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Understanding Drivers' Compliance Behavior: Data-Driven Assessment of Longer Yellow Intervals

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Abstract

Red-light running (RLR) behavior poses significant risks at signalized intersections and has emerged as a leading cause of intersection-related crashes. The Phoenix metropolitan area had 113 RLR-related fatalities and 9,320 injuries from 2014 to 2020. To effectively mitigate RLR violations and uphold the safety of all road users, it is crucial to investigate RLR behavior at local intersections, evaluate the impact of different signal timing parameters—such as the yellow interval—on the frequency of RLR violations, and, finally, identify effective countermeasures. This study investigated the effect of updating the yellow interval on the frequency of red-light violations. Twelve intersections within the City of Phoenix were carefully selected as study sites. Then, smart sensors were installed to collect various data types, such as signal timing parameters, the vehicle count, and RLR violation data. Based on the ITE 2020 guidelines, yellow intervals were adjusted at each intersection. The effects of increased yellow intervals on RLR violations were examined by utilizing a comprehensive experimental before-and-after design. The before-and-after study results indicated that increasing the yellow intervals significantly reduced the average frequency of RLR violations for both through and left-turn movements by 83% and 72%, respectively. The results of this research are instrumental in informing transportation agencies, enabling them to adopt evidence-based approaches to signal timing strategies that enhance intersection safety and effectively reduce RLR violations.

Keywords

change interval, signal timing, signalized intersection, traffic signal, before and after safety studies, red light running

Red-light running (RLR) is one of the riskiest behaviors at signalized intersections. The critical decision-making process drivers undergo when approaching an intersection, determining whether to proceed or stop, is pivotal to understanding RLR violations. If drivers perceive that they have adequate time to clear the intersection, they are more likely to proceed; otherwise, they choose to stop (*1*). However, when drivers opt to proceed and the signal transitions to red before they pass the stop bar or completely clear the intersection, they are deemed red-light runners (*1*). The definition of red-light running violations differs from one state to another, based on their respective laws. In Arizona, red-light runners are considered vehicles that pass the connection of the curb lines while the traffic signal shows a red indication (*2*, *3*). Figure 1 shows the curb lines' meeting point. According to a report published by the Insurance Institute for Highway Safety (IIHS), RLR violations caused 928 fatalities in 2020 in the United States. In addition, an estimated 116,000 people suffered injuries in RLR-related crashes (*4*). From 2014 to 2020, the Phoenix metropolitan area experienced 113 RLR-related fatalities and 9,320 injuries, underscoring the importance of addressing the RLR issue (*5*). Additionally, the RLR frequency statistics have been extensively studied in various locations. In 1998, Retting et al. reported 8,121 RLR incidents in 2,694 h in Arlington, Virginia, resulting in an average of 3 RLR violations per hour (*6*). In another

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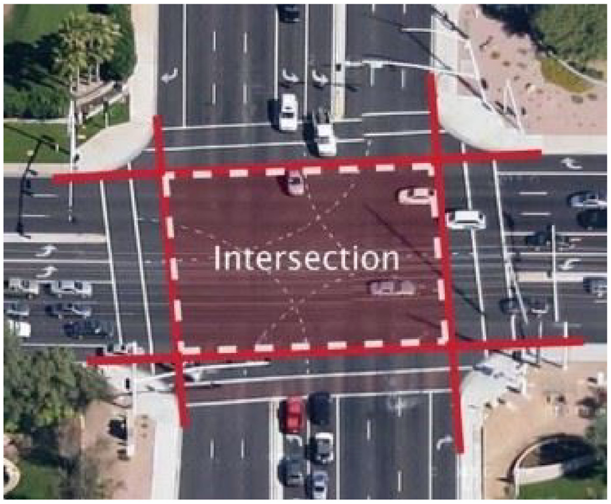

Figure 1. Definition of curb lines at an intersection.

study in Fairfax, Virginia, 573 RLR violations were recorded in 232 h before the installation of red-light cameras (*7*). In Oxnard, California, the rate was 13.2 RLR violations per 10,000 vehicles (*8*), while Iowa had a range of 0.45 to 38.50 RLR violations per 1,000 vehicles (*9*). In Texas in 2003, Bonneson et al. reported a rate of 4.1 RLR violations per 1,000 vehicles (*10*).

Consequently, to ensure the safety of all road users, it is important to engage in comprehensive research endeavors that investigate RLR behavior at local intersections. Moreover, evaluating the impact of signal timing parameters, such as yellow and red clearance intervals, on the frequency of RLR violations is important. Developing effective countermeasures is vital in combating RLR violation incidents and promoting a safe journey for all road users.

Determining optimal traffic signal timings, such as yellow and red clearance intervals, has been the subject of research and discussion in the field of traffic engineering. Balancing intersection safety and operational efficiency remains challenging, particularly when calculating yellow and red clearance intervals. Despite decades of research, a consensus on the most appropriate method for determining these intervals is yet to be reached. The yellow interval, a critical parameter for mitigating RLR violations, has gained significant attention. Inadequate allocation of yellow intervals can lead to the "dilemma zone," where drivers face difficulties in stopping safely before the stop bar or crossing it before the red signal. Since 1965, the Institute of Transportation Engineers (ITE) has developed various methods for calculating these intervals; such methods primarily rely on the kinematic equation method (*11*). According to ITE, the kinematic equation method is the most popular and widely accepted technique for determining yellow intervals.

In March 2020, ITE released updated guidelines introducing an extended kinematic equation for determining yellow and red clearance intervals. The revised methodology proposes a new speed profile as the reference for vehicles traversing the intersection. Consequently, the extended kinematic equation results in longer yellow intervals for left-turn movements compared with the original kinematic equation (*12*). However, limited studies have focused on utilizing real-world data to validate the effectiveness of the newly recommended extended kinematic equation. Therefore, this study in Phoenix, Arizona, examines the practical implications of implementing these revised guidelines at 12 intersections. This study explores the effects of longer yellow intervals on through-movement and left-turn-movement RLR violations, filling a research gap. An experimental design has been meticulously structured to explore short-term and long-term effects of longer yellow intervals. This distinctive framework enables the examination of incremental effects to thoroughly comprehend the nuanced changes introduced. To the best of the authors' knowledge, no previous research has undertaken such a holistic and multifaceted exploration of the impacts of longer yellow intervals.

Literature Review

Red-light running (RLR) is often an unintentional action by road users. However, it can be influenced by several factors inherent to the traffic environment that affect drivers' adherence to traffic regulations. Previous studies have consistently demonstrated that RLR incidents tend to increase as traffic volume rises (*13–15*). Moreover, geometric characteristics, including intersection width and approach grade, were found to influence drivers' compliance behavior (*16*). Similar studies found that distance to intersection, time to intersection, velocity at the yellow onset, position of the vehicle in the traffic flow, lane position, headway, and gap to the preceding vehicle are among the most influential factors on drivers' stop/go decisions at the onset of yellow (*16–19*). It was found that RLR violations tend to increase with closer vehicle proximity to intersections and higher approach speeds. The correlation between signal timing parameters and RLR violations has been extensively discussed in the literature. Past research has shown a correlation between longer cycle lengths and a higher frequency of RLR violations (*1*). According to the studies conducted by Van der Horst and Wilmink (in 1986) and Hagenauer et al. (in 1982), increasing the yellow and red clearance intervals showed significant effectiveness in reducing RLR violations (*20*, *21*). However, in 1997, Retting and Greene found that increasing the red clearance intervals did not reduce RLR (*22*). A more recent (2023) study by Karimpour et al. found that increasing the intersection delay, number of approach lanes, and split failures leads to a greater likelihood of observing red-light violations (*15*).

Based on current literature, signal timing emerges as a significant and influential factor contributing to RLR violations. By strategically modifying signal timing parameters, such as by adjusting yellow intervals, optimizing red clearance intervals, and implementing well-coordinated signal plans, substantial reductions in RLR occurrences can be achieved, significantly enhancing intersection safety and promoting compliance with traffic regulations (*23*). A study by Bonneson and Zimmerman in 2004 found that increasing the yellow interval by 1 s (within a limit of 5.5 s) significantly reduced the frequency of RLR violations. In a comprehensive before-and-after study conducted by Bonneson and Zimmerman in 2004, they examined ten intersections across five cities in Texas. Their research confirmed that drivers might adapt to the extended yellow interval. However, it is essential to note that this adjustment by drivers does not undermine the advantages and effectiveness of implementing a longer yellow interval (*24*). In 2008, Retting et al. evaluated the impact of longer yellow intervals on red-light violation in a similar study. A before-and-after study was conducted at two intersections in Philadelphia, PA, and the results showed that RLR frequency was reduced by 36% after increasing the yellow intervals. Furthermore, in 2008, Retting et al. found that red-light camera enforcement and the increased yellow interval reduced the RLR frequency by 96% (*25*). Further investigation by van der Horst and Wilmink in 1986 showed that long yellow intervals can encourage bad driving behavior (*20*). In a recent (2023) study conducted by Jalali Khalilabadi et al., the severity of RLR violations was examined. The research showed that longer yellow intervals and a longer cycle length were associated with a reduction in less severe RLR violations but an increase in more severe RLR violations (*26*).

Current Practices & Guidelines

The current ITE-recommended equation for calculating the yellow intervals is shown below (*11*):

$$Y \geqslant t + \frac{1.47(V_{85} - V_E)}{a + 32.2g} + \frac{1.47V_E}{2a + 64.4g} \tag{1}$$

where

Y = minimum yellow interval (in seconds).
t = perception–reaction time (in seconds); this is the time needed for an approaching driver to "perceive" the yellow indication and to "react" by braking to a stop or deciding to pass through the intersection. The default value is 1.0 s.
V_{85} = 85th percentile approach speed (mph); this is the speed at which a "reasonable" driver is assumed to approach the intersection.
V_E = intersection entry speed (mph); this is the speed at which a "reasonable" driver is assumed to cross the stop line of the intersection when they have been slowing down in preparation for making a left turn.
a = deceleration (ft/s^2); this is the rate at which it is assumed a driver will slow down on seeing the yellow signal. The default value is 10 ft/s^2.
g = grade of approach (downhill is a negative grade)

According to the ITE 2020 guidelines, using a minimum perception–reaction time (t) of 1.0 s and a deceleration (a) of 10 ft/s^2 would be most appropriate. For calculating through-movement yellow intervals, the speed limit + 7 (the 85th-percentile approach speed: V_{85}) is recommended when field-measured speed data are unavailable. For left-turn movements, it is recommended that the speed limit should be used as an estimation for the 85th percentile left-turn approach speed (V_{85}) according to ITE 2020 guidelines. Furthermore, the intersection entry speed (V_E) for through movements would be equal to the 85th-percentile of approach speed, while the intersection entry speed (V_E) for left-turn movements would equal 20 mph in the absence of field-measured speed data (*11*).

This study employed the extended kinematic equation (i.e., Equation 1) to calculate the yellow intervals for through and left-turn movements. The newly calculated intervals are presented in Table 1 alongside the previously implemented yellow intervals. The comparison between the old and newly measured intervals showed that the increases in the yellow intervals for through movements range from 0.4 to 0.6 s. However, for the yellow intervals for left-turn movements, the increases range from 0.3 to 3.2 s when comparing the old and newly measured intervals.

Study Site and Data Collection

An assessment of signalized intersections in the City of Phoenix was conducted for site selection, utilizing crash data collected between 2016 and 2021. The assessment involved ranking intersections based on crash frequency, severity, and collision type to determine their respective (MAG) Intersection Safety Scores and prioritizing them accordingly. Each Intersection Safety Score (ISS) was determined based on guidelines from the Maricopa Association of Governments (MAG). The calculation of the ISS assigns weights of 25% to the crash frequency, 50% to the crash severity, and 25% to the crash type

Table 1. Calculated Yellow Intervals for Through and Left-Turn Movements

	Yellow intervals (s) for through movements				Yellow intervals (s) for left-turn movements			
	ITE 2020 guidelines		Previous practice		ITE 2020 guidelines		Previous practice	
Study site	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB
#1	4.1	4.1	3.6	3.6	4.7	NA*	3	NA
#2	4.1	4.1	3.6	3.6	4.7	4.7	3	3
#3	3.8	4.5	3.2	4	NA	NA	NA	NA
#4	4.1	4.1	3.6	3.6	4.7	4.7	3	3
#5	3.8	4.5	3.2	4	NA	NA	NA	NA
#6	4.9	4.5	4.3	4	6.2	5.5	3	3
#7	4.9	3.4	4.3	3	6.2	3.3	3	3
#8	4.9	4.5	4.3	4	6.2	5.5	3	3
#9	4.9	4.5	4.3	4	6.2	5.5	3	3
#10	4.5	4.5	4	4	5.5	5.5	3	3
#11	4.5	4.5	4	4	5.5	5.5	3	3
#12	4.5	4.5	4	4	5.5	5.5	3	3

Note: EB = eastbound; WB = westbound; NB = northbound; SB = southbound; * = no left-turn phase; NA = not available.

(*27*). Additionally, the feasibility of installing smart sensors was considered, given that eliminating intersections requires significant infrastructure upgrades. Consequently, the 12 intersections with the highest rankings and which did not necessitate additional upgrades for sensor installation were selected as study sites. Figure 2 provides an overview of these chosen locations strategically distributed across the City of Phoenix to capture diverse traffic patterns and behavior. To maintain confidentiality and protect the privacy of the study sites, this study refrains from disclosing the specific names of the intersections.

Out of the 12 study sites, four with wider intersections were equipped with two smart sensors, ensuring comprehensive coverage of the entire intersection. In these four study sites, the width of the intersection surpassed the coverage capabilities of a single-fisheye Miovision camera (model 360), leading to the implementation of a dual-camera system for video detection at these intersections. It is crucial to emphasize that this configuration has no impact on data collection or detection processes, and there is no differentiation in functionality between single-camera and dual-camera systems. Miovision's SmartView 360 video-based sensors were utilized at all selected study sites. A clustering analysis was conducted to identify study sites sharing similar characteristics. This classified the 12 sites into three groups of four based on their traffic flow and RLR characteristics. Within each cluster, one intersection was designated as a "control" site, another as an "incremental" site, another as a "periodical" site, and the last as a "long-term" site. Control sites were incorporated to mitigate potential influences such as fluctuating traffic volumes during holidays, ensuring the reliability of statistical analyses. At the

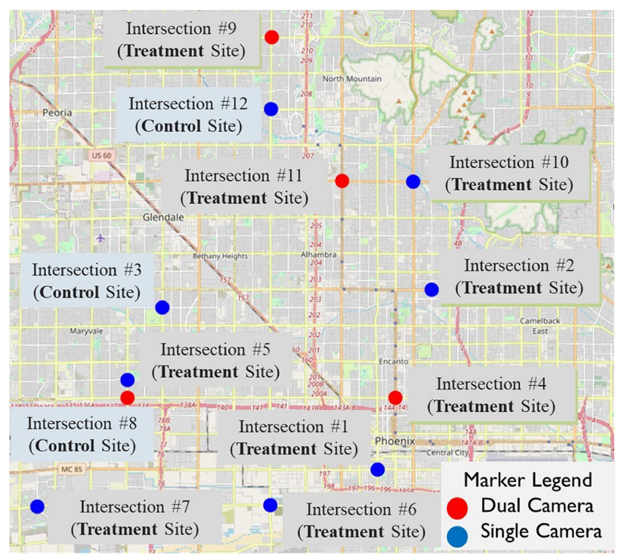

Figure 2. The 12 selected study sites.

control sites, yellow intervals remained consistent throughout the study period. The remaining sites were categorized as treatment sites and divided into groups based on their through and left-turn movement characteristics. For through movements, treatment sites were classified as incremental, periodical, and long term, while for left-turn movements, they were categorized as incremental and long-term sites. This systematic classification facilitated a comprehensive examination of diverse intervention impacts on drivers' compliance behavior, enhancing the understanding of the research topic. Figure 2 depicts the locations of control and treatment sites.

Table 2. Descriptive Statistics of the Study Sites

Study site	Study site type	Speed limit (mph)				Number of through lanes				Number of left-turn lanes			
		EB	NB	WB	SB	EB	NB	WB	SB	EB	NB	WB	SB
#1	Periodical	35	35	35	35	2	2	2	2	1	1	1	1
#2	Incremental	35	35	35	35	3	1	2	1	1	1	1	1
#3	Control	30	40	30	40	1	3	1	2	1	1	1	1
#4	Incremental	35	35	35	35	2	2	3	2	1	1	1	2
#5	Periodical	30	40	30	40	1	3	1	2	1	1	1	1
#6	Periodical	45	40	45	40	2	3	3	2	1	1	1	1
#7	Long term	45	25	45	25	2	1	2	1	1	1	1	1
#8	Control	45	40	45	40	2	3	2	3	1	1	1	1
#9	Incremental	45	40	45	40	3	3	3	3	1	1	1	1
#10	Long term	40	40	40	40	2	3	3	2	1	1	1	1
#11	Long term	40	35	40	40	3	3	3	3	1	1	1	1
#12	Control	40	40	40	40	3	3	3	3	1	1	1	1

Note: EB = eastbound; WB = westbound; NB = northbound; SB = southbound.

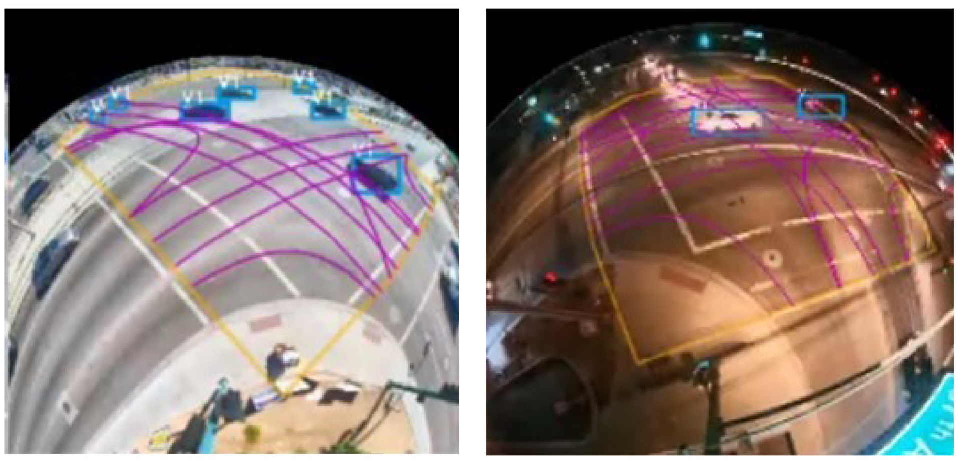

Figure 3. The smart sensors' detection overlay configuration.

Table 2 presents descriptive characteristics of the selected study sites.

Data Collection, Preprocessing, and Outlier Filtering

Data were collected using Miovision© smart sensors installed at the 12 selected study sites. The Miovision SmartView 360 sensors offer a range of capabilities, including capturing traffic count data, signal timing information, and incidents of RLR violations. These video-based sensors can detect vehicles as they cross the stop bar. An algorithm is employed to timestamp the presence of a vehicle at the stop bar, allowing for the identification of RLR violations when the signal status indicates red at that specific timestamp. Turning-movement counts and signal timing information were also utilized to identify and eliminate any outliers in the dataset. The configuration of the Miovision video-based sensors is illustrated in Figure 3. Furthermore, to evaluate the effectiveness of the RLR detection algorithm utilized by the Miovision system, a thorough review and analysis of the ground truth videos recorded by the smart sensors was conducted. To validate the data, the ground truth verification process involved the research team carefully reviewing recorded videos captured by video-based sensors to confirm instances of RLR events.

To ensure the robustness and reliability of the results, it is essential to identify and exclude outliers from all datasets. Initially, data associated with prolonged signal timing intervals, such as a long cycle length, were excluded from the analysis. Such instances were primarily attributed to factors such as signal communication loss, transitional periods, or emergency-vehicle preemption. Next, to maintain data integrity, instances of deep RLR (i.e., RLR that occurred after 7 s into the red phase) were removed from the dataset. These deep-RLR incidents occurred because of false detection, where smart sensors mistakenly identified conflicting movements as instances of RLR.

Lastly, in this study, the outlier removal process utilized the moving interquartile range (IQR) algorithm (*28*). The IQR is defined as the difference between the first quartile (Q_1) and the third quartile (Q_3). In IQR outlier-filtering methods, any values falling outside of the range of $[Q_1 - 1.5 \times IQR, Q_3 + 1.5 \times IQR]$ are considered outliers (*28–31*). The moving IQR outlier-filtering methodology was used to remove erroneous data with similar temporal and spatial characteristics. Therefore, the data were aggregated in 15-min time bins, and the moving-IQR outlier filtering was implemented on the delay, signal timing parameters, and traffic flow at each intersection. The IQR in each 15-min time bin was calculated for each of the aforementioned variables, and the outlier filtering was applied to remove values falling outside of the range of $[Q_1 - 1.5 \times IQR, Q_3 + 1.5 \times IQR]$.

It is important to highlight that during the study, the data collected from intersection #1 were deemed invalid because of issues with the controller phasing data stemming from miscommunication or a loss of communications received from the smart sensors.

Methodology

Experimental Design

A comprehensive before-and-after study was conducted to thoroughly evaluate the impact of yellow intervals on drivers' compliance behavior. This followed a well-established approach utilized in previous research (*32–35*). The study design incorporated multiple periods, each spanning 2 weeks, ensuring robust data collection and analysis. The study design encompassed the following timeline:

- Baseline: September 1, 2022 to November 21, 2022
- Period 1: November 21, 2022 to December 5, 2022
- Period 2: December 5, 2022 to December 19, 2022
- Period 3: December 19, 2022 to January 2, 2023
- Period 4: January 2, 2023 to January 16, 2023
- Period 5: January 16, 2023 to January 30, 2023
- Period 6: January 30, 2023 to February 13, 2023

A new yellow interval was implemented within each period, and the data obtained from the installed smart sensors were subjected to rigorous exploratory data analysis. In this study, we defined a "period" as a 2-week interval in our experimental design. At the start of each period, we adjusted the yellow interval to match our experimental plan updates. These 2-week periods allow us to investigate both short-term and gradual impacts of changing yellow intervals. For all the study periods, careful attention was given to controlling external factors that could potentially influence the outcomes, such as weather conditions, traffic volumes, and roadway conditions. By employing this rigorous before-and-after study design, the research aims to provide valuable insights into the effects of yellow intervals on drivers' compliance behavior and ultimately inform evidence-based strategies for enhancing intersection safety.

Within the scope of this study, several distinct study sites were selected. Some sites were designated as control sites, with no modifications to the existing yellow intervals. A clustering analysis was conducted to identify study sites with similar characteristics. The results of the clustering analysis were used to categorize the 12 study sites into three groups of four based on their traffic flow and RLR characteristics. Within each cluster, we designated one intersection as a control site, another as an incremental site, one as a periodical site, and the last as a long-term site. The inclusion of control sites mitigated the potential influence of factors such as varying traffic volumes and patterns during holiday seasons, ensuring robust statistical analysis. For the control sites, the yellow intervals remained consistent with the baseline throughout the entire study duration. The remaining sites were categorized as treatment sites and subdivided into three groups for through movements and two groups for left-turn movements based on their characteristics. For through movements, the treatment sites were categorized into 1) incremental, 2) periodical, and 3) long-term sites, and for left-turn movements, the treatment sites were categorized into 1) incremental and 2) long-term sites. This categorization allowed for a comprehensive examination of the effects of different intervention approaches on drivers' compliance behavior, thus contributing to a more nuanced understanding of the research topic. Table 3 provides a detailed overview of the implemented yellow intervals for through movements.

The incremental sites were selected to investigate whether a partial increase in yellow intervals, rather than complete adherence to ITE guidelines, could effectively reduce RLR violations. At these sites, the yellow intervals were incrementally extended for both through and left-turn movements. The yellow intervals were incrementally increased for the incremental sites over five periods to reach the calculation in the ITE 2020 guidelines at the start of period 5.

At the periodical sites, the yellow interval for through movement was cyclically modified. The new yellow

Table 3. Implemented Yellow Intervals for Through Movements

Intersection	Type of intersection	Baseline		Period 1		Period 2		Period 3		Period 4		Period 5	
		EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB
Intersection #1	Periodical site	3.6	3.6	4.1 (+0.5)	4.1 (+0.5)	3.6 (−0.5)	3.6 (−0.5)	4.1 (+0.5)	4.1 (+0.5)	3.6 (−0.5)	3.6 (−0.5)	4.1 (+0.5)	4.1 (+0.5)
Intersection #2	Incremental site	3.6	3.6	3.7 (+0.1)	3.7 (+0.1)	3.8 (+0.1)	3.8 (+0.1)	3.9 (+0.1)	3.9 (+0.1)	4 (+0.1)	4 (+0.1)	4.1 (+0.1)	4.1 (+0.1)
Intersection #3	Control site	3.2	4	3.2 (0)	4 (0)	3.2 (0)	4 (0)	3.2 (0)	4 (0)	3.2 (0)	4 (0)	3.2 (0)	4 (0)
Intersection #4	Incremental site	3.6	3.6	3.7 (+0.1)	3.7 (+0.1)	3.8 (+0.1)	3.8 (+0.1)	3.9 (+0.1)	3.9 (+0.1)	4 (+0.1)	4 (+0.1)	4.1 (+0.1)	4.1 (+0.1)
Intersection #5	Periodical site	3.2	4	3.8 (+0.6)	4.5 (+0.5)	3.2 (−0.6)	4 (−0.5)	3.8 (+0.6)	4.5 (+0.5)	3.2 (−0.6)	4 (−0.5)	3.8 (+0.6)	4.5 (+0.5)
Intersection #6	Periodical site	4.3	4	4.9 (+0.6)	4.5 (+0.5)	4.3 (−0.6)	4 (−0.5)	4.9 (+0.6)	4.5 (+0.5)	4.3 (−0.6)	4 (−0.5)	4.9 (+0.6)	4.5 (+0.5)
Intersection #7	Long-term site	4.3	3	4.9 (+0.6)	3.4 (+0.4)	4.9 (0)	3.4 (0)	4.9 (0)	3.4 (0)	4.9 (0)	3.4 (0)	4.9 (0)	3.4 (0)
Intersection #8	Control site	4.3	4	4.3 (0)	4 (0)	4.3 (0)	4 (0)	4.3 (0)	4 (0)	4.3 (0)	4 (0)	4.3 (0)	4 (0)
Intersection #9	Incremental site	4.3	4	4.4 (+0.1)	4.1 (+0.1)	4.5 (+0.1)	4.2 (+0.1)	4.6 (+0.1)	4.3 (+0.1)	4.7 (+0.1)	4.4 (+0.1)	4.9 (+0.2)	4.5 (+0.1)
Intersection #10	Long-term site	4	4	4.5 (+0.5)	4.5 (+0.5)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)
Intersection #11	Long-term site	4	4	4.5 (+0.5)	4.5 (+0.5)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)	4.5 (0)
Intersection #12	Control site	4	4	4 (0)	4 (0)	4 (0)	4 (0)	4 (0)	4 (0)	4 (0)	4 (0)	4 (0)	4 (0)

Note: EB = eastbound; WB = westbound; NB = northbound; SB = southbound.

intervals were implemented for 2 weeks, followed by a 2-week period during which the original yellow interval was reinstated. This cyclic pattern allowed for an examination of the impact of alternating yellow intervals on drivers' compliance behavior in the short term and facilitated a comparative analysis of the effectiveness of different intervals. Because of the substantial increases in yellow intervals (i.e., ranging from 0.3 to 3.2 s) when comparing the old and newly measured intervals for left-turn movements, we did not designate any periodical sites for the study of left-turn movements. This decision was made to avoid potential safety concerns by reducing the yellow intervals by 3.2 s. For the periodical sites, we adjusted the yellow intervals at the start of each period, either increasing or decreasing them, and collected data for 2 weeks before making another adjustment in the subsequent 2 weeks.

To assess the effects of increasing the yellow interval on drivers' compliance behavior over an extended period, long-term sites were specifically chosen for both through and left-turn movements. At these sites, the yellow interval was adjusted to the newly updated intervals and maintained at a constant value throughout the subsequent periods. The selection of long-term sites allowed for a comprehensive evaluation of the sustained impact of the increased yellow interval on drivers' adherence to traffic regulations. The yellow intervals were initially updated for the long-term sites to align with ITE 2020 guidelines at the start of period 1 and remained unchanged during subsequent periods.

In this study, the occurrences of RLR violations were aggregated on a daily basis to determine the RLR frequency per day for each study site, enabling statistical analysis. Moreover, to account for the impact of traffic volume on RLR frequency, the RLR rate was determined by normalizing the RLR frequency to a per-1000-vehicle basis. This normalization process allowed a more accurate comparison of RLR rates across different traffic volumes.

Before-and-After Analysis

To evaluate the comparative differences between the before-and-after study groups, Welch's statistical *t*-test was employed (*36*). When a single comparison between two groups is required, and the group sizes or variances are unequal, Welch's *t*-test is used as it accommodates such conditions (*37*). Welch's *t*-test calculates the *t* statistic as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad (2)$$

Table 4. Average Red-Light Running Frequency per Day for Through Movements

Study site	Study site type	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
#3	Control	161	137	167	125	137	164	167
#8	Control	281	283	327	247	274	322	370
#12	Control	338	NA**	282	230	301	232	271
#2	Incremental	188	193	195	123	127	128	143
#4	Incremental	226	192	176	157	163	157	157
#9	Incremental	156	104	97	84	70	93	NA
#5	Periodical	353	202	339	199	339	212	327
#6	Periodical	223	91	192	78	140	NA	NA
#7	Long term	110	52	51	50	49	59	65
#10	Long term	216	82	106	73	113	102	NA
#11	Long term	244	114	144	110	143	124	NA

Note: The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells containing lower values and bolder shades indicating cells with higher values. ** = absence of data (which could have arisen from communication disruptions or network-related problems); NA = not available.

where x_i represents the sample mean, s_i represents the standard deviation, and N_i represents the size of sample i. Furthermore, the improvement effectiveness was calculated using an odds ratio of improvements in the treatment sites to that in the control sites during the same period. Including control sites in the analysis accounts for any underlying general trends that may affect the occurrence of RLR violations at the study sites. This approach ensures a more accurate evaluation of the effectiveness, strengthens the validity and reliability of the findings, and provides a corrective measure to mitigate the influence of external factors on the observed outcomes (*33*, *38*). To calculate the odds ratio(OR), the equation suggested by Hauer in 1997 was employed (*39*). The equation presented here is a tailored variation of the traditional odds ratio calculation that is designed to improve interpretability. As a result of this modification, odds ratios exceeding 1.00 in our study signify a reduction in the likelihood of RLR incidents.

$$OR = \frac{K\ N}{L\ M\ \left(1 + \left(\frac{1}{L}\right) + \left(\frac{1}{M}\right)\right)} \tag{3}$$

where K represents the pre-RLR frequency for the treatment sites, L denotes the post-RLR frequency for the treatment sites, M represents the pre-RLR frequency for the control sites, and N denotes the post-RLR frequency for the control sites. The 95% confidence interval (CI_{95}) can be derived as

$$CI_{95\%} = \exp[\ln(OR) \pm 1.96s] \tag{4}$$

where s is the standard deviation of $\ln(OR)$. This can be calculated as

$$s^2 = \frac{1}{K} + \frac{1}{L} + \frac{1}{M} + \frac{1}{N} \tag{5}$$

Results

Preliminary Data Analysis

Tables 4 and 5 display the average daily RLR frequencies for the study sites for through and left-turn movements. The tables have been meticulously color coded to correspond with each specific study site. This coding strategy directly compares the frequencies of RLR in each row. It is essential to understand that lighter hues employed in the cells denote lower values, while the utilization of darker shades signifies higher values within the same row of data. Throughout the study, the signal timing at control sites remained unchanged. Notably, the data gathered from the control sites indicate no specific trend in the change in RLR frequency during the study periods at control sites.

Based on the results provided in Tables 4 and 5, the yellow intervals gradually increased at the incremental sites until they reached the ITE 2020 yellow interval in period 5 for both through and left-turn movements. Results indicate a decrease in RLR frequency in the later periods compared with the baseline. At the periodical sites, where the yellow intervals were altered every period between the previous-practice intervals and the ITE 2020 intervals, the data suggest a reduction in RLR frequency during periods with the new yellow intervals compared with those with the old yellow intervals. As for the long-term sites, where the ITE 2020 yellow intervals were implemented in the first period and remained unchanged, the data indicate a decrease in RLR frequency following the implementation of the new intervals in period 1.

Table 5. Average Red-Light Running Frequency per Day for Left-Turn Movements

Study site	Study site type	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
#8	Control	235	201	227	171	201	197	232
#12	Control	160	NA**	165	131	152	163	160
#2	Incremental	24	12	12	10	10	8	11
#4	Incremental	37	31	29	12	27	24	42
#9	Incremental	157	138	130	61	128	50	NA
#6	Long term	23	5	8	5	4	NA	NA
#7	Long term	11	7	9	6	6	7	7
#10	Long term	25	4	5	4	7	8	NA
#11	Long term	148	82	95	78	99	88	NA

Note: The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells containing lower values and bolder shades indicating cells with higher values. ** = absence of data (which could have arisen from communication disruptions or network-related problems); NA = not available.

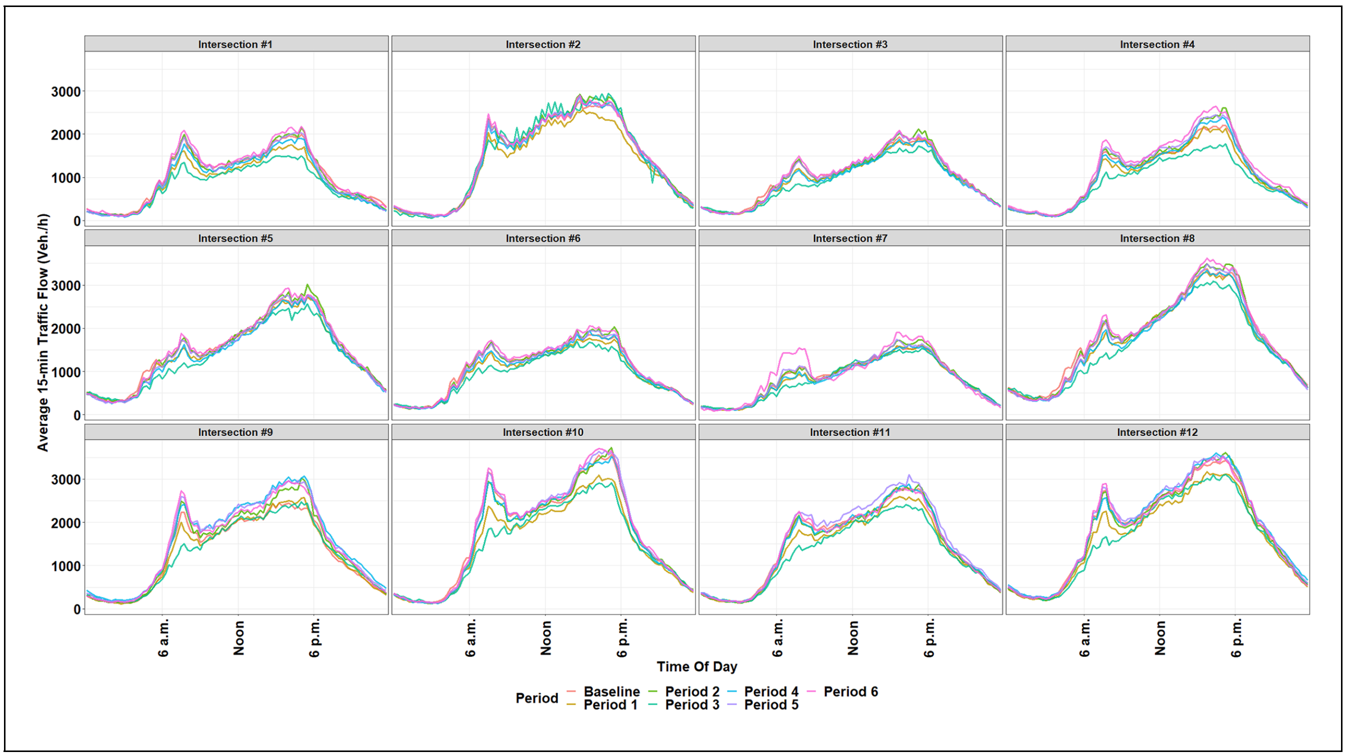

Figure 4. Average traffic flow profile.
Note: Veh = vehicles.

Although the preliminary findings indicate that increased yellow intervals resulted in a lower frequency of RLR violations, it is essential to consider the strong correlation between traffic volume and RLR frequency. This correlation suggests that higher traffic volumes lead to increased RLR frequencies. Consequently, during period 3, which encompassed the holiday season and had a reduced traffic volume, the RLR frequency was the lowest among all study periods. Figure 4 illustrates the daily profile of the average traffic flow for each period at every study site. To ensure a fair comparison and enable statistical inferences, the RLR

Table 6. Statistical *t*-Test Results for Red-Light Running (RLR) Rate (RLR per 1000 Vehicles per Day) for Through Movements

Study site	Study site type	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
#3	Control	6.63	5.97	8.28	5.73*	5.97	6.72	6.68
#8	Control	6.46	6.99	9.11	6.24	6.64	7.54	8.37**
#12	Control	7.80	NA	9.44	5.98*	6.60*	5.09*	6.21*
#2	Incremental	5.49	5.88	6.67**	3.64*	4.05*	3.66*	3.99*
#4	Incremental	9.09	8.49	8.19	7.78*	5.67*	5.95*	5.66*
#9	Incremental	4.99	3.43*	3.47*	2.84*	1.83*	2.45*	NA***
#5	Periodical	9.94	5.97*	11.09	6.10*	10.1	6.07*	9.25
#6	Periodical	8.89	3.95*	9.37	3.57*	5.67*	NA***	NA***
#7	Long term	5.42	2.64*	2.91*	2.60*	2.51*	2.84*	2.92*
#10	Long term	5.17	2.27*	3.27*	2.11*	2.75*	2.3*	NA***
#11	Long term	6.80	3.55*	5.13	3.60*	4.08*	3.33*	NA***

*= statistically significant *decrease* compared with the *baseline* at the 0.05 level; ** = statistically significant *increase* compared with the *baseline* at the 0.05 level; *** = absence of data (which could have arisen from communication disruptions or network-related problems); NA = not available.

frequency was normalized by dividing the number of violations by the number of vehicles and multiplying by 1000, giving the RLR rate.

To gain a comprehensive understanding of the implications of increased yellow intervals on RLR violations, the study extensively analyzes the results of Welch's statistical *t*-test on the RLR rate for both through and left-turn movements in the following sections.

Through Movements

Table 6 displays the statistical *t*-test results for the RLR rate for through movements. The data in these tables reflect the daily average RLR rates during each period. Specifically, these values denote the average frequency of RLR violations per day per 1,000 vehicles. In situations with no asterisks, no statistically significant disparity was detected between the baseline and the corresponding period. At the control sites, where the yellow intervals remained unchanged throughout the study, no specific patterns were observed. That is, during the majority of the periods, the RLR rate did not exhibit a statistically significant difference when compared with the baseline condition at the 95% confidence interval. Nevertheless, it is noteworthy that two exceptions stand out in period 3, where a statistically significant difference is observed. This aberration can be ascribed to the impact of national holidays on traffic flow, as these lead to a significant decrease in instances of RLR violations. This effect is consistently observed across all other sites, rendering period 3 an exception, and consequently it was excluded from our analysis. At the incremental sites, the yellow intervals were increased incrementally over five periods to reach the calculation in the ITE 2020 guidelines at the start of period 5. This means that in each period, the yellow intervals were increased by 0.1–0.2 s. When comparing periods 3, 4, 5, and 6 with the baseline, it is evident that the average RLR rate decreased significantly at three incremental sites. However, the results of the statistical *t*-test for incremental sites during the initial implementation period, when the yellow intervals were increased by 0.1 s, were inconclusive. Specifically, it was found that the difference between the average RLR rate in period 1 and the baseline was not statistically significant for two of the incremental sites: intersection #2 and intersection #4. Additionally, when comparing the average RLR rate in period 2 to the baseline, it was noticed that there was a statistically significant increase in the average RLR rate at intersection #2 during period 2 compared with the baseline. On the other hand, the average RLR rate in period 2 was not statistically different from the baseline at intersection #4.

The statistical *t*-test results for the RLR rate at the periodical sites indicate a significant decrease in the average RLR rate during periods where the new yellow intervals are implemented (periods 1, 3, and 5), compared with the periods with the old intervals (baseline and periods 2, 4, and 6). The findings of the *t*-test of the RLR rate at the long-term sites indicate a significant decrease in the average RLR rate during period 1, when the new yellow intervals were implemented, compared with the baseline. The average RLR rate during periods 2, 3, 4, 5, and 6 was significantly lower than the baseline RLR rate, except for one instance. At intersection #11 during period 2, the average RLR rate was lower than the baseline, but the difference was not statistically significant at the 95% confidence level.

Left-Turn Movements

Table 7 displays the statistical *t*-test results for the RLR rate for left-turn movements. The information presented in this table represents the daily average RLR rates for each time period. To be more precise, these values indicate the average frequency of RLR violations that

Table 7. Statistical *t*-Test Results for Red-Light Running (RLR) Rate (RLR per 1000 Vehicles per Day) for Left-Turn Movements

Study site	Study site type	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
#8	Control	23.24	21.37	27.06	18.50*	20.88	20.15	22.98
#12	Control	14.77	NA	21.56	13.01*	13.75	15.09	14.80
#2	Incremental	5.13	2.36*	3.10*	2.26*	2.15*	1.58*	2.39*
#4	Incremental	4.93	3.71	4.17	1.92*	3.33*	2.65*	4.41
#9	Incremental	16.13	14.92	17.16	6.97*	12.75	5.07*	NA**
#6	Long term	4.00	0.84*	2.10*	0.97*	0.87*	NA	NA
#7	Long term	3.87	2.73*	3.47	2.30*	2.15*	2.48*	2.21*
#10	Long term	4.10	0.76*	1.09*	0.72*	1.18*	1.23*	NA
#11	Long term	17.59	9.14*	12.10*	9.06*	10.69*	8.27*	NA

*= statistically significant *decrease* compared with the *baseline* at the 0.05 level; ** = absence of data (which could have arisen from communication disruptions or network-related problems); NA = not available.

Table 8. Results of the Before-and-After Study of the Effects of Increasing Yellow Intervals

	Through movements			Left-turn movements		
	Before	After	Odds ratio	Before	After	Odds ratio
Treatment sites	221	113	1.83 (1.37–2.44)	64	31	1.72 (1.07–2.76)
Control sites	253	237		203	176	

occurred on a daily basis per 1,000 vehicles. When there are no asterisks, no statistically significant differences were found between the baseline and the respective period. At the control sites, where yellow intervals remained consistent throughout the study, no distinct patterns were apparent. In the majority of the periods, the RLR rate showed no statistically significant difference compared with the baseline condition within the 95% confidence interval. However, two exceptions stand out in period 3, where a statistically significant difference was observed. This divergence can be attributed to the influence of national holidays on traffic flow, leading to a significant decrease in RLR violations. This impact was consistently observed across all other sites during period 3. It is evident from the comparison of periods 3, 4, 5, and 6 with the baseline that the average RLR rate decreased at three incremental sites. However, the reduction was not statistically significant for some periods and study sites. For example, at intersection #2, the average RLR rate decreased in period 3 compared with the baseline, but the difference was not statistically significant at the 95% confidence level. Similar results were found for period 4 at intersection #9 and at intersection #4 for period 6. Overall, it was found that the incremental increase in yellow intervals for left-turn movements significantly reduced red-light violations.

The findings of the *t*-test of the RLR rate at the long-term sites indicate a significant decrease in the average RLR rate during period 1, when the new yellow intervals were implemented, compared with the baseline. Moreover, except for one case, the average RLR rate during periods 2, 3, 4, 5, and 6 was significantly lower than the baseline RLR rate. At intersection #7 during period 2, the average RLR rate was lower than the baseline, but the difference was not statistically significant at the 95% confidence level.

Effectiveness of Longer Yellow Intervals

The effectiveness of the improvements was evaluated by calculating the odds ratio and comparing the degree of improvement observed in the treatment sites to that in the control sites over the same period. The effectiveness of the improvements was calculated and is presented in Table 8. The odds ratio was determined based on the average daily RLR frequencies for the treatment and control sites, considering the periods before and after implementing the ITE 2020 guidelines. Equation 3, a tailored variation of the traditional odds ratio calculation, was utilized to compute the odds ratio. The utilization of this modified equation allows for improved interpretability in our analysis. Odds ratios exceeding 1 signify a decrease in the probability of RLR incidents. Based on the average safety effectiveness observed across all intersections, the estimated enhancement in safety resulting from the extension of yellow intervals indicates an 83% reduction in RLR violations for through movements. The mean estimated effect of the longer yellow intervals for left-turn movements is a reduction of 72% in RLR violations. It is important to highlight that this analysis considered the average RLR violations across all study sites for both treatment and control sites. However, the degree of improvement and the reduction rates may vary between intersections, as each intersection has unique characteristics, demographics, and traffic patterns.

Discussion

Previous research results consistently indicate that longer yellow intervals significantly reduce the frequency of RLR violations. Nevertheless, there remains a lack of consensus around the extent to which yellow intervals should be extended. Striking a balance between intersection safety and traffic efficiency is critical in this context. The findings derived from the incremental sites suggest that full implementation of the ITE 2020 guidelines for calculating yellow intervals may not be necessary. The study's results revealed a 60% reduction in the red-light running (RLR) rate for left-turn movements during period 3, where the yellow intervals were increased to 40% of the ITE 2020 recommendations, compared with the baseline condition. This finding contributes valuable insights to the discussion on whether complete implementation of the 2020 ITE guidelines is necessary. Additionally, it aligns with the NCHRP report 731 recommendations, which advocates using speed limit – 5 as a substitute for the 85th-percentile approach speed for left-turn movements, resulting in a shorter yellow interval than that specified in the ITE 2020 guidelines.

Moreover, it is crucial to examine the influence of yellow intervals on the proportion of RLR violations that occur during the red clearance interval phase and after the red clearance interval phase. Figure 5*a* provides an overview of the distribution of RLR incidents over the time during which the violations occurred. The graph illustrates that most RLR violations took place within the initial few seconds after the onset of the red signal, with fewer violations occurring deeper into the red phase. Furthermore, an essential component of evaluating RLR violations is assessing the severity of these incidents, which pertains to how late into the red phase RLR violations occur. The statistical analysis of the average depth of RLR violations into the red phase for each period indicates that changing yellow intervals does not significantly influence the depth of violations into the red phase. RLR violations occurring after the red clearance phase are of greater concern in relation to risk than those occurring during the red clearance phase. This is because the conflicting approach has a green indication after the red clearance phase, thus increasing the potential for hazardous situations. Figure 5*b* presents the percentage of violations that occurred during the red clearance phase and the percentage that occurred after the red clearance phase. It can be observed that altering the yellow intervals did not have a discernible effect on the percentage of RLR violations.

Additionally, it is essential to consider vehicle classification. The data obtained from the Miovision video-based sensors about vehicle classification include categories such as cars, articulated trucks, pickup trucks, and single-unit trucks. We specifically divided cars into passenger cars and non-passenger cars. Figure 6 illustrates the average RLR rate per 1000 vehicles for each vehicle classification group in each period. This graph demonstrates that non-passenger cars exhibit a higher RLR rate than passenger cars.

To gain a comprehensive understanding of RLR behaviors, this study conducted an analysis of RLR incidents over weekends compared with weekdays. Figure 7, *a* and *b*, depicts the boxplot distributions of RLR violations over the weekends and weekdays across study periods. Based on the RLR distribution, it can be observed that although the rate of RLR differs on weekends compared with weekdays, the overall trend remains the same. Notably, the implementation of longer yellow intervals at long-term sites (intersections #7, #10, and #11 for through movements and intersections #6, #7, #10, and #11 for left-turn movements) results in a reduction in RLR violations during both weekdays and weekends for both through and left-turn movements. Furthermore, through movements in periodical sites (intersections #5 and #6) consistently demonstrate a consistent pattern on weekdays and weekends. In these instances, periods with longer yellow intervals correspond to lower RLR rates than those with shorter yellow intervals. This trend is also observed in incremental sites for both through and left-turn movements (intersections #2, #4, and #9) on both weekdays and weekends. Later periods with longer yellow intervals exhibit lower RLR rates than the baseline condition.

Striking a balance between safety and mobility has long posed a challenge for transportation agencies. While this study specifically delves into the impact of longer yellow intervals on drivers' compliance, there exists an opportunity for forthcoming research to scrutinize the broader ramifications of altered signal timing settings on overall intersection efficiency. Table 9 provides the daily delay averages for each period at every study site for through movements. In this study, the simple delay was calculated using high-resolution event-based data. The simple delay refers to the time between stop-bar detector activation during the red phase and the subsequent transition to the green phase. It is essential to acknowledge that the simple delay does not encompass factors such as the startup delay, deceleration, or queue length beyond. Notably, at long-term sites, where longer

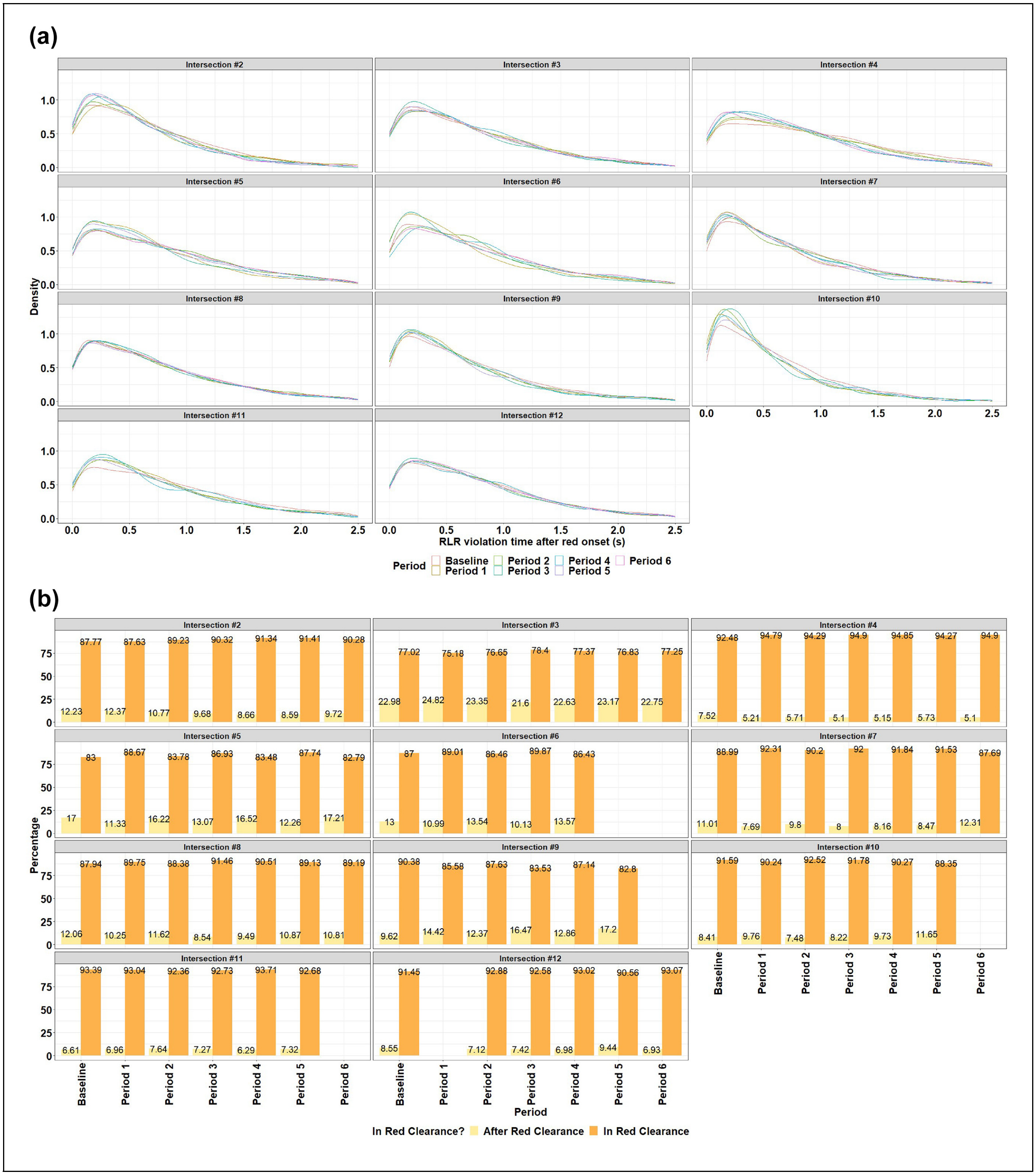

Figure 5. (*a*) Time distribution of red-light running (RLR) violations (seconds after red onset). (*b*) Proportions of RLR violations that occurred during the red clearance interval and after the red clearance interval.

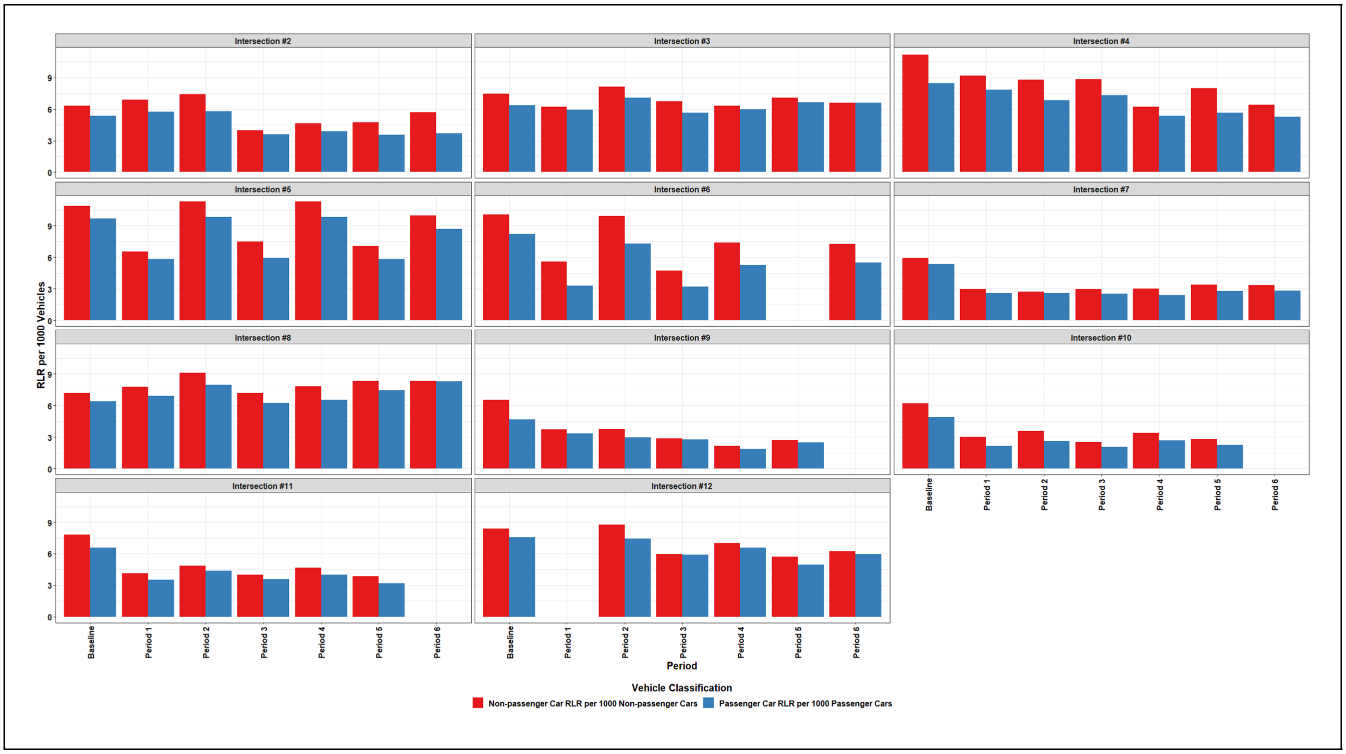

Figure 6. Distribution of red-light running (RLR) across the vehicle classification scheme.

yellow intervals were implemented at the start of period 1, a significant increase is observed in later periods compared with the baseline. However, this pattern is not consistent across all periods; for instance, the delay in period 5 is not significantly different from the baseline. Further investigation of the control, incremental, and periodical sites revealed inconclusive results, as random variations occurred, with some periods showing a significant increase in delay compared with the baseline, while in other periods, no significant changes were observed. The initial findings underscore the complexity of intersection dynamics, emphasizing the imperative for further exploration in future research endeavors.

Conclusion

Red-light running (RLR) behavior is one of the riskiest behaviors at signalized intersections and is becoming a prominent cause of intersection-related crashes. This study aims to investigate the impact of increasing yellow intervals on drivers' compliance behavior in the City of Phoenix, Arizona. To analyze the effectiveness of increasing yellow intervals in reducing RLR violations, 12 intersections in the City of Phoenix were studied through a rigorous before-and-after analysis. At each study site, signal timing information, turning movement counts, high-resolution event-based data, and RLR violations were collected using video-based smart sensors. The comprehensive before-and-after study incorporated multiple periods, each lasting 2 weeks. During each period, a new yellow interval was implemented. A subset of the study sites were designated as control sites, while the remaining were treatment sites. No changes were made to the yellow intervals at the control sites.

The study found that increasing yellow intervals led to a significant reduction in RLR violations. The study revealed that at the control sites, where the yellow intervals remained constant throughout the periods, no significant changes were observed overall. The average RLR rate decreased at the periodical and long-term sites, while inconclusive results were observed during the initial stages of implementation at the incremental sites. The reductions in RLR violations were sustained over time, with decreases of 83% for through movements and 72% for left-turn movements. In light of the empirical findings derived from our study conducted at 12 study sites, which demonstrated that increasing the yellow intervals would significantly decrease RLR violations, we have recommended increasing the yellow intervals for through and left-turn movements. However, it is crucial to acknowledge that determining the optimal yellow intervals for all intersections is a multifaceted challenge, given its intricate connection with factors including driver behavior and demographics, traffic patterns, and intersection geometry.

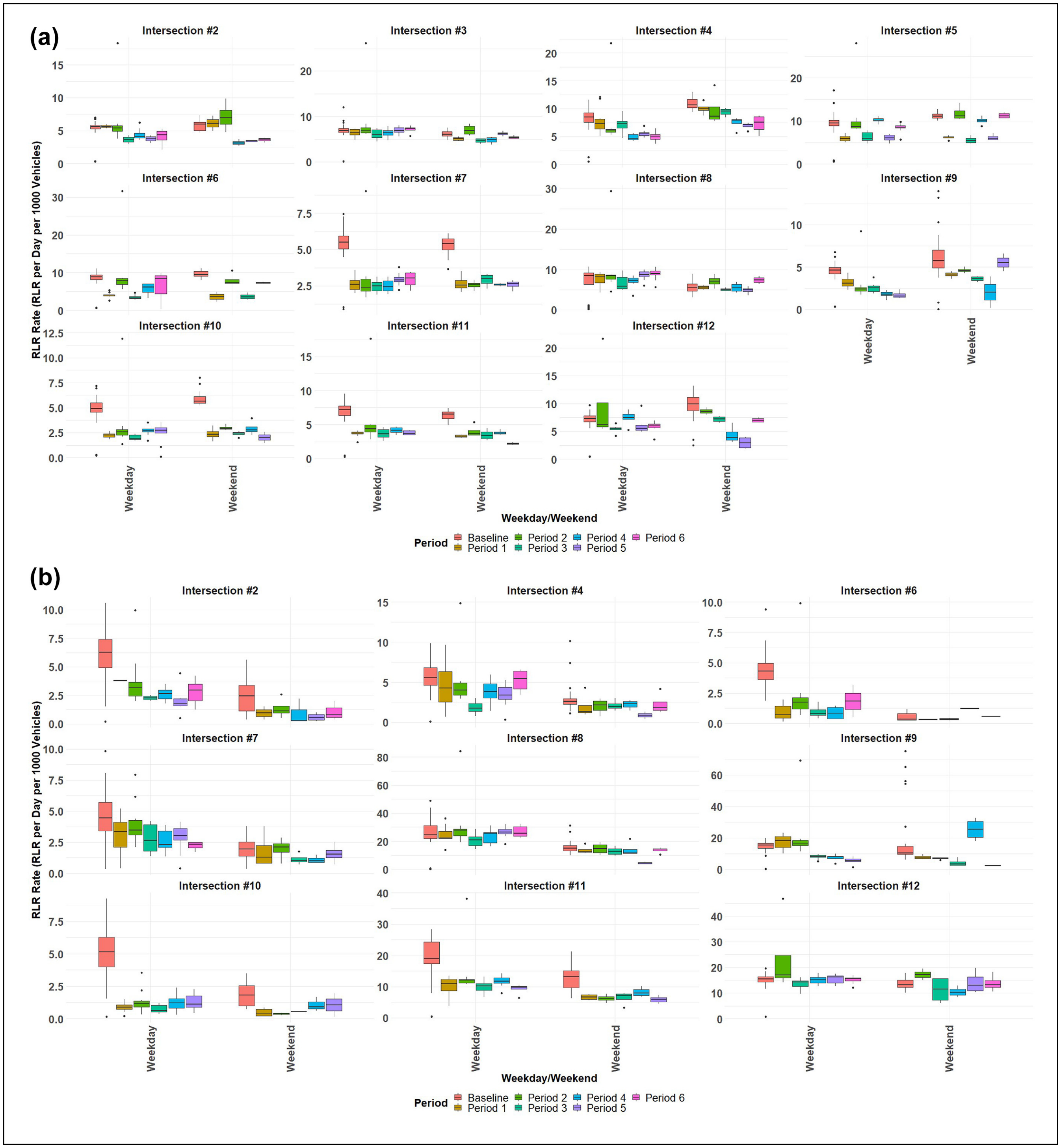

Figure 7. Distribution of red-light running (RLR) violations over weekends versus weekdays for (*a*) through movements and (*b*) left-turn movements.

While enforcement countermeasures, such as law enforcement and intersection surveillance, play a role in addressing RLR, the current study focuses exclusively on the impact of increasing yellow intervals as an engineering countermeasure to enhance drivers' compliance behavior. It does not consider other potential contributing factors, including geometric design, cycle length, green interval, and environmental conditions. It is important to note that excluding these variables may have influenced the observed effects. Consequently, further research is warranted to comprehensively assess the impact of all relevant factors and provide a more comprehensive

Table 9. Statistical *t*-Test Results for Average Delay

Study site	Study site type	Average delay (seconds per vehicle)						
		Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
#3	Control	18.99	18.92	19.79	18.04	18.68	19.38	20.07
#8	Control	48.55	50.16*	50.39*	47.24	49.06	48.77	50.26*
#12	Control	33.05	NA	36.86	33.79	41.33*	38.89*	35.19
#2	Incremental	28.89	33.60	31.84*	32.73	30.60	32.01*	31.85*
#4	Incremental	19.83	18.59	20.54	17.62**	20.32	21.12	21.67
#9	Incremental	26.97	28.67	29.23*	28.35	35.24*	30.58*	NA
#5	Periodical	25.33	26.08	26.10	25.65	25.68	26.33	26.55
#6	Periodical	20.39	22.47	25.37*	23.61*	26.05*	NA	NA
#7	Long term	7.17	7.24	7.87	6.67	7.23	8.00	9.78*
#10	Long term	29.09	32.12*	33.91*	32.33*	34.15*	32.62	NA
#11	Long term	59.91	62.36	63.49*	61.68	64.51*	62.88	NA

*= statistically significant increase compared with the baseline at the 0.05 level; ** = statistically significant decrease compared with the baseline at the 0.05 level; NA = not available.

understanding of their influence on drivers' compliance behavior and the effectiveness of interventions. Furthermore, the study design had inherent limitations in relation to time constraints, such as the duration required for data collection at each treatment site and the potential for prolonged effects that may have influenced the observed results. Moreover, there is potential for future research to center on the analysis of RLR violations across different vehicle classifications and explore the potential impact of driver demographics, including factors such as age and gender, on signal light compliance. To obtain a more definitive conclusion about the impact of increasing yellow intervals on driver compliance behavior, it is recommended that the study should be expanded to include more diverse study sites, consider various traffic signal timing settings, and collect data over an extended period. Future studies could also assess whether law enforcement measures, such as RLR camera enforcement, affect driver behavior. Additionally, incorporating modeling techniques into future research could provide a more comprehensive understanding of the diverse impacts of various factors on RLR violations.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: P. Jalali Khalilabadi, A. Karimpour; data collection: P. Jalali Khalilabadi, A. Karimpour, S. T. Ramos; analysis and interpretation of results: P. Jalali Khalilabadi, A. Karimpour; draft manuscript preparation: P. Jalali Khalilabadi, A. Karimpour, Y.-J. Wu, S. T. Ramos. All authors reviewed the results and approved the final version of the manuscript.

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