Impacts of Red Light Photo Enforcement Cameras on Clearance Lost Time at Signalized Intersections

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ABSTRACT
Red light running (RLR) is one of the most common violations drivers commit at signalized intersections. To avoid RLR violations, some drivers may decide to stop abruptly, even though they had the opportunity to cross the stop line before the onset of the red light. This action happens more frequently at the intersections with a red light camera (RLC). The consequence of this change in drivers' stopping behavior is the potential reduction of the usable clearance interval and the slight decline in the intersection capacity. However, the Highway Capacity Manual (HCM) and the Alabama Department of Transportation (ALDOT) Traffic Signal Design Guide and Timing Manual take different approaches to estimate the clearance lost time (CLT) for capacity analysis of signalized intersections; there is not an adjustment factor for considering the impact of RLCs. In an attempt to quantify the effect of RLCs on the capacity of signalized intersections, field data were collected at eight intersections: four with RLCs and four without, in the cities of Opelika, and Auburn, Alabama. A total of 1,191 cycles and a total of 1,863 drivers' responses to clearance intervals were used to estimate the CLT. It was found that the estimated CLT at the approach with a RLC is approximately 2.7 seconds longer than the default value presented by HCM and about 1.1 seconds longer than one estimated by ALDOT method. On average, the unused yellow time was a half second longer in RLC intersections than the intersections without RLCs.

Keywords: Red-light Running Camera, Clearance Lost Time, Highway Capacity Manual, Signalized Intersection

INTRODUCTION

Red-light running cameras (RLCs) at intersections are gaining widespread popularity. The first U.S. application of RLCs was in New York City in 1991 (*1*). Afterward, a multitude of cities across the nation began to implement enforcement cameras. The main objective of the new system was to improve intersection safety through capturing red-light runners who may cause severe crashes and pose serious danger to the other road users. As of October 2013 an estimated 521 RLC programs were operating in 26 states and Washington, DC. (*2*).

When a driver approaches a signalized intersection during a steady yellow signal indication, the driver is being warned that the right-of-way is about to change from their phase to some other phase with which they will be in conflict. Drivers who cross the stop line and proceed through the intersection after the onset of the red indication can be identified by police enforcement or a RLC. In order to avoid this violation, some non-aggressive drivers may stop abruptly, even if they had a chance to cross the line during the yellow interval. As many studies have indicated (3-*9*), this action contributes to the risk of a rear-end crash and is stated as a negative impact of RLCs; however, it is negligible when compared to their known benefits in reduction of angle or sideswipe crashes. Besides the safety effects, RLCs influence the operational aspects of the intersection. As mentioned earlier, RLCs make some individuals drive more cautiously; therefore, the amount of yellow time used by vehicles at intersections with RLCs will be reduced and the intersection capacity may slightly decline. In an attempt to investigate the impact of RLCs on the capacity of signalized intersections, field observations were conducted during a continuous three-hour period from 3:30 p.m. to 6:30 p.m. at eight intersections in Auburn-Opelika, Alabama.

In the following sections, the findings of past studies related to the impact of RLC programs on drivers' behaviors are summarized. The process of data collection is then described and the data required to estimate the clearance lost time are identified. Based on the definition of clearance lost time (CLT) in HCM, this value for each approach monitored by a RLR camera was ascertained and compared with the CLT values at the intersections with no cameras. They were also compared with the default values specified in recent studies on CLT in order to determine whether or not RLCs had an effect on the CLT. Recommendations will be developed based on the analysis results on adjustment to the default value of CLTs.

LITRETURE REVIEW

There have been numerous studies on the effectiveness of RLC programs in different states. Some (*5- 14*) used reliable data and incorporated control for regression to the mean (RTM) in the evaluation methodology in order to focus on the safety effect of RLCs at intersections and some provided evidence of citywide reduction in RLR violations, suggesting a generalized effect on drivers' behavior (*15 and 16*). Retting et al. (*17*) showed that the violation rate was reduced by about 40% during the first year after the RLCs were installed. McCartt and Wen (*11*) examined the effects of RLCs on RLR by comparing the number of violations before and after the installation. Regression models were used to observe any spillover effects. The researchers observed a statistically significant reduction in the number of violations occurring 0.5 second (39%) and 1.5 seconds (86%) after the lights turned red. Moreover, odds of violations at non-camera intersections on the same corridor decreased 14%, 25%, and 63% for 0.5 second, 1 second, and 1.5 seconds after red light indication, which means that the RLCs had a positive impact on increasing the stopping decisions.

Amongst the many researched safety benefits of installing RLCs, few studies have examined drivers' behavior change in relation to RLCs. Gates et al.(*18*) examined the impact of driver behavior in the presence of RLCs, in addition to providing suggestions for yellow phase and all-red clearance timings. The researchers used 82 intersections in four regions of the United States, 10 of which had RLCs. Video cameras were used to capture driver behavior for 7,306 vehicles. From the analysis the following were found: at RLC intersections drivers tended to react 5% (0.05 seconds) quicker to a yellow light change when stopping; the deceleration rate is not affected by RLCs; the likelihood of a driver stopping is increased by 2.4% with a RLC present; entry time during a red light is reduced by 43% (0.24 seconds) with RLCs; and RLR rates are almost double at intersections with yellow times less than or equal to 4.5 seconds. Another study explored the effects of lengthening the yellow signal phase on RLR and the additional incremental effect of RLC enforcement (*19*). The researchers used video cameras to examine two intersections, a total of six approaches, in Philadelphia, Pennsylvania, and an additional three comparison intersections in Atlantic County, New Jersey. The yellow times were increased by approximately one second at each of the intersections with data being collected before the change and six weeks after. Logit analysis was used to model driver behavior as to whether the driver would run the red light or not. The results of this study found that after increasing the yellow time, RLR declined 36% with a 96% reduction after the installation of the RLCs. Retting used data from RLCs that recorded the number of drivers taking a defensive approach when confronting a yellow signal (*20*). They concluded that the clearance interval does affect RLR. Other similar study by Van der Horst on driver behavior at non-camera intersections in Netherlands concluded that a 1s extension of yellow interval results in about 50 percent reduction in RLR violations (*21*).

Based on the ALDOT's "Traffic Signal Design Guide and Timing Manual" (*22*), CLT is assumed to be half of the yellow interval plus the entire all-red interval. It also assumes that the lost time is generally fixed, regardless of cycle length. Two other studies determined the CLT in different manners. Webster and Cobbe (*23*) recommended the CLT to be one second less than the clearance interval period, and Miller (*24*) suggested to consider a half second shorter clearance interval as a CLT.

Past studies identified many contributing factors regarding RLR crashes, including: increase in traffic volume is known to be associated with an increase in RLR; delays caused by congestion negatively affect drivers' behavior, contributing to the number of RLR instances; and inadequate signal timing generally cause an increase in RLR by heavy vehicles. Few prior studies have examined drivers' behavior change caused by RLCs. Based on the past results summarized above, available studies mainly focused on the impact of signal timing (especially the yellow time) on driver decision making. It was found that the shorter yellow time resulted in the higher rate of RLR. Little documentation has been found concerning the effects of RLCs on CLT and the capacity of signalized intersections.

DEFINITION of CLEARANCE LOST TIME

At every signalized intersection, the intersection was not used by traffic during two time periods of each phase: a portion of the beginning of the green period and a portion of the yellow change interval plus the all-red clearance interval. The first is called the start-up lost time and the latter is the CLT. The sum of these lost times for each movement is used to estimate the capacity and delay for each movement and the overall intersection. Equation (1) represents how the signalized intersection capacity (c_i) is determined (*25*).

$$c_i = s_i \frac{g_i}{C} \quad (1)$$

Where i represents the movement number, g_i denotes the effective green for the movement i, s_i represents the saturation flow rate, and C is the cycle length. In order to find the effective green, the following equations are provided in HCM (*25*):

$$g_i = G_i + Y_i - t_L \quad (2)$$

$$Y_i = y_i + ar_i \quad (3)$$

$$t_L = l_1 + l_2 \quad (4)$$

$$l_2 = y + ar - e \quad (5)$$

Where *ar* denotes the all-red time clearance interval, the period in the signal cycle during which all approaches have a red light indication: l_2 denotes CLT, *e* represents the extension of green, y_i is the yellow change interval, Y_i is the clearance interval, and G_i is the green time. Webster and Cobbe (*23*) suggested considering all clearance interval minus 1 second as CLT, while another study by Miller (*24*) recommended using 0.5 second instead of 1 second. The HCM defines a default value of 2 seconds CLT for each phase. The longer the CLT (l_2) results in the less effective green time and the less capacity (c_i from Equation 1). The HCM defines CLT as "*The time, in seconds, between signal phases during which an intersection is not used by any critical movements.*" Based on this definition, in this research, the actual CLTs for 1,863 cycles were recorded and the mean and standard deviation of recorded CLT were calculated.

DATA COLLECTION

Beginning April 1, 2013, RLCs officially began monitoring traffic at four signalized intersections in Opelika, AL (26). The treated intersections were: US 280/Gateway Drive at HWY 15/Pepperell Parkway; Frederick Road at US 280/Gateway Drive; US 280/Gateway Drive at I-85 Off-ramp/Interstate Drive; and HWY 15/West Point Parkway at US 431/Fox Run Parkway/Lafayette Parkway, as shown by black circles in Figure 1. Monitored approaches are marked with advanced signs, informing approaching motorists they would be monitored by RLCs. As for investigating the effect of RLC on drivers' behavior, it was necessary to gather data at non-treated intersections with similar geometric and traffic characteristics as well. Following figure also represents the annual average daily traffic (AADT) in Auburn-Opelika roads for 2012. Non-camera intersections in this study are: Wire Rd and Shug Jordan; E University Dr and Opelika Rd; US 280 and Veterans Pkwy; and S College St and Shug Jordan Pkwy, as shown by white circles in Figure 1.

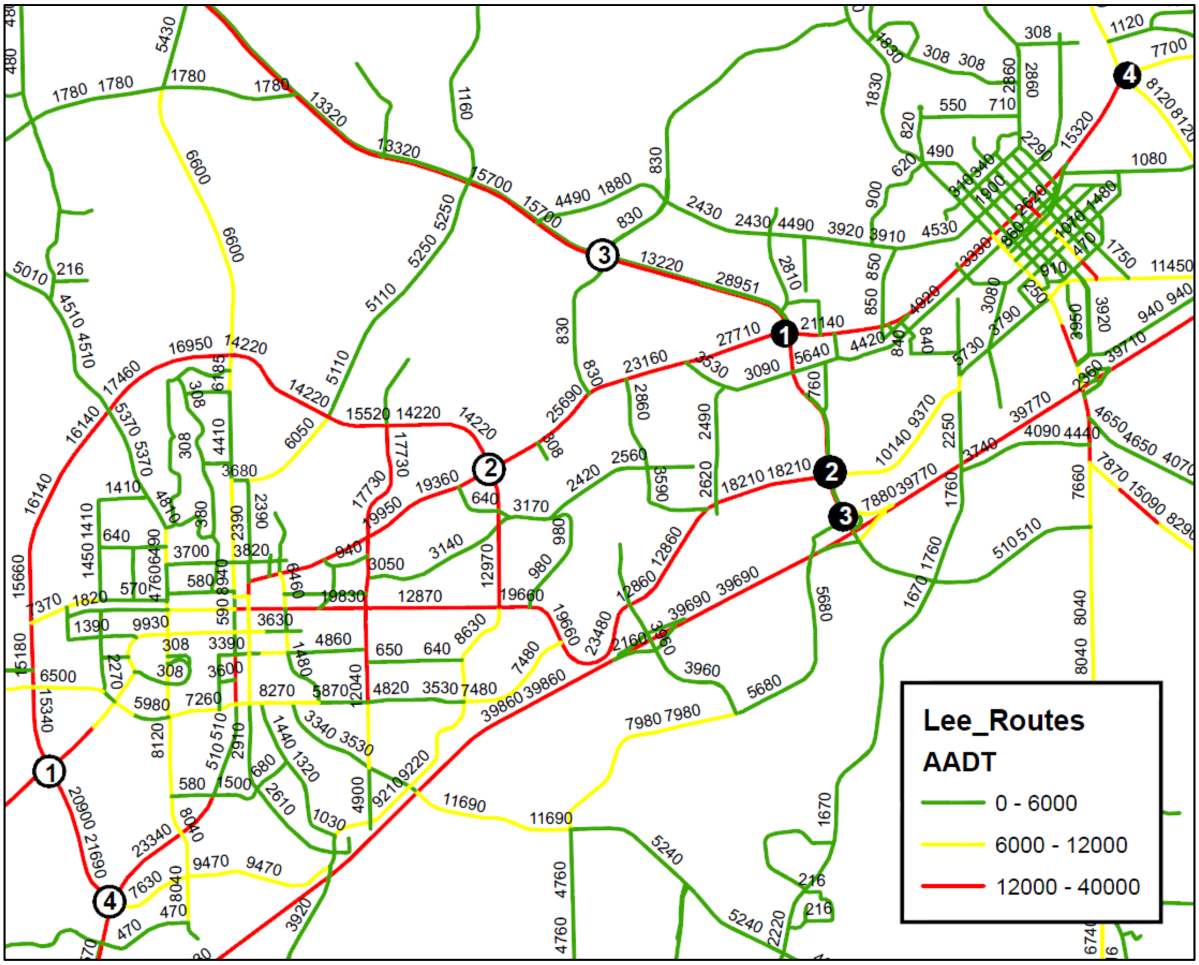

FIGURE 1 Locations of Study Intersections (www.dot.state.al.us)

Data were collected in May 2014 after the cameras had been operational for one year. Weekday observations were scheduled during a continuous three-hour period (3:30 p.m. to6:30 p.m.). The number of vehicles crossing the stop line and stopping behind the line during the clearance interval and the time when the vehicles crossed/stopped were recorded by watching the videos taken in the field. Data were collected separately for each approach and each movement with a different clearance interval. For instance, the intersection of Pepperrell Parkway and Gateway Drive has eight clearance intervals: four for thru traffic and four for left turns. It should be noted that at all of the studied intersections the right turn lanes are separated by channelizing islands and there are no countdown timers installed at the studied locations. Table 1 presents signal timing and number of lanes for monitored approaches for each studied movement. Time data was recorded to the hundredth of a second (two decimal digits), and then was rounded to a tenth of a second.

TABLE 1 Signal Timing and the Number of Cycles at each Intersection

	Number	Intersection Name	Number of Crossing/Stopping	Number of usable Cycles	Yellow Time (s)	All-red Time (s)	Number of Lanes		
			All Movements				**Left**	**Thru**	**Right**
RLC Intersection	1	Gateway Drive and Pepperell Parkway	322	181	4.5	1.5	2	2	1
	2	Frederick Road and Gateway Drive	474	260	4.5	1.5	1	2	1
	3	Gateway Drive and I-85 Off-ramp	129	106	3.8	2	1	2	1
	4	West Point Parkway and Fox Run Parkway	198	141	4.5	1.5	1	1	1
			Left Turns- Only						
	1	Gateway Drive and Pepperell Parkway	204	106	3	1.5	-	-	-
			All Movements						
Non-camera Intersection	1	Wire Rd and Shugg Jordan	107	83	4.5	2.1	1	2	1
	2	University and Opelika Rd	318	211	4.6	1.7	1	2	1
	3	US 280 and Veterans	43	41	4.3	2.5	1	1 or 2	1
	4	S College and Shugg Jordan	68	62	4.9	1.3	1	1 or 2	1

While collecting data, for many cycles, it was observed that zero vehicles crossed the stop line during the yellow and all-red intervals. It was the consequence of one of the following cases:

1- All vehicles arriving at intersections during the yellow intervals stopped; and
2- No vehicle approached the intersection during yellow/all red time

Researchers recorded these two situations in different manners. The first case was coded as 0, which means zero seconds of CLT was used. The second case was removed from the records because the clearance interval was not tested by any drivers.

DATA ANALYSIS

First, the distribution of RLR during the clearance interval is examined and then the range of the actual CLT can be estimated by using traditional statistical measures of sample minimum, maximum, mean, and standard deviation. Accordingly, the actual clearance lost times at the intersections are investigated and compared together to the lost times proposed by ALDOT's manual and the HCM, which are used in intersection capacity estimation.

Distribution of Number of Vehicles Running Yellow or Red Time

Figure 2 presents scatter plots as a summary of a set of bivariate data (vehicle number and their time crossing the stop line during clearance intervals) at four RLC intersections. The horizontal axis shows the number of vehicles that proceeded through the intersection after the onset of the yellow indication and the vertical axis indicates time in seconds after yellow light indication.

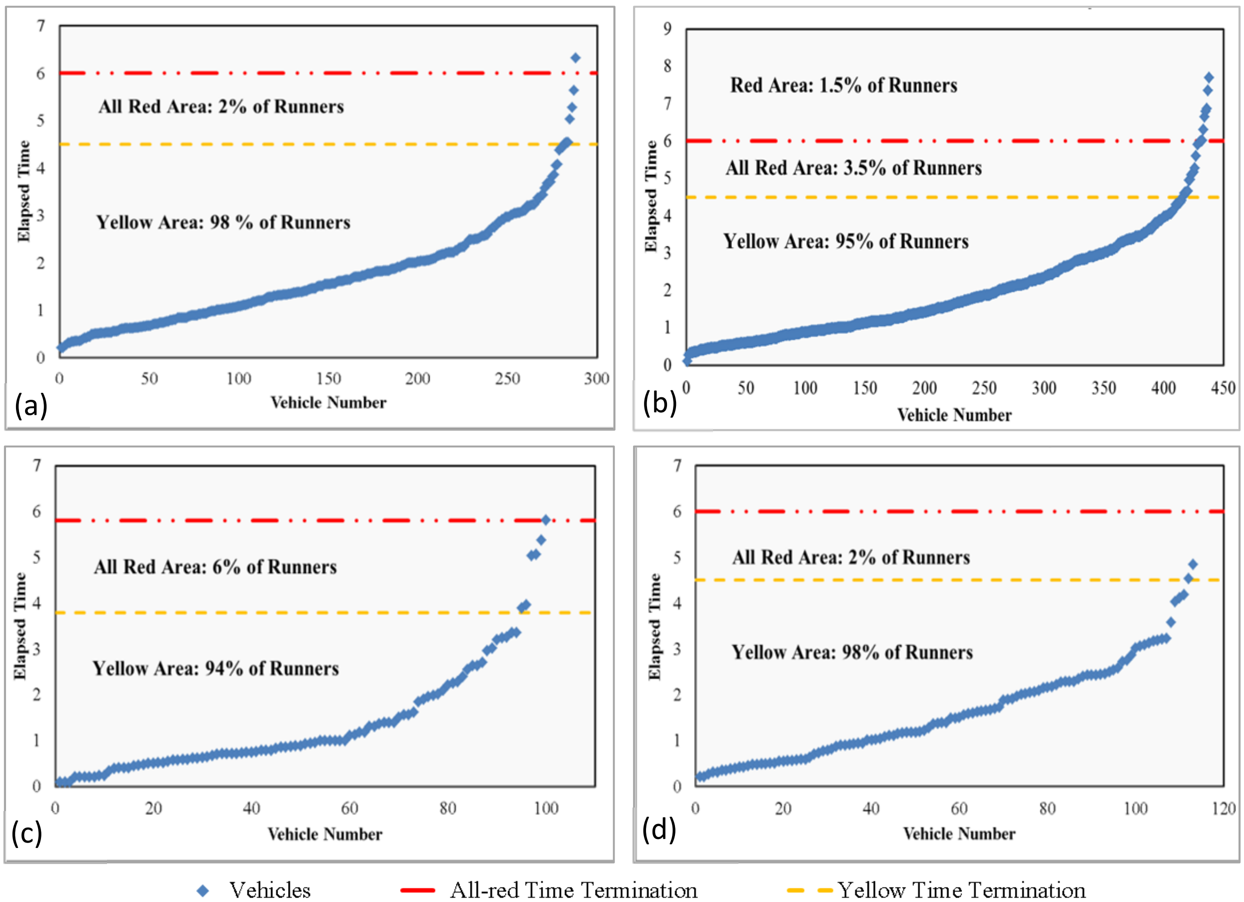

FIGURE 2 Yellow/Red Light Running Time at Each RLC Intersection: (a) Intersection of Gateway Drive and Pepperell Parkway- Thru Traffic Only; (b) Intersection of Frederick Road and Gateway Drive; (c) Intersection of Gateway Drive and I-85 Off-ramp; and (d) Intersection of West Point Parkway and Fox Run Parkway

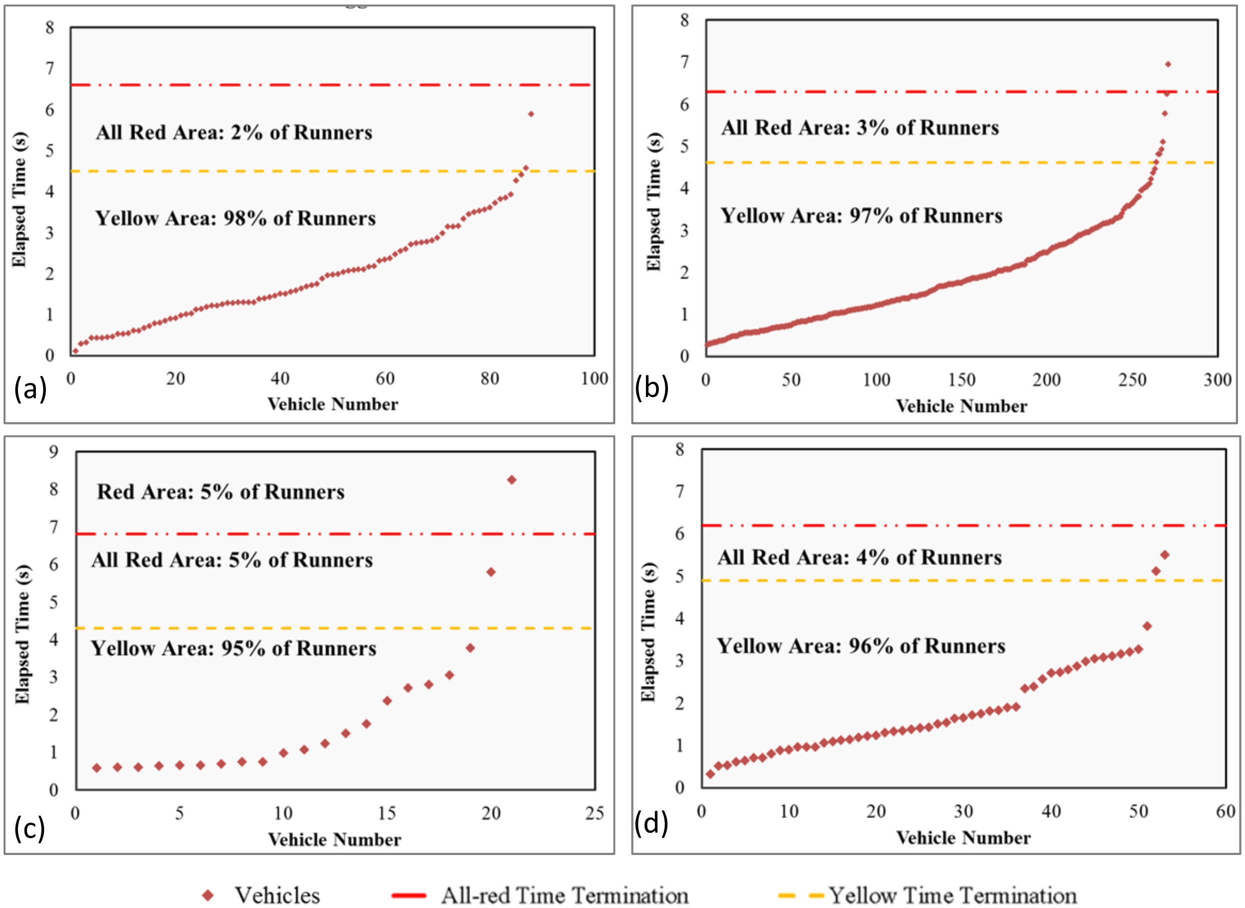

FIGURE 3 Yellow/Red Light Running Time at Each Non-Treated Intersection: (a) Intersection of Wire Rd and Shug Jordan; (b) Intersection of E University Dr and Opelika Rd; (c) Intersection of US 280 and Veterans Pkwy; and (d) Intersection of S College St and Shug Jordan Pkwy

As shown in Figure 2, at treated intersections over 90% of crossing vehicles crossed the stop line during the yellow intervals, 2–6% used the all-red intervals, and approximately 0-1.5% were observed to run the red light after the clearance interval. On the other side, Figure 3 shows at non-treated intersections the majority (over 90%) of crossing vehicles crossed the stop line during the yellow intervals, 2–5% of used the all-red intervals, and approximately 0-5% were observed to run the red light after the clearance interval. It is evident that a decreasing amount of vehicles went through the intersection as the time elapse increases after the yellow light indication.

Clearance Lost Time Estimation

During data collection, the usage of yellow time during each cycle (e.g., the crossing time for the last vehicle using the intersection at the end of each phase) was recorded. Based on the HCM definition, the time when the last vehicle uses the intersection is important to determine the CLT. Statistical analysis was conducted to estimate the minimum and maximum values of the CLT(s), the sample mean (s), and the standard deviation (s). A t-test was also employed to examine whether or not there is a statistically significant difference between the CLT values in RLC intersections and non-camera intersections. The results in Table 2 show the detailed information about CLT for four intersections with RLCs and four without RLCs as well as the average-used yellow time. Because the clearance intervals at non-camera intersections are 1-2 seconds longer than the RLC intersections, the mean CLT values were adjusted by the average clearance interval at treated intersections (5.7 s). In other words, the CLT would be the difference between 5.7 seconds and the used yellow time when the non-camera intersection be controlled by the same signal timing as camera intersections. Therefore, the adjusted CLT is found to be 4 seconds (5.7s -1.7s) for the first, 4.2s (5.7s – 1.5s) for the second, 4.7 seconds (5.7s -1.0s) for the third, and 4.0s (5.7s – 1.7s) for the fourth non-treated intersection. The adjusted mean CLT for the four non-camera intersections was compared to the mean CLT for the four RLC intersections.

TABLE 2 Clearance Lost Time at each Intersection

	Intersection	**Average Used Yellow Time (s) (Y_i-l_2)**	**Clearance Lost time (s)**			
			Mean	**Min**	**Max**	**Std.**
Camera Intersections	1	0.9	4.5	0.0	6	1.5
	2	1.2	4.8	0.0	6	1.2
	3	0.8	5.0	0.2	5.8	1
	4	1.0	5.0	1.2	6	1
	Overall	**1.0**	**4.7**	**0**	**5.7**	**1**
Non-camera Intersections	1	1.7	4.9/4.0*	0.7	6.6	1.4
	2	1.5	4.8/4.2*	0	6.3	1.5
	3	1.0	5.8/4.7*	0	6.8	1.7
	4	1.7	4.5/4.0*	0.7	6.2	1.4
	Overall	**1.5**	**4.9/4.2***	**0**	**6.4**	**1.5**
	p-value	**0.00**	**0.04**	**-**	**-**	**-**

Note: *Adjusted Mean by the Length of Total Clearance Intervals

In Table 2, the minimum lost time equal to zero for the first and second RLC intersections, as well as the second and third non-camera intersections, indicating that there existed at least one RLR vehicle entered these intersections after the all-red termination. In other words, since the clearance time was used by a vehicle to cross the intersection, no CLT can be recorded (CLT=0). At the third and fourth RLC intersections and the first and last non-camera intersections, the minimum lost times are more than zero (i.e. 0.2 seconds, 1.2 seconds, 0.7 seconds, and 0.7 seconds), which indicate all recorded vehicles entered the intersection during the clearance interval. The maximum CLT, which is equal to the clearance interval (except for the first intersection), implied that the yellow time was not used by drivers in at least one cycle. Note that the average clearance interval for the first intersection is less than the maximum CLT, because at this intersection, left-turns and thru movements have different clearance interval times (i.e., 4.5 seconds for left-turns and 6 seconds for thru movements). Therefore, the average clearance interval for the first intersection was found to be 5.4 seconds using a weighted average method ((181*6.0+141*4.5)/ (181+141) ≈ 5.4s). This time equals the mean CLT plus the average used yellow time (i.e., 4.5 seconds plus 0.9 seconds) as expected.

Using a t-test, it was found that there was a statistically significant difference between the value of CLT, as well as the used yellow time, of the two intersection groups (p-value ≤ 0.05), showing that the drivers reacted completely different at these intersections. Furthermore, data in

Table 2 reveals that the intersections equipped with RLCs are half a second less in use compared with those without cameras, the overall crossing times (Y_i-l_2) are 1.0 second and 1.5 seconds. In other words, the CLT at treated intersections are a half second longer than the untreated intersection. While it was understood from the Equations 2 and 3 that the lower the Y_i-l_2, the lower the capacity of the intersection, it can be concluded that the capacity of signalized intersections decreases with the installation of RLCs.

Table 3 presents the comparison results between CLTs calculated by the HCM and ALDOT methods and the actual CLT measured in the field. The fifth and sixth columns of Table 3 show the CLT based on the HCM which is 2 seconds and ALDOT's Manual, which is determined to be half of the yellow interval plus the entire all-red interval. The results showed there was an average of 2.7 seconds difference between HCM default CLT and field observed data, and an average 1.1 seconds difference between ALDOT method and the field values at intersections with RLCs. The deviation between HCM and ALDOT method and field data at intersections without cameras are 2.9 seconds and 0.8 seconds.

TABLE 3 Relative Changes in Clearance Lost Times

Intersection	Average CLT	Average Yellow Interval	Average All-red Interval	HCM Default	ALDOT Method	Deviation from HCM Default	Deviation from ALDOT Value
Camera Intersections	4.7	4.2	1.5	2	3.6	2.7	1.1
Non-camera Intersections	4.9	4.6	1.8	2	4.1	2.9	0.8

The analysis results reveal that both the HCM and ALDOT Manual methods estimated a shorter CLT and thus may overestimate the intersection's capacity if using the default values. The ALDOT Method gives a better estimate of the CLT because it took the specific signal timing plan at each intersection into consideration. The RLC seem to have a slight impact on the CLT. Based on this study, a half second can be added to the CLT as an adjustment factor for RLCs at signalized intersections.

Percentile of Used Yellow Time

Another way to determine how a RLC impacts the intersection capacity would be to consider the 85th percentile used yellow time. Figure 4 is drawn based on the recorded used yellow time for 1,191 cycles, illustrating a used yellow time at or below 85% of cycles experienced. The horizontal axis shows the amount of used yellow time by drivers and the vertical axis indicates the percent of cycles with a given used yellow time.

Based on Figure 4, in 85% of cycles, drivers accept the first 2.3 seconds of yellow time in order to enter the RLC intersection. In other words, RLC intersections are often in use for only 2.3 seconds during the clearance interval and the intersection is not used for the rest of the interval. Regarding the non-camera intersections, 3.2 seconds of yellow time was used in 85% of cycles. The used yellow time is 0.9 seconds longer for non-camera intersections than RLC intersections. Using this method, an increase in CLT was determined to range between 0 and 0.9 seconds as a result of RLCs installation at signalized intersections.

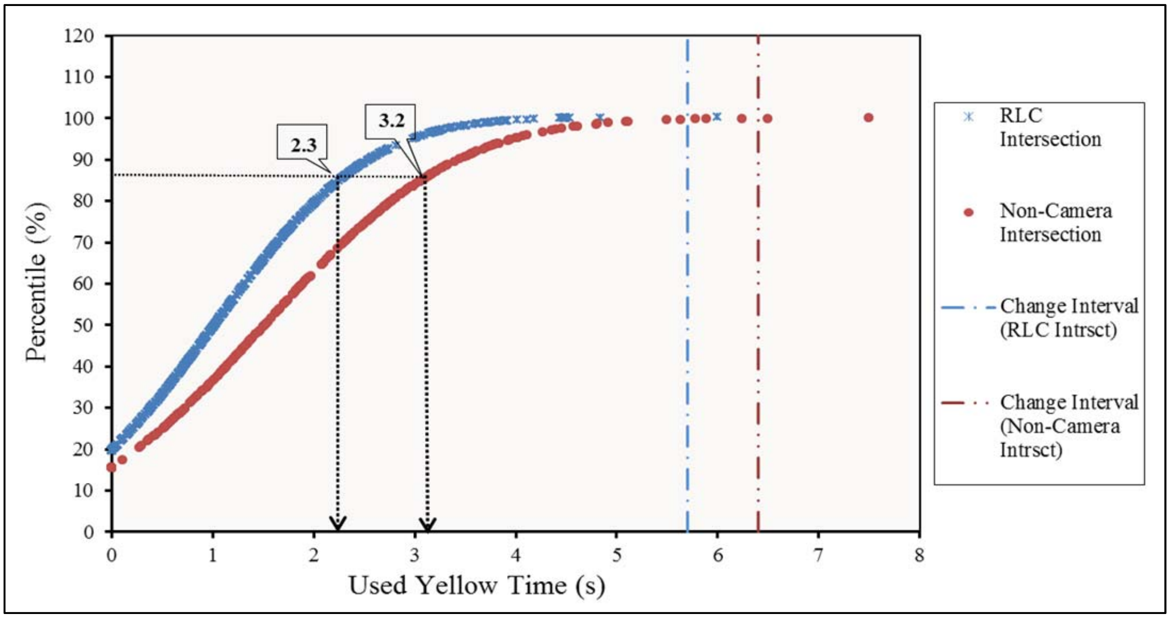

FIGURE 4 The Percentile of Used Yellow Time

CONCLUSION

Having knowledge of being monitored by cameras, drivers are more likely to brake sooner during the yellow or all-red intervals. This change in driver stopping behavior results in the reduction of the usable amount of yellow time and a decline in the intersection capacity. The literature review revealed that relatively little is known about the impacts of RLCs on CLT at signalized intersections. This study presents a method to quantify the impact of RLCs on CLT by a cross-section comparison for two groups of intersections with and without RLCs. In addition, the HCM default CLT value and the ALDOT method were compared with the actual mean CLT observed in the field. The results showed that the actual mean CLT at camera-equipped intersections is about 2.7 seconds longer than the default value specified in the HCM and about 1.1 seconds longer than one estimated by ALDOT method. The results indicated that the CLT at the treated intersections is between 0 seconds and 0.9 seconds, and on average 0.5 seconds, longer than untreated intersections. However, the exact value might vary among jurisdictions depending on the signal timing and the advance publicity for the program.

It should be noted that although the researchers made an effort to find and compare intersections with the similar characteristics (e.g. signal timing, traffic volume, number of thru, left and right lanes), it is clear that the value of the CLT is strongly related to the clearance interval duration. Thus, in order to give the best estimation of CLT change due to photo enforcement programs, it is recommended to conduct a before-after study at the intersections targeted to be installed with RLCs. Comparison between the CLT values before and after the program's implementation will shed light on the exact effect of the camera on driver behavior and intersection capacity reduction.

While the current study is conducted just after one year from the camera installation date, it is expected that as the time passes, the program will be more publicized and thus the drivers' behavior will continue to change more. As a consequence, a larger number of drivers will be cautious while approaching these intersections, especially those who have received a citation before, potentially increasing the CLT in the future.

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