
NOC	−0.093	−2.665	na	na	−0.810	−0.069	−1.119	na	na	−0.113
PC	0.693	2.121	na	na	0.132	5.188	1.795	4.416	2.265	0.009
LT	0.762	2.070	0.998	1.777	0.052	na	na	na	na	na
ST	na	na	na	na	na	−2.520	−2.564	na	na	−0.014
Rural	−9.085	−2.026	5.042	2.219	0.002	na	na	na	na	na
ALA	−1.417	−2.698	2.329	4.083	0.008	na	na	na	na	na
LVG	1.278	6.338	1.737	4.907	0.126	na	na	na	na	na
Number of observations	3,474					731				
Log likelihood at convergence	−755.615					−68.603				
Restricted log likelihood	−2,407.993					−506.691				
χ^2 (degree of freedom)	3,304.757 (13)					876.175 (7)				
Adjusted R^2	.685					.863				
Percentage of correct predictions	86.93					95.08				

random parameters were tested to check for the best distribution. Normal distributions resulted in the best statistical fits. Table 5 shows results of the mixed logit estimates of driver responses to CY and CR indications. For both models, the base scenario was the occurrence of a go decision; the alternative specific constant and all remaining independent variables were assigned to the utility function of the stop decision. In each model, random parameters were those that produced statistically significant standard errors for the assumed distribution. All estimated parameters included in the models were statistically significant, and all signs were plausible.

All common variables between the two models had similar signs. In other words, each variable that increased the probability of a go decision at the onset of CY also increased the probability of a go decision at the onset of CR. The only difference was for the alternative specific constant, which accounted for the systematic bias of all unobserved attributes that contributed to stop-or-go decisions. The negative constant for the response to the CY indication in the models suggested that unaccounted-for attributes (e.g., driver's characteristics, weather condition, ambient light, and pavement condition) collectively reduced the probability of stop events in this data set. Conversely, the positive constant for the response to the CR indication in the models suggested that unaccounted-for attributes (e.g., driver's characteristics, weather condition, ambient light, and pavement condition) collectively increased the probability of stop events in this data set.

The variables for average red time per cycle per hour (RED), TTSL, and number of cycles (NOC) were fixed (nonrandom) parameters included in both models. All three variables had similar influences on the probability of a stop decision at the onset of CY or CR but differed in magnitude. According to the marginal effects, a 1-s increase in RED decreased the probability that a car would stop in response to the CY by 41.4% and to the CR indication by 9.0%. Similarly, an increase of one additional cycle per hour decreased the probability of a stop decision in response to the CY indication by 81.0% and in response to the CR indication by 11.3%.

The data set includes some observations with a short cycle length but a large RED. This finding is somewhat counterintuitive to the general assumption that NOC increases would result in longer RED. Moreover, an increase in NOC increases the drivers' exposure rate to signal changes and therefore decreases stop decisions. TTSL at the onset of the CY indication was the most influential variable. When the vehicle was 1 s farther from the stop line, the probability of stopping in response to the CY indication increased by 136.3%.

Vehicle type had a statistically significant relationship with the response to the CY and CR indications. In response to CY, the light truck (LT) variable was a normally distributed parameter with a mean of 0.76 and an SD of 1.00. In approximately 76% of cases, a light truck as subject vehicle increased the likelihood of a stop event in response to CY. In response to CR, the passenger car (PC) variable was normally distributed with a mean of 5.19 and an SD of 4.42. In approximately 88% of cases, the probability of a stop event increased for a passenger car as subject vehicle. In modeling driver response to the onset of CY, PC was a fixed parameter that increased the probability of a stop decision; in response to CR, the semitrailer (ST) variable was a fixed parameter that decreased the probability of a stop decision.

Area type was a random parameter defined as rural or nonrural. This variable had a statistically significant relationship with response to the CY indication. The rural variable was normally distributed, with a mean of −9.09 and an SD of 5.04. In approximately 96% of cases, being in a rural location decreased the probability of a car stopping in response to a CY.

Actions of other vehicles (adjacent or in front) were statistically significant random variables in response to the CY indication. Adjacent lane action was a normally distributed parameter with a mean of −1.42 and an SD of 2.33. In approximately 73% of cases, the presence of a vehicle on an adjacent lane that goes through the intersection decreased the probability of a stop decision by the subject vehicle. Lead vehicle going was another normally distributed parameter with a mean of 1.28 and an SD of 1.74. In approximately 77%

of cases, the presence of a leading vehicle that went through the intersection increased the likelihood of a stop decision by the subject vehicle.

Modeling Latency on Major Approach

Latency was defined as the TTSL at the onset of the CR indication for an RLR. Latency was analyzed by multiple linear regression to investigate the effects of several explanatory variables. Different combinations of independent variables were tested through a backward stepwise procedure. Vehicle type [PC, LT, ST, or truck (T), where T is the base type] and RED produced the best statistical fit in the final model. Linear regression estimation was performed in R statistical software (Version 3.0.3). The resulting least squares linear regression equation for the latency (in seconds) of RLRs was estimated as follows:

$$\text{latency} = \text{EXP}\begin{pmatrix} -1.453 + 0.458 \times \text{PC} - 0.134 \times \text{LT} + 0.524 \\ \times \text{ST} - 4.5 \times 10^{-4} \times \text{RED}^2 + 0.017 \times w \end{pmatrix} \quad (2)$$

where w is the width of the intersection (in feet) and the remaining variables are defined as in Table 4; R^2 is .59. The signs and magnitudes of parameter estimates in Equation 2 indicated that latency increased most when the subject vehicle was ST or PC. Strong evidence indicated that RED was associated with latency after accounting for vehicle type and intersection width. When all other variables were held constant, latency decreased with longer RED and increased with larger intersection width.

Driver Response to Onset of CG on Minor Approach

One variable that could significantly influence the risk of collision with an RLR is the time that it takes a vehicle on the minor approach to reach the conflict area. Time to collision (TTC) is a commonly used severity indicator of traffic conflicts and near misses. TTC is defined as "the time required for two vehicles to collide if they continue at their present speeds and on the same path" (*24, 25*). The minor approach was observed to determine TTC values for the first vehicle at the onset of the CG indication. In 121 h of observation, 7,456 vehicles were counted. Figure 2 is a boxplot of TTC values for the first conflict point and the average distance from the conflict point to the stop line for each intersection; NW and SE indicate northwesterly and southeasterly vehicle directions, respectively.

TTC varied by intersection approach. This variance was due, at least in part, to differences in the distance from the stop line to the conflict zone. Some combination of development density and functional classification of the roadways also influenced TTC values. Distance to the conflict zone was the same at Site E (urban setting) and Site C (suburban setting), but TTC was slightly higher at Site C. These factors suggest that the TTC for the lead vehicle on the minor approach should be calculated for each intersection to ensure that appropriate values are selected to protect vehicles on the minor approach and reduce delays.

To develop guidance that could be applied directly to signal timing practices, the first percentile values of TTC were calculated to account for the most critical conflicts. When a normal distribution of the TTC data was assumed, the first-percentile TTC for a conflict zone was located 2.33 SDs below the mean, as indicated by the following equation:

$$\text{1st percentile TTC} = \mu + (-2.326 \times \sigma) \quad (3)$$

where μ is the mean and σ is the SD of the TTC value. Table 6 displays the descriptive statistics of TTC for the first conflict point at each location.

Determination of Red Clearance Interval

With the developed model of latency (Equation 2) and the calculated TTC values on the minor approach (Table 6), the red clearance

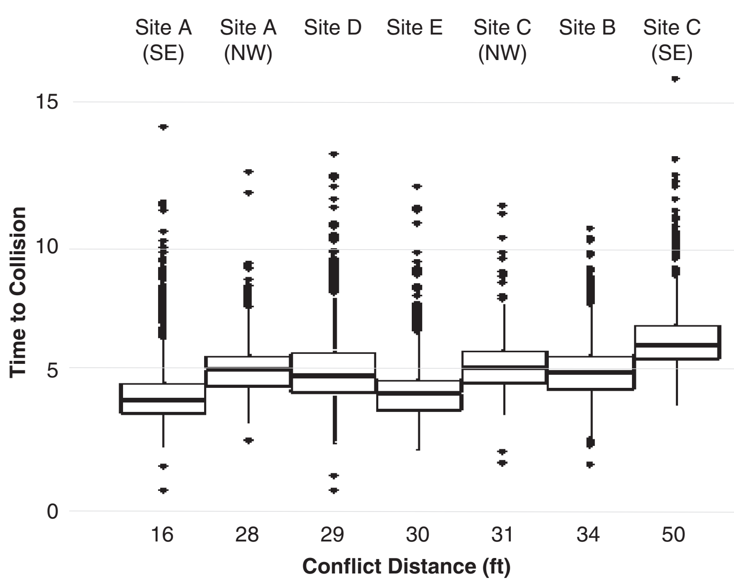


FIGURE 2 Time to collision at each intersection.

TABLE 6 Descriptive Statistics for Time to Collision at Each Intersection

Location	Mean (s)	SD	1st Percentile (s)
Site A			
NW	4.938	1.176	2.203
SE	4.100	1.273	1.139
Site B	4.865	1.237	1.988
Site C			
NW	5.053	1.210	2.239
SE	5.906	1.183	3.154
Site D	4.121	1.221	1.281
Site E	4.811	1.243	1.920
All locations	4.707	1.263	1.769

interval can be calculated for various vehicle types. Figure 3 shows an example conflict zone (C) in which Vehicle 1 runs the red light on the major approach and Vehicle 2 enters the intersection in response to a CG indication on the minor approach (T_1 = latency, T_2 = intersection clearance time, and T_3 = TTC). A realistic value for duration of the red clearance interval could be calculated with the following equation:

$$\text{red clearance interval} = T_1 + T_2 - T_3 \tag{4}$$

The corresponding values of T_1 and T_3 could be determined from previous analysis, but T_2 must be calculated for each specific intersection. Therefore, a modified version of the red clearance interval equation from the current *Traffic Engineering Handbook* (*26*) was used:

$$T_2 = \frac{w + L}{v} \tag{5}$$

where

w = width from the stop line to the far-side furthest conflict zone (ft);
v = approach speed (ft/s); and
L = vehicle length (ft).

Like in the TTC calculation, T_2 was calculated with a conservative value for approach speed (v = 45 mph) to maximize safety. To account for the length of various vehicle types, L was obtained from *A Policy on Geometric Design of Highways and Streets* (*27*).

A red clearance interval was calculated by applying T_1 (Equation 2), T_2 (Equation 5), and T_3 (Table 6) values to Equation 4. These red clearance interval values are plotted against the RED for various vehicle types and intersection widths in Figure 4.

Duration of the red clearance interval decreased as RED increased. Figure 4 demonstrates that a 1-s red clearance interval (dashed line) was adequate for passenger cars, light trucks, and trucks to clear an intersection of 80 ft or less in width or an intersection with a RED of 60 s or longer. However, this clearance interval was not adequate to accommodate the safe clearance of ST vehicles in intersections with larger width or shorter RED values.

SUMMARY AND CONCLUSION

Driver responses to signal changes on major and minor approaches were investigated. On the major approach, driver responses to CY and CR indications were analyzed with binary mixed logit models. In response to a CY indication, the likelihood of a go decision by the subject vehicle was increased by a longer RED, a greater NOC, a rural location, and the presence of an adjacent vehicle that went through the intersection. This likelihood of a go decision was decreased by a longer TTSL, a PC or an LT vehicle classification, and the presence of a lead vehicle that went through the intersection. In response to a CR indication, the probability that the subject vehicle would be an RLR was increased by a longer RED, a greater NOC, and an ST vehicle classification. This likelihood was decreased by a longer TTSL and a PC vehicle classification. Even though these variables played a pivotal role in stop-or-go decisions, the significance of the constant indicated the importance of attributes that were unaccounted for, such as driver demographics and ambient characteristics.

Red light running also was investigated by considering the timing of the red clearance interval. Latency was modeled, driver response to a CG on the minor approach was investigated, and intersection clearance time was calculated. These three items were used to calculate the duration of the red clearance interval on the basis of vehicle classification, intersection width, and RED duration. Duration of the red clearance interval decreased with increases in RED. A 1-s red

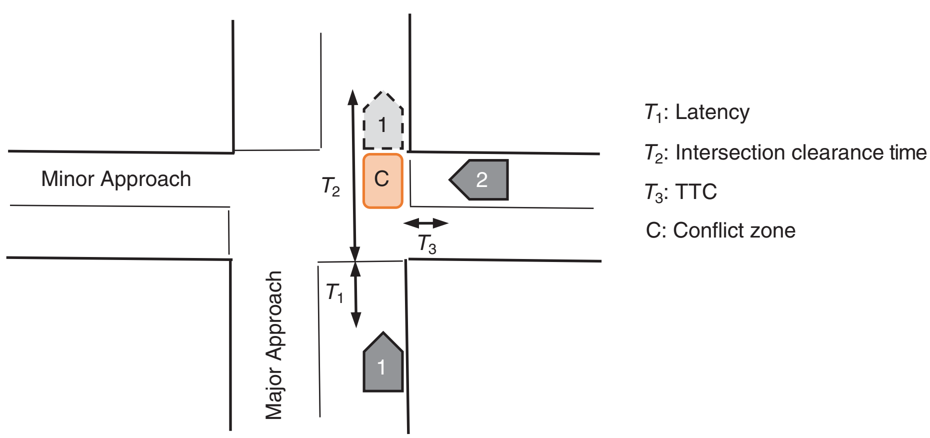


FIGURE 3 Example of conflict zone.

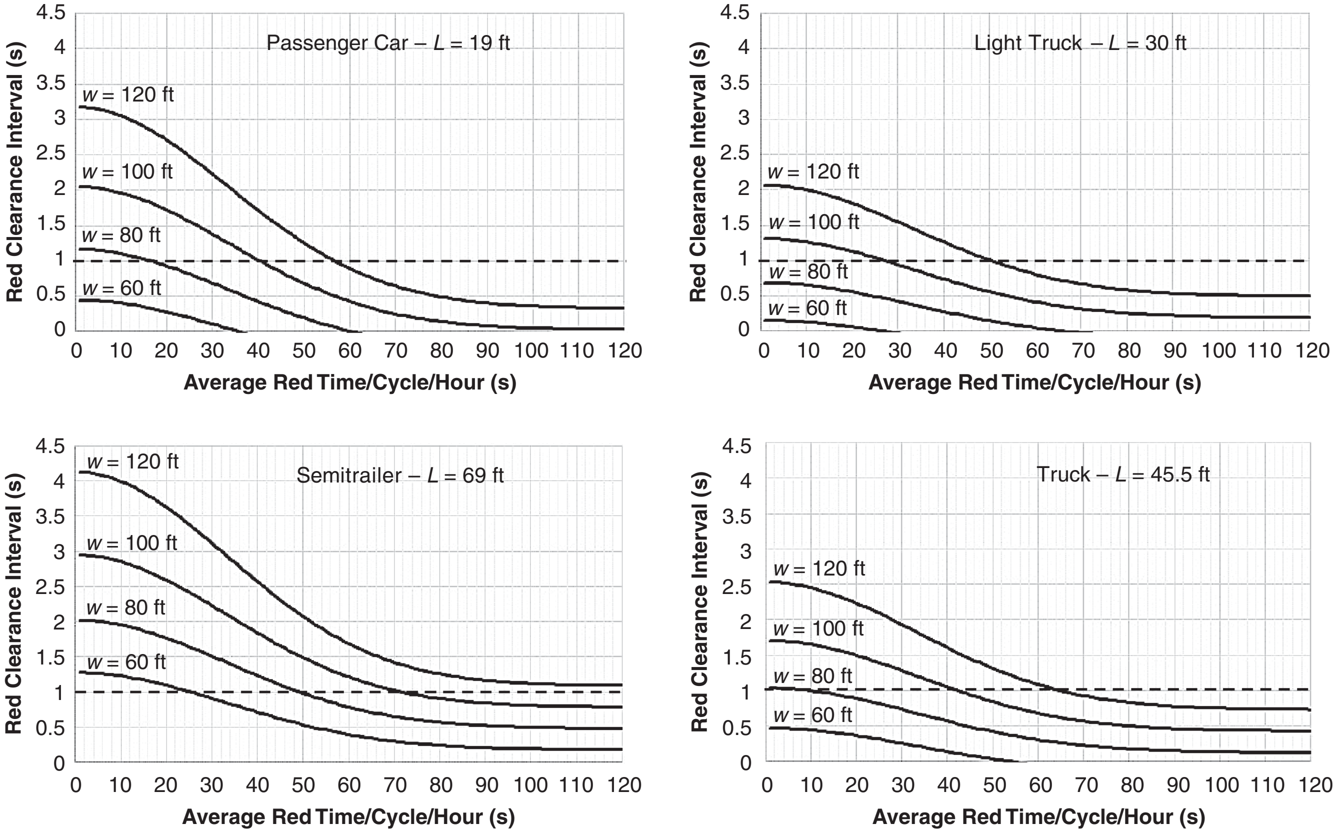


FIGURE 4 Red clearance interval, by RED.

clearance interval was adequate for PC, LT, and T vehicles at intersections up to 80 ft wide or with a RED of at least 60 s per cycle. This clearance interval was insufficient for semitrailers at intersections that were wider or had shorter RED values.

The RED could account for the influence of driver familiarity with the subject intersection. When drivers know that stopping will add considerable delay to their travel time, they tend to go through the intersection, particularly in response to the onset of a CY indication. The findings of the study indicate that reducing RED could reduce the likelihood of red light running because a 1-s increase in RED resulted in a 9% increase in the likelihood of red light running. However, additional investigation of red light running demonstrated that longer RED values decreased the latency; therefore, shorter red clearance intervals were needed. Indeed, longer RED values increased the probability of red light running, strengthening the argument for including red clearance intervals in timing plans. At the same time, longer RED values negatively influenced the duration of the red clearance interval such that a 1-s red clearance interval was always adequate for safe clearance of PC, LT, and T vehicle types when RED exceeded 60 s.

A 1-s red clearance interval was inadequate for the safe clearance of ST vehicles. This finding is critical, given that models of driver responses to CR indications had suggested that, all other variables being the same, semitrailers were more likely than other vehicle types to run the CR indication. This finding implies that under specific circumstances, calculating the red clearance interval with a 20-foot vehicle length could result in unsafe signal timing practices (*1*). These suggestions are of particular importance at rural intersections.

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