Investigating Road Users' Compliance with Yellow and Clearance Time Intervals for Signal Timing Design

Final Report

By

Yao-Jan Wu, Ph.D., P.E., University of Arizona

Abolfazl Karimpour, Ph.D., SUNY Polytechnic Institute

Pouya Jalali Khalilabadi, University of Arizona

THE UNIVERSITY OF ARIZONA
COLLEGE OF ENGINEERING
Center for Applied
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16. ABSTRACT

Red-light running (RLR) behavior is one of the riskiest behaviors at signalized intersections and is becoming a prominent cause of intersection-related crashes. In the Phoenix metropolitan area, there were 113 RLR-related fatalities and 9,320 injuries from 2014 to 2020. To address this issue and ensure 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 yellow change and red clearance intervals on the frequency of RLR violations, and develop effective countermeasures. This study was conducted in the City of Phoenix to assess the impact of updating yellow change and red clearance intervals based on the ITE 2020 guidelines released in March 2020. The project team selected twelve intersections in the City of Phoenix and installed smart sensors to monitor the frequency of RLR violations. Then, in Phase 1 of this study, yellow change intervals were updated based on the ITE 2020 guidelines at each study site, and the frequency of RLR violations was observed in a before-and-after study design. The results indicated that increasing the yellow change intervals could effectively reduce the frequency of RLR violations. Additionally, in order to gain a deeper understanding of driver behaviors and the effects of updating red clearance intervals, both individually and in conjunction with updated yellow change intervals, a comprehensive experiment was conducted in Phase 2. The results showed that implementing ITE 2020 guidelines for red clearance intervals was ineffective in reducing RLR violations.

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EXECUTIVE SUMMARY

Red-light running (RLR) is one of the riskiest behaviors at signalized intersections and is becoming a prominent cause of intersection-related crashes. In the Phoenix metropolitan area, there were 113 RLR-related fatalities and 9,320 injuries from 2014 to 2020. To address this issue and ensure 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 yellow change and red clearance intervals on the frequency of RLR violations, and develop effective countermeasures. Ensuring intersection safety while maintaining an acceptable level of efficiency has been a longstanding focus of research in the field of traffic engineering. Given the similar concerns of the City of Phoenix, this study aims to provide valuable guidance to inform decision-making processes related to traffic signal timings. This project examines whether implementing the Institute of Transportation Engineers' Guidelines for Determining Traffic Signal Change and Clearance Intervals released in March 2020 (ITE 2020 guidelines) on yellow change and red clearance intervals can enhance safety at signalized intersections.

A rigorous selection process was utilized to identify study sites. In order to select the candidate intersections for study, the signalized intersections in the City of Phoenix were ranked using the following criteria: 1) RLR-related crash frequency and severity, 2) top 100 intersections ranked by crash risk provided by the Maricopa Association of Governments (MAG), and 3) former RLR camera locations. Lastly, the feasibility of smart sensor installation was considered, and the twelve study sites were selected. The yellow change and red clearance intervals were calculated based on the ITE 2020 guidelines' equations for through and left-turn movements at each study site. The study was conducted in two Phases. Phase 1 primarily focused on analyzing the effect of yellow change intervals on driver compliance behavior. Subsequently, Phase 2 investigated the influence of red clearance intervals, both independently and in conjunction with yellow change intervals, on intersection safety and RLR violations.

The proposed before-and-after study in Phase 1 consists of a comprehensive experimental design, incorporating multiple periods, each lasting two weeks. During each period, a new traffic signal change interval was implemented. A subset of the study sites was designated as control

sites, while the remaining served as treatment sites. No changes were made to the yellow change intervals at the control sites. The treatment sites were divided into three groups for through movements: 1) incremental, 2) periodical, and 3) long-term sites, and two groups for left-turn movements: 1) incremental and 2) long-term sites. The yellow change intervals at the incremental sites were gradually increased. At the periodical sites, the yellow change intervals were modified every period, with the new ITE 2020 yellow change intervals implemented for two weeks and then alternating back to the City of Phoenix Traffic Services Traffic Engineering Handbook's (COP policy) intervals for the following two weeks. For the long-term sites, the yellow change intervals were increased to the new updated amount and held constant for the subsequent periods. Long-term sites were selected to examine the effects of increasing the yellow change interval on drivers' compliance behavior over an extended period.

According to the statistical analysis (using a 95% confidence level), the results of Phase 1 of the study for both through and left-turn movements are summarized below.

1. For the control sites, there was no significant reduction in the average rate of RLR (measured as RLR per 1000 vehicles per day) for through movements when comparing the latest periods with the baseline period. The same results were observed for the left-turn movements.

2. For the incremental sites (yellow change intervals were gradually increased), the average rate of RLR (measured as RLR per 1000 vehicles per day) for through movements showed a significant reduction when comparing the latest periods with the baseline period. However, during the initial stages of implementation, where yellow change intervals were only increased by 0.1~0.2 seconds, the evaluation results were inconclusive. Similarly, the average rate of RLR for the left-turn movements showed a significant reduction when comparing the latest periods with the baseline period. However, the results during the initial stages of implementation, where yellow change intervals were only increased by 0.3~1.1 seconds, were inconclusive.

3. For periodical sites (where yellow change intervals were modified every period), the average rate of RLR (measured as RLR per 1000 vehicles per day) for through movements

significantly decreased during periods with the ITE 2020 yellow change intervals compared to periods with the COP policy's ' yellow change intervals.

4. For long-term sites, the average rate of RLR (measured as RLR per 1000 vehicles per day) for both through and left-turn movements significantly reduced compared to the baseline.

Based on the findings and results of Phase 1 of the study, the project team has proposed several recommendations to the City of Phoenix to improve safety at signalized intersections by better understanding road users' compliance with the traffic signal. These recommendations include:

1. Based on the data collected at the incremental sites, the findings indicate that fully implementing ITE 2020 guidelines for the calculations of yellow change intervals may not be necessary. This conclusion is supported by the significant decrease in RLR frequencies observed after Period 3 at the incremental sites.
2. For calculating through-movement yellow change intervals, "Speed Limit +7" as the 85th percentile approach speed is recommended when field-measured speed data is unavailable. For left-turn movements, it is recommended to use "Speed Limit - 5" as an estimation for the 85th percentile left-turn approach speed according to the National Cooperative Highway Research Program (NCHRP) report 731, leading to shorter yellow change intervals.
3. In order to obtain a more comprehensive understanding of the effects of implementing the ITE 2020 guidelines on RLR violations, it is recommended to explore the utilization of other advanced technologies as an alternative approach. By employing such technologies, it would be possible to compare and analyze the outcomes obtained from various systems and locations, facilitating a more profound comprehension of the matter.
4. Phase 1 of the study focused solely on analyzing the effect of yellow change intervals on driver compliance behavior. Further research was conducted in Phase 2 to investigate the impact of red clearance intervals, both individually and in conjunction with yellow change intervals, to gain a more comprehensive understanding of their combined effects on intersection safety.

In Phase 2, a study was conducted to investigate the impact of red clearance intervals, both individually and in conjunction with yellow change intervals. Additionally, the long-term effects of implementing updated yellow change intervals were investigated. Similar to Phase 1, a rigorous before-and-after analysis was conducted to examine the relationship between signal timing parameters and RLR violations through a comprehensive experimental design.

According to the statistical analysis (using a 95% confidence level), the results of Phase 2 of the study for both through movements and left-turn movements are summarized below.

1. The updating of red clearance intervals in accordance with the ITE 2020 guidelines had an insignificant impact on drivers' compliance behavior for through movements. It is worth noting that the red clearance intervals recommended by the ITE 2020 guidelines are closely aligned with the COP policy for through movements.
2. Increasing red clearance intervals based on ITE 2020 showed limited effectiveness in reducing RLR violations for left-turn movements. Notably, at certain study sites, where red clearance intervals were increased to meet the ITE 2020 guidelines, a significant increase in RLR violations was observed for left-turn movements.
3. It was observed that the significant decrease in RLR violations following the implementation of longer yellow change intervals persisted throughout the study at the designated long-term sites where the red clearance intervals were left unchanged to assess the long-term effects of increased yellow change intervals.

Based on the findings and results of Phase 2 of this study, the project team has proposed several recommendations to the City of Phoenix to improve safety at signalized intersections by better understanding road users' compliance with the traffic signal. These recommendations include:

1. Considering the minimal disparity between the calculation of red clearance intervals according to the ITE 2020 guidelines and the COP policy, and the lack of significant reduction in RLR violations for through movements observed after updating the red clearance intervals, it is recommended to maintain the current practices for red clearance intervals instead of adopting the ITE 2020 guidelines for through movements.

2. Based on the observations regarding the implementation of increased red clearance intervals for left-turn movements, it was found that adhering to the ITE 2020 guidelines showed limited effectiveness in reducing RLR violations. Also, it was observed that the increasing red clearance intervals led to an increase in RLR violations for left-turn movements. As a result, it is recommended to maintain the current practices for red clearance intervals for left-turn movements instead of implementing the ITE 2020 guidelines.

3. Further study is strongly recommended to draw more robust conclusions. Particularly, due to the permissive-protected nature of left-turn movements at certain study sites and the difficulty in capturing RLR violations during transitions between phases, it is crucial to conduct additional research using a new system and an alternative algorithm for RLR detection. Employing other advanced technologies will enable more comprehensive analysis and provide valuable insights into optimizing RLR mitigation strategies.

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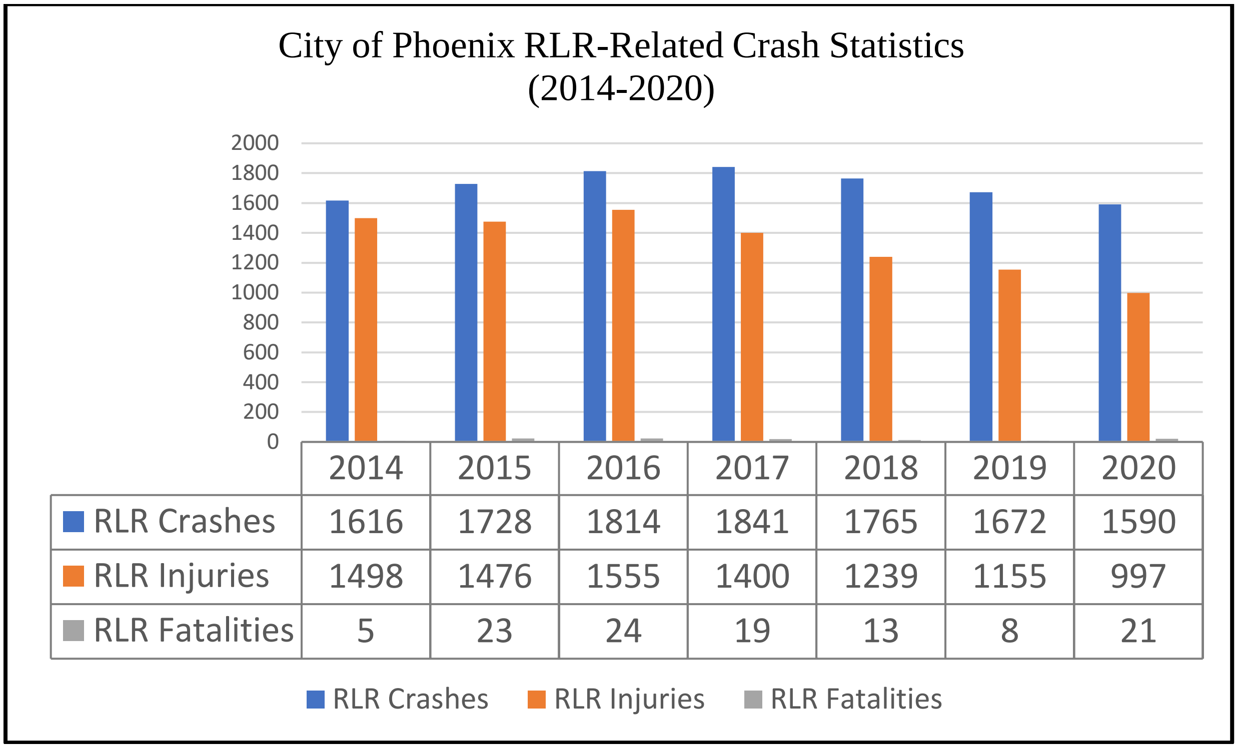
Chapter 1

Introduction

1. INTRODUCTION

Red-light running (RLR) is one of the riskiest behaviors at signalized intersections. Once a vehicle approaches an intersection and the green light is about to terminate, the driver must decide whether to stop or go. If the driver determines sufficient time to pass the intersection, a go decision is likely to be made. If there is insufficient time to clear the intersections entirely, a stop decision is likely to be made. If the driver chooses to proceed, and the signal turns red before the driver passes the stop bar or clears the intersection, depending on state law, the driver is considered a red-light runner.

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 collisions (IIHS, 2022). Similar to other cities, RLR violations have become one of the most severe causes of fatal crashes in the Phoenix metropolitan area, with 113 fatalities and 9,320 injuries reported from 2014 to 2020. Figure 1.1 shows the statistics for RLR-related crashes in the City of Phoenix from 2014 to 2020. To ensure the safety of all road users and reduce RLR-related crashes, it is imperative to conduct a comprehensive examination of RLR behavior at local intersections. This entails assessing the influence of various signal timing parameters on the frequency of RLR violations and developing effective countermeasures to address any identified issues.



	2014	2015	2016	2017	2018	2019	2020
RLR Crashes	1616	1728	1814	1841	1765	1672	1590
RLR Injuries	1498	1476	1555	1400	1239	1155	997
RLR Fatalities	5	23	24	19	13	8	21

Figure 1.1 RLR-related crash statistics in the City of Phoenix

1.1 Project Background

The City of Phoenix Street Transportation Department has a Traffic Services Traffic Engineering Handbook (COP policy) for determining the duration of traffic signal intervals. The COP policy states that the Institute of Transportation Engineers (ITE) kinematic equation should be used and references the pre-2020 equation, and also states that any deviations from the policy must be approved by the Deputy Street Transportation Director of theTraffic Services Division. The details of the COP policy and how it differs from ITE 2020 guidelines are provided in the Traffic Signal Timing Report (Freas, 2022). Below are the current City of Phoenix equations for calculating the yellow change and red clearance intervals:

$$Y \geq t + \frac{1.47V}{2a + 64.4g} \qquad \text{(Equation 1)}$$

Where:

Y = minimum yellow change interval (in seconds) with a maximum of 5 seconds (if the calculation exceeds 5 seconds, any excess time from the calculation is added to the red clearance interval);

t = perception-reaction time (in seconds); 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 of 1.0 seconds.

V= intersection entry speed (mph); the approach speed limit is assumed.

a = deceleration (ft/s^2); the rate at which it is assumed a driver will slow down

upon seeing the yellow signal. The default value of 10 ft/s^2.

g = grade of approach (downhill is negative grade)

$$R = \left[\frac{W}{1.47V}\right] \qquad \text{(Equation 2)}$$

Where:

R = red clearance interval (seconds);

V= intersection entry speed (mph); the approach speed limit is assumed.

W = distance to traverse the intersection (width), stop line to far side no-conflict point along the vehicle path (ft.);

The updated ITE guidelines for calculating traffic signal timing were released in March 2020 (ITE, 2020). Since 1965, ITE has developed a variety of methods for calculating yellow change and red clearance intervals, all of which are based on the kinematic equation method. According to ITE, the kinematic equation method is the most popular and widely accepted technique for determining yellow change intervals. Comparing the new ITE 2020 guidelines to the prior ones, three key modifications exist. The first modification is the speed at which a reasonable driver approaches an intersection. If a speed study is not done and the 85th percentile speed is not available, the 85th percentile approach speed for through movements may be estimated and substituted by the value of "Posted Speed Limit +7," and for the left-turn movements, the "Posted

Speed Limit" can be used as the 85th percentile approach speed. The second key modification proposes a method for left-turn yellow interval calculations. The third major modification in the new ITE 2020 guidelines is that a maximum yellow change interval of 7.0 seconds is advised for left-turn movements. Below are the current ITE-recommended equations for calculating the yellow change and red clearance intervals:

$$Y \geq t + \frac{1.47(V_{85} - V_E)}{a + 32.2g} + \frac{1.47V_E}{2a + 64.4g} \qquad \text{(Equation 3)}$$

Where:

Y = minimum yellow change interval (in seconds);

t = perception-reaction time (in seconds); 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 of 1.0 seconds.

V_{85}= 85th percentile approach speed (mph); the speed at which a "reasonable" driver is assumed to approach the intersection.

V_E= intersection entry speed (mph); 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); the rate at which it is assumed a driver will slow down

upon seeing the yellow signal. The default value of 10 ft/s^2.

g = grade of approach (downhill is negative grade)

$$R = \left[\frac{W + L}{1.47V_E}\right] - t_s \qquad \text{(Equation 4)}$$

Where:

R = red clearance interval (seconds);

W = distance to traverse the intersection (width), stop line to far side no-conflict point along the vehicle path (ft.);

L = length of the vehicle (ft.); 20 ft is often used as the representative length for vehicles entering the intersection.

t_s = conflicting vehicular movement start-up delay (seconds); an optional parameter with an initial value set at 0.0 seconds. Values may be used based on engineering judgment or a study's support.

1.2 Project Objectives

The challenges and difficulties associated with determining traffic signal timings have been extensively discussed among scholars and professionals in the field of traffic engineering. It has long been an area of study to determine the proper traffic signal timings to ensure intersection safety while maintaining an acceptable level of efficiency. However, there is still no broad consensus on the most appropriate method for calculating yellow change and red clearance intervals (Freas, 2022). ITE indicates they believe there has been sufficient theoretical work, research, and practice to reach a consensus recommendation. However, they acknowledge that this is not true for all potential elements or aspects of the process, so they recommend areas for further research. Many practitioners do not accept the ITE 2020 guidelines due to a lack of specific field research. Several studies are underway, such as the Federal Highway Administration's Pooled Fund Study: Traffic Signal Change and Clearance Interval, to address this concern. As the City of Phoenix has the same concerns, this study is being undertaken to provide guidance to the City of Phoenix. This project aims to examine whether implementing ITE 2020 guidelines on yellow change and red clearance intervals can enhance safety at signalized intersections. Twelve study sites were initially selected based on several criteria, including the frequency and severity of RLR-related crashes and infrastructure feasibility. Then, at each study site, smart sensors were installed. Finally, an experimental design for before-and-after analysis was implemented to determine the relationship between signal timing parameters and red light violations. As it is shown in Figure 1.2, the steps that were taken in this study include: 1) reviewing new ITE 2020 guidelines, 2) selecting and refining study sites, 3) implementing sensors at selected intersections, 4) calculating yellow change and red clearance intervals, 5) developing the experimental design, 6) implementing the experimental design, and 7) data collection and analysis.

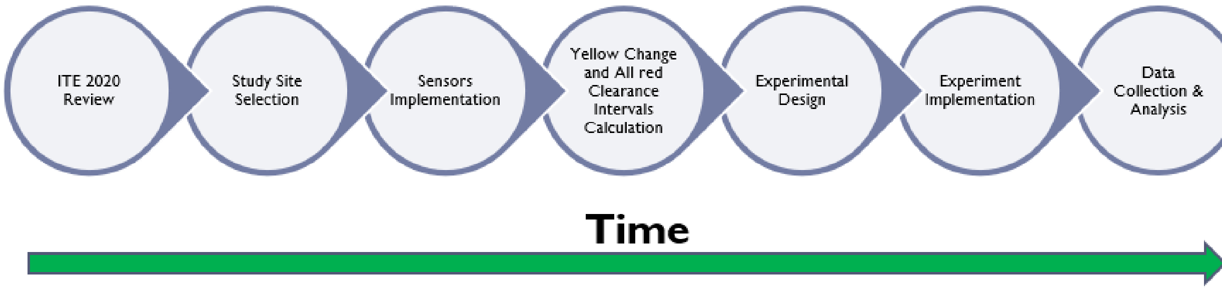


Figure 1.2 The project timeline overview

Chapter 2

Literature Review

2. LITERATURE REVIEW

2.1 Yellow Change and Red Clearance Intervals Impact on Red-Light Running

One of the primary countermeasures that have been widely shown to be effective in reducing the frequency of RLR violations is modifying the signal timing parameters (such as increasing the yellow change intervals) (Hallmark et al., 2012).

Bonneson & Zimmerman (2004) showed that increasing the yellow change intervals by one second (provided that it does not exceed 5.5 s) could decrease the RLR frequency by at least 50 percent. Bonneson & Zimmerman (2004) conducted a before-and-after study over ten intersections in five Texas cities. Further observation confirmed that drivers adjust to the increase in yellow change intervals. However, this adaption does not negate the benefits of longer yellow change intervals (Bonneson & Zimmerman, 2004). In a similar study, Retting et al. (2008) evaluated the impact of longer yellow change intervals on the red-light violation. A before-and-after study was conducted at two intersections in Philadelphia, PA, and the results showed that RLR frequency was reduced by 36 percent after increasing the yellow change intervals.

The impact of changing the red clearance intervals on RLR violations and right-angle crashes has been widely studied. However, no specific results were found to support the positive impact of this countermeasure on reducing the RLR violation. For instance, Retting & Greene (1997) found that increasing the red clearance intervals was ineffective in reducing the red-light violation (Retting & Greene, 1997). Datta et al. (2000) found a significant drop in right-angle crashes as a result of increasing the red clearance intervals (Datta et al., 2000). Similar to increasing the yellow change intervals, increasing the red clearance intervals is a cost-effective and easy-to-implement countermeasure. Still, it can decrease the intersection's capacity and increase the delay (Hallmark et al., 2012).

2.2 Experimental Design Literature Review

To study the evaluation of a countermeasure or a newly established system, two methodologies might be applied: 1) before-and-after analysis and 2) with-or-without analysis (Bonneson & Zimmerman, 2004; Chiou & Chang, 2010; Kergaye et al., 2009; Lum & Halim, 2006; Park et al., 2010; Retting et al., 2008). For instance, Lum and Halim (2006) conducted a before-and-after study to evaluate the impact of Green Signal Countdown Devices (GSCD) on RLR behaviors (Lum & Halim, 2006). In a similar study, Retting et al. (2008) employed a before-and-after analysis to investigate the influence of longer yellow change intervals and camera enforcement on RLR frequency (Retting et al., 2008). Furthermore, the before-and-after analysis was used by Choiu and Chang (2010) to evaluate the installation of Red Signal Countdown Devices (RSCD). Park et al. (2010) employed a before-and-after analysis to study the safety evaluation of decreasing the posted speed limit. However, one limitation of the before-and-after study approach is that road and traffic conditions may vary between study periods. Changes in the road and intersection geometry, traffic demand and distribution on the network, speed limits, and so on are all examples of changing situations. If considerable changes occur, the before-and-after study may be compromised. A with-or-without analysis was conducted to investigate the driver responses to GSCD (Chiou & Chang, 2010).

2.3 ITE 2020 Guidelines

The Institute of Transportation Engineers (ITE) has completed a multi-year effort to offer recommendations on the yellow change and red clearance intervals for signalized intersections. The logic behind the methodology for determining the length of the yellow change intervals is that it should give a reasonable amount of time to drivers approaching the intersection to either safely and comfortably stop or traverse the distance and legally enter and clear the intersection before the onset of red. ITE 2020 guidelines propose using equations 3 and 4 to determine the yellow change and red clearance intervals. These equations are derived from the kinematic equation. The yellow change interval is established as the combination of the perception-reaction time (PRT) and the time it takes for the vehicle to stop (Braking Distance). The red clearance interval is calculated as the time a passing vehicle takes to clear the intersection. There are two assumptions in this current approach: 1) uniform deceleration and 2) drivers who choose to go rather than stop are assumed to travel through the intersection at a constant speed equal to their approaching speed.

The perception reaction time in Equation 3 is commonly assumed to be one second. However, it can be increased using engineering judgment. The 85th percentile approach speed under the free-flow conditions should be determined as the value for approach speed. If the through movements' 85th percentile speed is unavailable and a speed study is not conducted, then the through movements' 85th percentile speed can be estimated based on Equation 5:

$$V = V_{85E} = SL + 7 \quad \text{(Equation 5)}$$

where, V_{85E} is the estimated through movements' 85th percentile speed in mph, and SL is the posted speed limit in mph. For the through movements, the intersection entry speed (V_E) is assumed to be the same as 85th percentile speed ($V_E = V$). For the turning movements, it is recommended to conduct a speed study to determine the actual intersection entry speed. However, if the actual data is unavailable, a general value of 20 mph for intersection entry speed (V_E) for left turns should be assumed. Moreover, ITE 2020 guidelines recommend using "speed limit" to estimate left-turn movements' 85th percentile approach speed. For the deceleration rate (a), it is recommended to use the value of 10 (ft./sec./ sec.) as it is appropriate for most users. The ITE also provided a minimum and maximum value for the yellow change intervals. Using the minimum value of 3 seconds and the maximum value of 6 seconds is recommended for the yellow change intervals for the through movements. However, the minimum value of 3 seconds and the maximum value of 7 seconds is recommended for left-turn movements.

2.4 Literature Takeaways

Previous studies have suggested that increasing the duration of the yellow change intervals at traffic signals could potentially reduce the frequency of RLR. However, the extent to which this increase would effectively reduce RLR remains unclear. It is currently unknown at what point an increase in the yellow change interval might instead result in an increase in the frequency of RLR rather than a decrease. Moreover, previous studies did not find a significant correlation between the red clearance interval and RLR. However, some studies found that increasing the red clearance interval could reduce right-angle crashes. Therefore, further research is needed to fully understand the relationship between signal timing parameters and RLR frequency and to determine the optimal duration of yellow change and red clearance intervals that can effectively reduce RLR.

Chapter 3

Study Sites Selection
&
Sensor Implementation

3. STUDY SITES SELECTION & SENSOR IMPLEMENTATION

3.1 Study Sites Selection

In order to select the candidate intersections for study, the signalized intersections in the City of Phoenix were ranked using the following criteria.

- RLR-related crash frequency and severity
- List of 100 intersections ranked by crash risk (provided by MAG)
- Former RLR camera locations
- Infrastructure feasibility

Arizona Crash Information System (ACIS) was queried for five years of crash data (from 2016 to 2021) to identify prospective intersections for smart sensor installation. Then, only crashes at four-way intersections resulting from disregarding traffic signals were collected. Intersections were then ranked based on the frequency and severity of the crashes. A sample of ACIS data is displayed in Figure 3.1.

IncidentID	IncidentOnroad	IncidentCrossingFeature	IncidentInjurySeverityDesc	PersonViolationDesc1
3641473	07 GREENWAY RD	29th Ave	Fatal	Disregarded Traffic Signal
3655207	07 CAMELBACK RD	16th St	Fatal	Disregarded Traffic Signal
3663901	07 32ND ST	Broadway Rd	Fatal	Disregarded Traffic Signal
3692790	07 7TH ST	I-17 Cardinal Frontage	Fatal	Disregarded Traffic Signal
3695155	07 87TH AVE	Lower Buckeye Rd	Fatal	Disregarded Traffic Signal
3717241	07 THUNDERBIRD RD	35th Ave	Fatal	Disregarded Traffic Signal
3724946	07 67TH AVE	Encanto Blvd	Fatal	Disregarded Traffic Signal
3724946	07 67TH AVE	Encanto Blvd	Fatal	Disregarded Traffic Signal
3732404	07 BUCKEYE RD	35th Ave	Fatal	Disregarded Traffic Signal
3737924	07 35TH AVE	Lower Buckeye Rd	Fatal	Disregarded Traffic Signal
3766271	07 27TH AVE	Indian School Rd	Fatal	Disregarded Traffic Signal
3640967	07 BELL RD	17th Ave	Suspected Serious Injury	Disregarded Traffic Signal
3675735	07 51ST AVE	I-10 Cardinal Frontage	Suspected Serious Injury	Disregarded Traffic Signal
3688382	07 51ST AVE	I-10 Non-Cardinal Frontage	Suspected Serious Injury	Disregarded Traffic Signal
3704717	07 48TH ST	Vineyard Rd	Suspected Serious Injury	Disregarded Traffic Signal
3725346	07 51ST AVE	I-10 Exit 139 C-Ramp	Suspected Serious Injury	Disregarded Traffic Signal
3728522	07 NORTHERN AVE	7th St	Suspected Serious Injury	Disregarded Traffic Signal
3737761	07 44TH ST	Washington St	Suspected Serious Injury	Disregarded Traffic Signal
3738098	07 INDIAN SCHOOL RD	31st Ave	Suspected Serious Injury	Disregarded Traffic Signal
3741467	07 INDIAN SCHOOL RD	43rd Ave	Suspected Serious Injury	Disregarded Traffic Signal
3746132	07 NORTHERN AVE	39th Ave	Suspected Serious Injury	Disregarded Traffic Signal

Figure 3.1 ACIS crash data sample

The list of 100 intersections and the intersections where RLR cameras had previously been installed were two additional datasets that were considered. The list of 100 intersections contains the top 100 intersections ranked by crash risk and intersection safety score provided by the Maricopa Association of Government (MAG). The document "MAG Network Screening Methodology for Intersections" provides a detailed description of the Intersection Safety Score (MAG, 2010).

Finally, the feasibility of smart sensor installation was considered after ranking the intersections. Due to the infrastructure limitation, the intersections that required new signal cables or new conduits in one or two legs were eliminated. As a result, the twelve intersections with the highest rank that did not require any upgrades for sensor installation were selected as the final candidates.

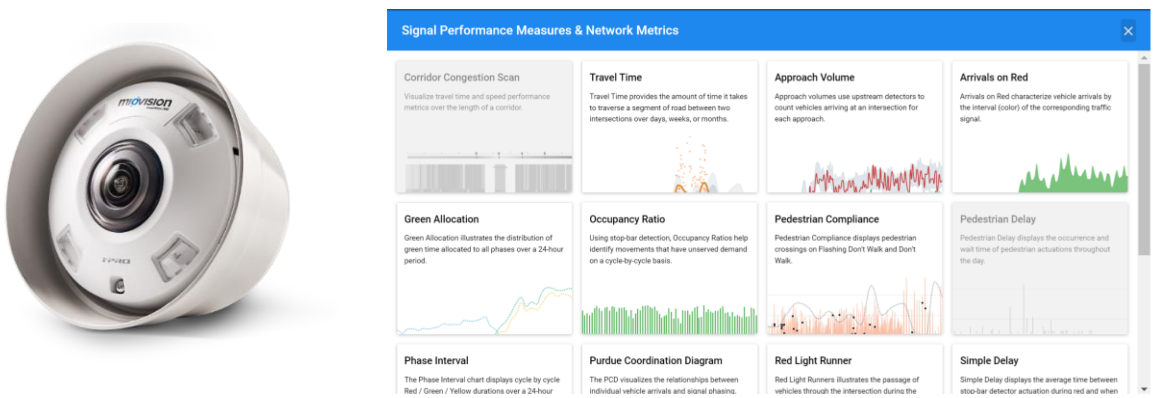
The final twelve selected study sites are listed in Table 3.1. As can be seen, four study sites required a dual-camera system to capture the entire intersection.

Table 3.1 Final Selected Twelve Intersections

Intersection	Camera & Extension Requirements
Intersection #1	Single Camera
Intersection #2	Single Camera + Extension
Intersection #3	Single Camera + Extension
Intersection #4	Dual Camera + Extension (Both)
Intersection #5	Single Camera + Extension
Intersection #6	Single Camera + Extension
Intersection #7	Single Camera + Extension
Intersection #8	Dual Camera
Intersection #9	Dual Camera + Extension (Both)
Intersection #10	Single Camera + Extension
Intersection #11	Dual Camera + Extension
Intersection #12	Single Camera

3.2 Field Implementation

The City of Phoenix traffic signal technicians installed the smart sensors (Miovision's SmartView 360) provided by AM Signal at the twelve study sites. The UArizona team worked closely with the City technicians to observe and document the procedure. The smart sensor, shown in Figure 3.2 (a), provides traffic-related data, signal timing information, and high-resolution event-based data. The available performance measures provided by the Miovision TrafficLink are shown in Figure 3.2 (b). TrafficLink is the Miovision Graphical User Interface (GUI) that allows users to select specific intersections and access their corresponding signal performance measures. These performance measures include red-light running (RLR), simple delay, and approach volume.

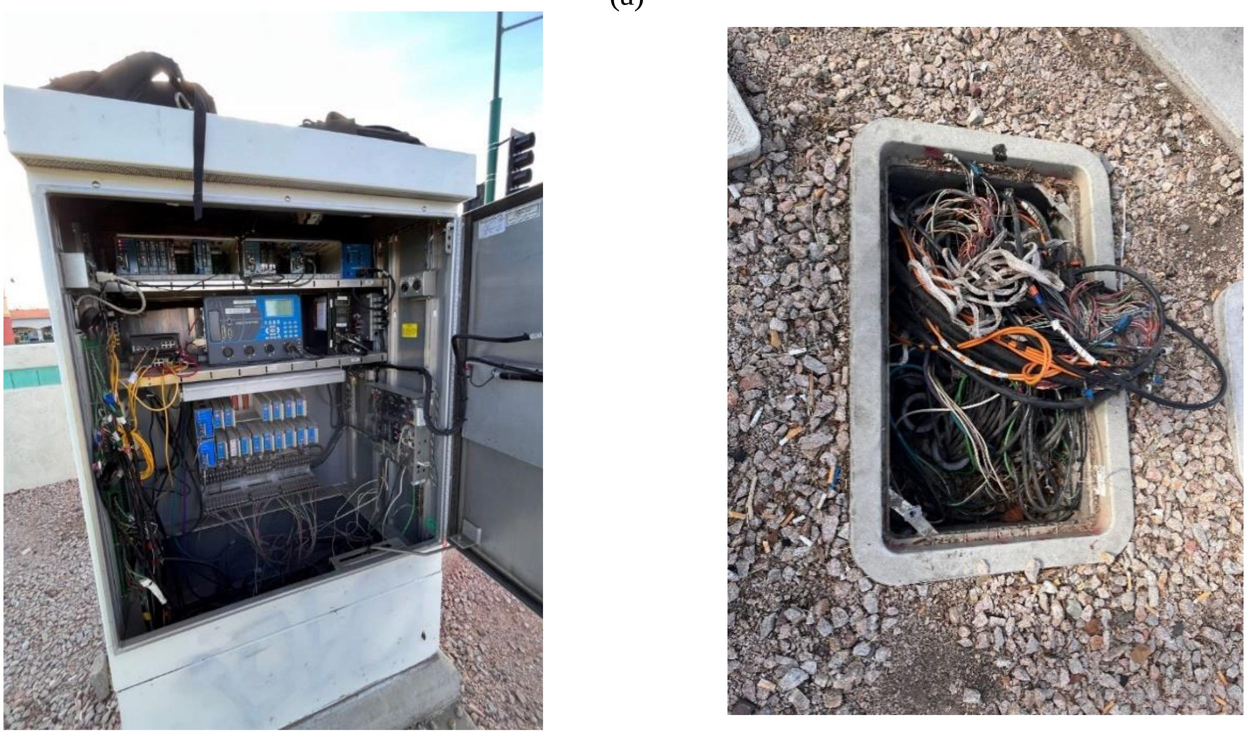


(a) (b)

Figure 3.2 a) Miovision's SmartView 360 Sensor, b) Miovision Traffic Link User Interface

Figure 3.3 (a) shows the installed cameras at two study sites. Miovision's SmartView 360 camera can extend the functionality of the Miovision Detection solution by identifying vehicles approaching intersections from a distance of up to 500 feet. It allows users to create multiple detection zones and detect vehicles across up to four lanes, enabling them to establish effective traffic control strategies and monitor traffic flow. Figure 3.3 (b) shows a traffic control cabinet and a conduit. It is worth noting that several candidate intersections were excluded from the study site selection process due to limitations in conduit capacity. (refer to Figure 3.3 (b)).

(a)



(b)

Figure 3.3 a) Miovision's smartview camera installed sensors, b) Traffic control cabinet & conduit

Chapter 4

Data Collection

&

Analysis

4. DATA COLLECTION & ANALYSIS

4.1 Data Collection

Data is collected through installed traffic sensors at twelve study sites. Miovision© Team provided data per the request of the UArizona team. The provided data includes three datasets: 1) Turning Movement Counts (TMC) data, 2) Traffic Signal Phase data, and 3) Red-Light Running (RLR) and Yellow-Light Running (YLR) data.

4.1.1 TMC Data

Turning Movement Counts (TMC) data provides the number of vehicles that pass through each approach for each movement of the intersections in each 15-minute time bin. The TMC data also includes vehicle classification. The data is aggregated on each 15-minute time bin. Table A.1 contains a sample of the TMC data (refer to Appendix A).

4.1.2 Traffic Signal Phase Data

Traffic Signal Phase data contains the controller phasing logs for each cycle. In other words, the research team was provided with information on when the green, red, and yellow signals started at each cycle for each approach and movement. By using this information, the cycle length, yellow change interval, green duration, and red duration for each cycle can be measured. Table A.2 contains a sample of the Traffic Signal Phase data (refer to Appendix A). As seen in Table A.2, the Traffic Signal Phase data includes the timestamp of the start and end of green, yellow, and red signals for each cycle and the duration of the aforementioned signals.

4.1.3 RLR & YLR Data

Red-Light Running (RLR) and Yellow-Light Running (YLR) data includes information about when the event occurred and other associated variables such as vehicle classification, yellow duration, etc. The information provides the exact timestamp that the vehicle ran the red light, the vehicle's approach and movement, vehicle class, and the signal timing parameters of the cycle of the RLR/YLR event that occurred. Table A.3 shows a sample of the RLR/YRL data (refer to Appendix A).

4.2 Data Quality Control and Outlier Filtering

In order to enhance the quality of the analysis and increase the reliability of the results, outliers need to be identified and removed from all the datasets. Filtering outliers was done through the following four steps:

1. The cycles with excessive cycle length and yellow change intervals were removed. The unusual signal timing intervals might be caused by signal communication loss, transition, emergency vehicle preemption, etc.
2. The very deep red light runners were eliminated from the dataset. These deep RLRs happened due to false detection. It was observed that smart sensors misdetected the conflicting movements as RLR.
3. A moving interquartile range (IQR) outlier-filtering method was used to remove outliers. (Karimpour et al., 2021).
4. Additionally, to assess the algorithm that the Miovision system uses to detect red-light violations, the ground truth videos recorded by the smart sensors were carefully reviewed and analyzed. Figure 4.1 illustrates the detection overlay configuration in the smart sensor.

Figure 4.1 Smart sensors' detection overlay configuration

4.3 Data Availability

Figure 4.2 shows the data availability for the study. Notably, there are gaps in the data for certain study sites. For instance, Intersection #1 has missing data after November 2^{nd}, while Intersection #2 lacked data for November and from December 20^{th} to January 3^{rd}. Similarly, Intersection #6 had missing data from January 5^{th} to February 9^{th}, while Intersection #9, Intersection #10, and Intersection #11 all had missing data from January 25^{th} to March 1^{st}. Lastly, the data for Intersection #12 was missing from November 1st to December 13th.

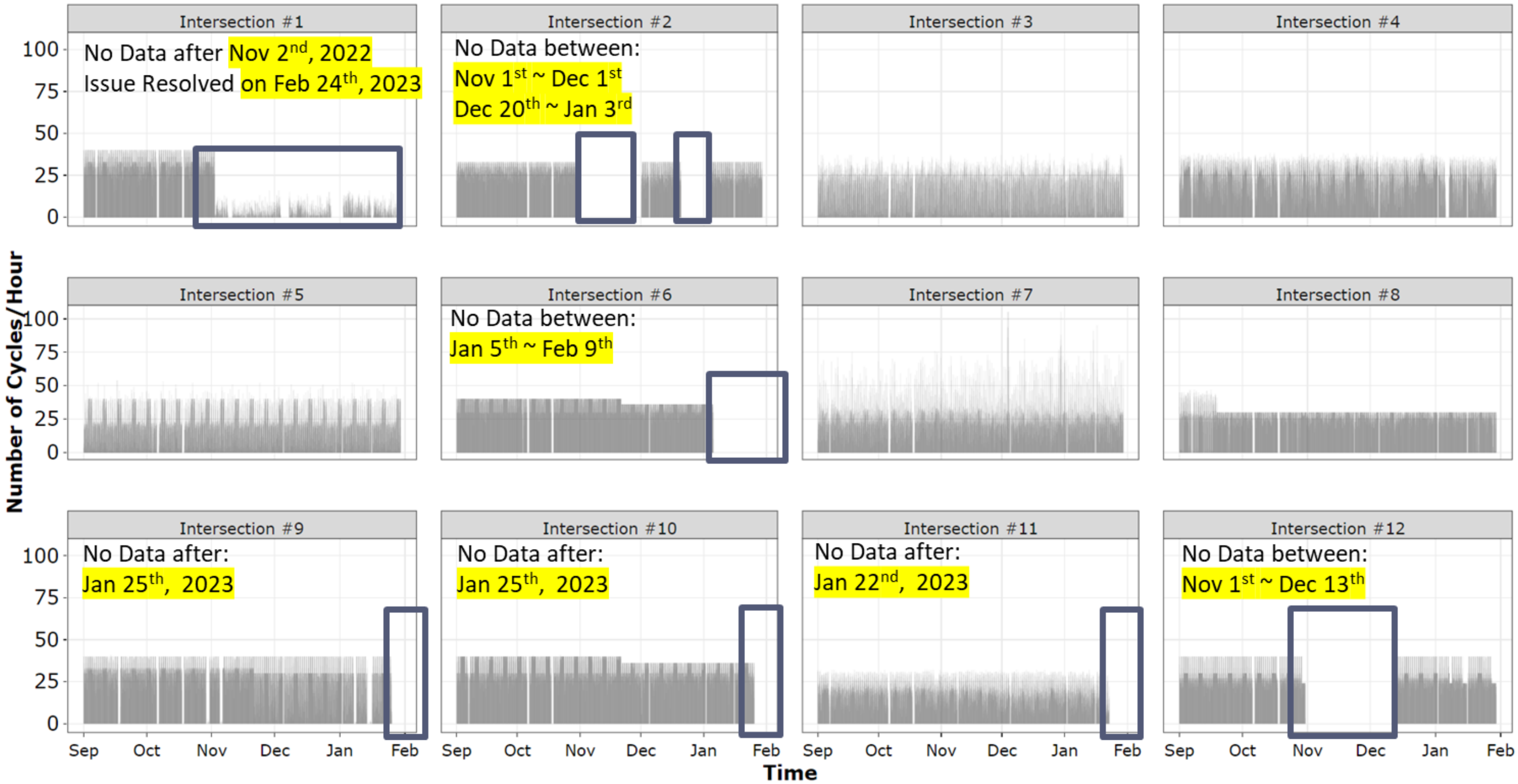


Figure 4.2 Data availability

PHASE 1

Yellow Change Intervals Study

Chapter 5

Experimental Design (Phase 1)

5. EXPERIMENTAL DESIGN (Phase 1)

5.1 Yellow Change Intervals Calculation Based on ITE 2020

The current ITE-recommended equation for calculating the yellow change intervals is shown below:

$$Y \geq t + \frac{1.47(V_{85} - V_E)}{a + 32.2g} + \frac{1.47V_E}{2a + 64.4g} \quad \text{(Equation 3)}$$

Where:

Y = minimum yellow change interval (in seconds).

t = perception-reaction time (in seconds); 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 of 1.0 seconds.

V_{85}= 85th percentile approach speed (mph); the speed at which a "reasonable" driver is assumed to approach the intersection.

V_E= intersection entry speed (mph); 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); the rate at which it is assumed a driver will slow down

upon seeing the yellow signal. The default value of 10 ft/s^2.

g = grade of approach (downhill is negative grade)

The following sections provide the details of yellow change interval calculation at twelve selected intersections for through and turning movements.

5.1.1 Through Movements

Due to the absence of approach speed at the selected study sites, in this study the "speed limit+7" was used in lieu of through movement's 85th percentile of approach speed. According to the ITE 2020 guidelines, the minimum perception-reaction time of 1.0 sec and deceleration of 10 ft/s^2 would be most appropriate to use. The intersection entry speed for through movements would be equal to the 85th percentile of approach speed. Since the selected intersections don't have any downgrade or upgrade approaches, the measured grade of approach (g) for all intersection approaches is equal to zero. Thus, for this study, the yellow change intervals for through movements were measured using Equation 6:

$$Y \geq 1 + \frac{1.47\ (SL + 7)}{2 \times (10)} \qquad \text{(Equation 6)}$$

Where:

SL = posted speed limit (in mph).

Table 5.1 contains the posted speed limit of each approach at twelve selected intersections.

Table 5.1 Study Sites Posted Speed Limit

Intersection	Speed Limit (MPH)			
	EB	NB	WB	SB
Intersection #1	35	35	35	35
Intersection #2	35	35	35	35
Intersection #3	30	40	30	40
Intersection #4	35	35	35	35
Intersection #5	30	40	30	40
Intersection #6	45	40	45	40
Intersection #7	45	25	45	25
Intersection #8	45	40	45	40
Intersection #9	45	40	45	40
Intersection #10	40	40	40	40
Intersection #11	40	35	40	40
Intersection #12	40	40	40	40

According to the posted speed limit, the through movements' yellow change intervals were calculated at each study site and shown in Table 5.2. Table 5.2 includes the COP policy's yellow change intervals and the difference between the newly measured and COP policy's intervals. Comparing the COP policy's yellow change intervals and the newly measured intervals, the increases range from 0.4 to 0.6 seconds for the through movements' yellow change intervals.

Table 5.2 Calculated Yellow Change Intervals for Thorough Movements

Intersections	Yellow Interval (ITE 2020)				Yellow Interval (COP Policy)				Delta Δ (ITE – COP)			
	EB	NB	WB	SB	EB	NB	WB	SB	EB	NB	WB	SB
Intersection #1	4.1	4.1	4.1	4.1	3.6	3.6	3.6	3.6	0.5	0.5	0.5	0.5
Intersection #2	4.1	4.1	4.1	4.1	3.6	3.6	3.6	3.6	0.5	0.5	0.5	0.5
Intersection #3	3.8	4.5	3.8	4.5	3.2	4	3.2	4	0.6	0.5	0.6	0.5
Intersection #4	4.1	4.1	4.1	4.1	3.6	3.6	3.6	3.6	0.5	0.5	0.5	0.5
Intersection #5	3.8	4.5	3.8	4.5	3.2	4	3.2	4	0.6	0.5	0.6	0.5
Intersection #6	4.9	4.5	4.9	4.5	4.3	4	4.3	4	0.6	0.5	0.6	0.5
Intersection #7	4.9	3.4	4.9	3.4	4.3	3	4.3	3	0.6	0.4	0.6	0.4
Intersection #8	4.9	4.5	4.9	4.5	4.3	4	4.3	4	0.6	0.5	0.6	0.5
Intersection #9	4.9	4.5	4.9	4.5	4.3	4	4.3	4	0.6	0.5	0.6	0.5
Intersection #10	4.5	4.5	4.5	4.5	4	4	4	4	0.5	0.5	0.5	0.5
Intersection #11	4.5	4.1*	4.5	4.5	4	4	4	4	0.5	0.1*	0.5	0.5
Intersection #12	4.5	4.5	4.5	4.5	4	4	4	4	0.5	0.5	0.5	0.5

*" If yellow change intervals for concurrently terminating phases differ, apply yellow change intervals greater than the minimum calculated value for the approach" [ITE, 2020]. Therefore, the **4.5 seconds** calculated for SB should be adopted for NB instead of using the calculated 4.1.

5.1.2 *Turning Movements*

Due to the absence of field-measured speed data at the selected study sites, the "speed limit" was used in this study as the turning movement's 85th percentile of approach speed. According to the ITE 2020 guidelines, the minimum perception-reaction time of 1.0 sec and deceleration of 10 ft/s^2 would be most appropriate to use. The intersection entry speed for turning movements would be equal to the general value of 20 mph for left turns in the lack of field-measured speed data. Since the selected study sites don't have any downgrade or upgrade approaches, the measured grade of approach (g) for all approaches is equal to zero. Thus, for this study, the yellow change intervals for turning movements were measured using Equation 7:

$$Y \geq 1 + \frac{1.47(SL - 20)}{10} + \frac{1.47 \times 20}{2 \times (10)} \qquad \text{(Equation 7)}$$

Where:

SL = posted speed limit (in mph).

According to the posted speed limit, the yellow change intervals were calculated for left-turn movements at each study site and shown in Table 5.3. Table 5.3 includes the COP policy’s yellow change intervals and the difference between the newly measured and COP policy’s intervals. Comparing the COP policy’s yellow change intervals and the newly measured intervals, the increases range from 0.3 to 3.2 seconds for the left-turn movements' yellow change intervals. Only ten intersections are used for studying left-turn movements since two intersections do not have any protected left-turn phase.

Table 5.3 Calculated Yellow Change Intervals for Left-Turn Movements

Intersections	Yellow Interval (ITE 2020)				Yellow Interval (COP Policy)				Delta Δ (ITE – COP)			
	EB	NB	WB	SB	EB	NB	WB	SB	EB	NB	WB	SB
Intersection #1	4.7	-	4.7	-	3	-	3	-	1.7	-	1.7	-
Intersection #2	4.7	4.7	4.7	4.7	3	3	3	3	1.7	1.7	1.7	1.7
Intersection #4	4.7	4.7	4.7	4.7	3	3	3	3	1.7	1.7	1.7	1.7
Intersection #6	6.2	5.5	6.2	5.5	3	3	3	3	3.2	2.5	3.2	2.5
Intersection #7	6.2	3.3	6.2	3.3	3	3	3	3	3.2	0.3	3.2	0.3
Intersection #8	6.2	5.5	6.2	5.5	3	3	3	3	3.2	2.5	3.2	2.5
Intersection #9	6.2	5.5	6.2	5.5	3	3	3	3	3.2	2.5	3.2	2.5
Intersection #10	5.5	5.5	5.5	5.5	3	3	3	3	2.5	2.5	2.5	2.5
Intersection #11	5.5	4.7*	5.5	5.5	3	3	3	3	2.5	1.7*	2.5	2.5
Intersection #12	5.5	5.5	5.5	5.5	3	3	3	3	2.5	2.5	2.5	2.5

*" If yellow change intervals for concurrently terminating phases differ, apply yellow change intervals greater than the minimum calculated value for the approach" [ITE, 2020]. Therefore, the **5.5 seconds** calculated for SB should be adopted for NB instead of using the calculated 4.7.

5.2 Experimental Design Details for Yellow Change Intervals

The proposed study design includes several periods. Figure 5.1 shows the proposed timeline for the study design. For each period, a new traffic signal change interval was implemented, and the data collected from the smart sensors was used for further exploratory data analysis. Among all study sites, some of the study sites were used as the control sites, and the rest were selected as the treatment sites. No modifications were made to the yellow change intervals at the control sites. The control sites were used to eliminate the effects of traffic volume and pattern variation during the holiday seasons in statistical analysis. The succeeding sections outline the specifics of the yellow change intervals implemented for through and left-turn movements.

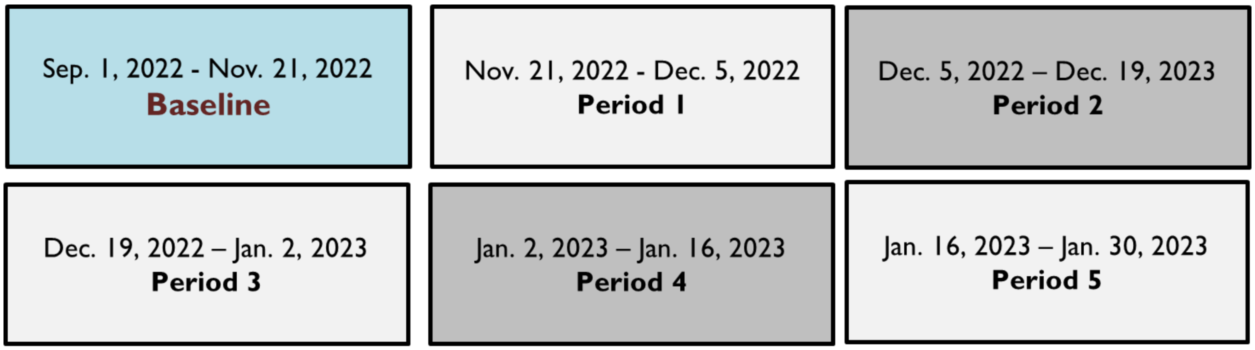


Figure 5.1 Periods of experimental study design

5.2.1 Through Movements

Comparing the COP policy's yellow change intervals and the ITE 2020 measured intervals, the increases range from 0.4 to 0.6 seconds for the through movements' yellow change intervals. To better understand driver behaviors and the influence of the yellow change interval over the short-term and long-term, the nine treatment sites were divided into three equal groups 1) incremental, 2) periodical, and 3) long-term sites. Moreover, Table 5.4 contains information on the yellow change intervals implemented for through movements and the corresponding increase compared to the previous period.

5.2.1.1 Incremental Sites:

For this group of intersections, the increase in the yellow change intervals was implemented in five periods, with each period being two weeks (refer to Figure 5.1). Therefore, at each of the three incremental sites, the yellow change intervals were increased by 0.1 to 0.2 seconds in each period, depending on how much the total calculated yellow change interval increased.

5.2.1.2 Periodical Sites:

In this set of study sites, the yellow change intervals were modified every period, with the new interval being used for two weeks and then alternating back to the COP policy's interval for the next two weeks. Periodical sites were selected to observe the compliance behavior of drivers over a short time frame. The ITE 2020 yellow change intervals were implemented at three selected periodical sites for the entire duration of the first, third, and fifth periods (two weeks each), while during the second and fourth periods, the yellow change intervals were reverted to their baseline condition at the selected periodical sites.

5.2.1.3 Long-term Sites:

Three study sites were selected to analyze the long-term effects of increasing yellow change intervals on drivers' compliance behavior. Once the new intervals were implemented at the beginning of the first period, these long-term sites did not undergo any further adjustments.

Table 5.4 Implemented Experimental Design for the Through Movements

Intersections	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)

5.2.2 Turning Movements

Only ten intersections were used for studying left-turn movements since two study sites do not have any protected left-turn phase. Two of the ten study sites were used as the control sites, and the remaining eight were used as treatment sites. A significant change in left-turn yellow intervals might raise safety concerns. Therefore, no study sites were designated for the periodic study. In this case, the eight treatment sites were divided into two groups of four: 1) incremental and 2) long-term sites. In addition, Table 5.5 contains information on the yellow change intervals implemented for left-turn movements and the corresponding increase compared to the previous period.

5.2.2.1 Incremental Sites:

The increase in the yellow change intervals was implemented at the selected incremental sites in five periods, with each period being two weeks (refer to Figure 5.1). Therefore, the yellow change intervals were increased by 0.3 to 0.7 seconds at the four incremental sites in each period, depending on how much the total calculated yellow change interval increased.

5.2.2.2 Long-term Sites:

The remaining four treatment sites were selected to study the impact of increasing yellow change interval on drivers' compliance behavior for left-turn movements in the long term. The long-term sites' signal timings were no longer modified after being increased to the new yellow change intervals in the first period.

Table 5.5 Implemented Experimental Design for the Left-Turn Movements

Locations	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	Incremental Site	3	-	3.3 (+0.3)	-	3.7 (+0.4)	-	4 (+0.3)	-	4.4 (+0.4)	-	4.7 (+0.3)	-
Intersection #2	Incremental Site	3	3	3.3 (+0.3)	3.3 (+0.3)	3.7 (+0.4)	3.7 (+0.4)	4 (+0.3)	4 (+0.3)	4.4 (+0.4)	4.4 (+0.4)	4.7 (+0.3)	4.7 (+0.3)
Intersection #4	Incremental Site	3	3	3.3 (+0.3)	3.3 (+0.3)	3.7 (+0.4)	3.7 (+0.4)	4 (+0.3)	4 (+0.3)	4.4 (+0.4)	4.4 (+0.4)	4.7 (+0.3)	4.7 (+0.3)
Intersection #6	Long-term Site	3	3	6.2 (+3.2)	5.5 (+2.5)	6.2 (0)	5.5 (0)	6.2 (0)	5.5 (0)	6.2 (0)	5.5 (0)	6.2 (0)	5.5 (0)
Intersection #7	Long-term Site	3	3	6.2 (+3.2)	3.3 (+0.3)	6.2 (0)	3.3 (0)	6.2 (0)	3.3 (0)	6.2 (0)	3.3 (0)	6.2 (0)	3.3 (0)
Intersection #8	Control Site	3	3	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)
Intersection #9	Incremental Site	3	3	3.6 (+0.6)	3.5 (+0.5)	4.3 (+0.7)	4 (+0.5)	4.9 (+0.6)	4.5 (+0.5)	5.6 (+0.7)	5 (+0.5)	6.2 (+0.6)	5.5 (+0.5)
Intersection #10	Long-term Site	3	3	5.5 (+2.5)	5.5 (+2.5)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)
Intersection #11	Long-term Site	3	3	5.5 (+2.5)	5.5 (+2.5)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)	5.5 (0)
Intersection #12	Control Site	3	3	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)	3 (0)

Chapter 6

Results
(Phase 1)

6. RESULTS (Phase 1)

The results section of this report consists of several parts. Initially, this project aimed to examine driver behavior for both through and left-turn movements. The through movements analysis results are presented first, followed by an overview of the left-turn movements findings. In order to evaluate the comparative differences between the before-and-after study groups, a statistical T-test was employed. The T-test is a common method used to assess the significance of differences observed between two datasets. The statistical T-test has been widely used in previous before-and-after studies (Gong et al., 2023; Jin et al., 2008; Slavin et al., 2013). In this study, a 95% confidence level is employed to determine the statistical significance of the difference in RLR rates between the before-and-after groups. If the p-value obtained from the T-test comparing the RLR frequency before and after changing the yellow change intervals is greater than the chosen significance level of 0.05, it indicates that the difference between the means of RLR frequency before and after changing the yellow change interval is not statistically significant. Detailed findings of the study pertaining to through and left-turn movements are presented in the subsequent sections.

6.1 Through Movements

Please refer to Chapter 5, where a detailed explanation of how the twelve study sites were classified into four distinct groups: Control Sites, Incremental Sites, Periodical Sites, and Long-term Sites. The subsequent sections elaborate on the analysis of each of these groups.

6.1.1 Control Sites:

Table 6.1 displays the average daily RLR frequency for the three control sites. As discussed in Chapter 5, the signal timing at control sites remained unchanged. The data suggests no significant change in RLR frequency between the baseline and the latest periods. However, it should be noted that there is a strong correlation between traffic volume and RLR frequency, meaning that higher traffic volumes result in higher RLR frequencies. Therefore, during Period 3, which includes the holiday season, the RLR frequency was at its lowest among all study periods due to reduced traffic volume. To address this issue, the RLR frequency was normalized by calculating the RLR rate, which is the RLR per 1000 vehicles.

Table 6.1 Average of RLR Frequency per Day for Through Movements at Control Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #3	161	137	167	125	137	164	167
Intersection #8	281	283	327	247	274	322	370
Intersection #12	338	-	282	230	301	232	271

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

The results of the statistical T-test conducted on the RLR rate at the control sites are presented in Table 6.2. By comparing Period 5 with the baseline, it can be observed that the average RLR rate slightly increased at two of the control sites, namely Intersection #3 and Intersection #8. However, this difference was not found to be statistically significant. On the other hand, the average RLR rate at Intersection #12 showed a significant decrease during Period 5 compared to the baseline. By comparing Period 6 with the baseline, an increase in the average RLR rate was observed at Intersection #3 and Intersection #8, with the difference being statistically significant at the latter location. Similar to Period 5, Intersection #12 experienced a significant drop in the average RLR rate compared to the baseline during Period 6.

Table 6.2 Statistical T-Test Results of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements at the Control Sites

Intersections	Baseline vs. Period 1 (Rate)	Baseline vs. Period 2 (Rate)	Baseline vs. Period 3 (Rate)	Baseline vs. Period 4 (Rate)	Baseline vs. Period 5 (Rate)	Baseline vs. Period 6 (Rate)
Intersection #3	6.63 vs. 5.97 (0.05)*	6.63 vs. 8.27** (0.02)	6.63 vs. 5.73 (0.02)	6.63 vs. 5.97 (0.07)	6.63 vs. 6.72 (0.8)	6.63 vs. 6.68 (0.9)
Intersection #8	6.46 vs. 6.99 (0.4)	6.46 vs. 9.11 (0.1)	6.46 vs. 6.24 (0.7)	6.46 vs. 6.64 (0.7)	6.46 vs. 7.54 (0.2)	6.46 vs. 8.37 (0.00)
Intersection #12	-	7.80 vs. 9.44 (0.5)	7.80 vs. 5.97 (0.00)	7.80 vs. 6.59 (0.08)	7.80 vs. 5.08 (0.00)	7.80 vs. 6.21 (0.00)

* P-value of T-test
** Cells with green color means that the difference is statistically significant at a 95% confidence level

6.1.2 Incremental Sites:

Table 6.3 contains the average daily RLR frequency for the three incremental sites. As explained in Chapter 5, the yellow change intervals at the incremental sites gradually increase until they reach the updated yellow change interval in Period 5. The data indicates a decrease in RLR frequency in the later periods compared to the baseline. Additionally, to provide a fair comparison, the RLR frequency was normalized by dividing the number of violations by the number of vehicles, giving the RLR rate per 1000 vehicles per day.

Table 6.3 Average of RLR Frequency Per Day For Through Movements at Incremental Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #2	188	193	195	123	127	128	143
Intersection #4	226	192	176	157	163	157	157
Intersection #9	156	104	97	84	70	93	-

* 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.

Table 6.4 displays the statistical T-test results for the RLR rate at the incremental sites. When comparing Periods 3, 4, 5, and 6 with the baseline, it is evident that the average RLR rate decreased significantly at all treated intersections. However, the results were inconclusive during the initial implementation period, when the yellow change intervals were increased by 0.1 seconds. 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 treated 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 to the baseline. On the other hand, the average RLR rate in Period 2 was not statistically different from the baseline at Intersection #4.

Table 6.4 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements at Incremental Sites

Intersections	Baseline vs. Period1	Baseline vs. Period 2	Baseline vs. Period 3	Baseline vs. Period 4	Baseline vs. Period 5	Baseline vs. Period 6
Intersection #2	5.49 vs. 5.88 (0.5) *	5.49 vs. 6.67** (0.03)	5.49 vs. 3.64 (0.03)	5.49 vs. 4.05 (0.00)	5.49 vs. 3.66 (0.00)	5.49 vs. 3.99 (0.00)
Intersection #4	9.09 vs. 8.49 (0.3)	9.09 vs. 8.19 (0.5)	9.09 vs. 7.78 (0.02)	9.09 vs. 5.67 (0.00)	9.09 vs. 5.95 (0.00)	9.09 vs. 5.66 (0.00)
Intersection #9	4.99 vs. 3.43 (0.00)	4.99 vs. 3.47 (0.01)	4.99 vs. 2.84 (0.00)	4.99 vs. 1.83 (0.00)	4.99 vs. 2.45 (0.00)	-

* P-value of T-test
** Cells with green color means that the difference is statistically significant at a 95% confidence level

6.1.3 Periodical Sites:

The data in Table 6.5 presents the average frequency of RLR per day for three periodical sites. The yellow change intervals at periodical sites were altered every period, as explained in Chapter 5. The new intervals were used for one period and then switched back to the COP policy's intervals for the next period. The data suggests a reduction in RLR frequency during periods with ITE 2020 yellow change intervals compared to those with COP policy's yellow change intervals. Additionally, to ensure a fair comparison and enable statistical inferences, the RLR frequency was normalized by dividing the number of violations by the number of vehicles and multiplying by 1000, which gives the RLR rate per 1000 vehicles per day.

Table 6.5 Average Of RLR Frequency Per Day for Through Movements at Periodical Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #1	-	-	-	-	-	-	-
Intersection #5	353	202	339	199	339	212	327
Intersection #6	223	91	192	78	140	-	167

* 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.

The statistical T-test results for the RLR rate at the periodical sites are presented in Table 6.6. These results indicate a significant decrease in the average RLR rate during periods where the new yellow change intervals were implemented (Periods 1, 3, and 5) compared to the periods with the COP policy's intervals (baseline, Periods 2, 4, and 6).

Table 6.6 Statistical T-Test Results of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements at Periodical Sites

Intersections	Baseline vs. Period1	Baseline vs. Period 2	Baseline vs. Period 3	Baseline vs. Period 4	Baseline vs. Period 5	Baseline vs. Period 6
Intersection #1	-	-	-	-	-	
Intersection #5	9.94 vs. 5.97** (0.00)*	9.94 vs. 11.09 (0.4)	9.94 vs. 6.10 (0.00)	9.94 vs. 10.1 (0.6)	9.94 vs. 6.07 (0.00)	9.94 vs. 9.25 (0.2)
Intersection #6	8.89 vs. 3.95 (0.00)	8.89 vs. 9.37 (0.8)	8.89 vs. 3.57 (0.00)	8.89 vs. 5.67 (0.00)	-	-

* P-value of T-test
** Cells with green color means that the difference is statistically significant at a 95% confidence level

6.1.4 Long-term Sites:

Table 6.7 displays the average daily frequency of RLR for three long-term sites. The implementation of new yellow change intervals in the first period, which remained unchanged throughout, is discussed in Chapter 5. The data indicates that RLR frequency decreased after the implementation of the new intervals in Period 1. Furthermore, RLR frequency did not return to baseline conditions when comparing the latest periods to the baseline. Previous research has shown that drivers adapt to the new timings over time, but this does not negate the benefits. Extending the study to more periods and conducting statistical tests to compare the baseline with later periods is crucial to investigate this further.

Table 6.7 Average of RLR Frequency Per Day for Through Movements at Long-Term Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #7	110	52	51	50	49	59	65
Intersection #10	216	82	106	73	113	102	-
Intersection #11	244	114	144	110	143	124	-

* 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.

The preceding sections highlighted the importance of considering traffic volume to avoid bias in the analysis and ensure a fair comparison. The RLR rate (RLR per 1000 vehicles per day) was calculated, and a statistical T-test was conducted. Table 6.8 presents the T-test results on the RLR rate at the long-term sites. The findings indicate a significant decrease in the average RLR rate during Period 1, when the new yellow change intervals were implemented, compared to the baseline. Additionally, 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.

Table 6.8 Statistical T-Test Results of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements At Long-Term Sites

Intersections	Baseline vs. Period1	Baseline vs. Period 2	Baseline vs. Period 3	Baseline vs. Period 4	Baseline vs. Period 5	Baseline vs. Period 6
Intersection #7	**5.42 vs. 2.64** (0.00)***	**5.42 vs. 2.91 (0.00)**	**5.42 vs. 2.60 (0.00)**	**5.42 vs. 2.51 (0.00)**	**5.42 vs. 2.84 (0.00)**	**5.42 vs. 2.92 (0.00)**
Intersection #10	**5.17 vs. 2.27 (0.00)**	**5.17 vs. 3.27 (0.02)**	**5.17 vs. 2.11 (0.00)**	**5.17 vs. 2.75 (0.00)**	**5.17 vs. 2.3 (0.00)**	-
Intersection #11	**6.80 vs. 3.55 (0.00)**	**6.80 vs. 5.13 (0.1)**	**6.80 vs. 3.60 (0.00)**	**6.80 vs. 4.08 (0.00)**	**6.80 vs. 3.33 (0.00)**	-

* P-value of T-test
** Cells with green color means that the difference is statistically significant at a 95% confidence level

6.2 Turning Movements

This section will cover the outcomes of applying the ITE 2020 guidelines to left-turn movements. Subsequent sections will present the statistical analysis of left-turn movements for both control sites and treatment sites.

6.2.1 Control Sites:

Table 6.9 presents the average daily frequency of RLR for the two control sites in the left-turn movements study, with no signal timing changes, as explained in Chapter 5. The data indicates no significant difference in the RLR frequency between the baseline and the latest periods. To eliminate bias in the analysis and ensure fairness in comparison, the RLR rate was calculated, and a statistical T-test was performed to determine if the difference in the average RLR rate is statistically significant at a 95% confidence level. The T-test results are presented in Table 6.10.

Table 6.9 Average of RLR Frequency Per Day for Left-Turn Movements at Control Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #8	235	201	227	171	201	197	232
Intersection #12	160	-	165	131	152	163	160

* 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.

Upon comparison of study periods with the baseline, it is evident that there was no significant change in the average RLR rate at a 95% confidence level. The data indicates that, for Intersection #8, there was a slight increase in the average RLR rate during periods 2, 5, and 6 compared to the baseline. In contrast, at Intersection #12, the average RLR rate decreased during periods 1, 3, 4, 5, and 6 compared to baseline. However, the statistical T-test shows that, except for period 3, none of the aforementioned differences are statistically significant at a 95% confidence level.

Table 6.10 Statistical T-Test Results of RLR Rate (RLR Per 1000 Vehicles Per Day) for Left-Turn Movements at Control Sites

Intersections	Baseline vs. Period1	Baseline vs. Period 2	Baseline vs. Period 3	Baseline vs. Period 4	Baseline vs. Period 5	Baseline vs. Period 6
Intersection #8	23.24 vs. 21.37 (0.4)*	23.24 vs. 27.06 (0.4)	23.24 vs. 18.5 (0.05)	23.24 vs. 20.88 (0.3)	23.24 vs. 20.15 (0.2)	23.24 vs. 22.98 (0.9)
Intersection #12	-	14.77 vs. 21.56 (0.2)	14.77 vs. 13.01 (0.04)	14.77 vs. 13.75 (0.2)	14.77 vs. 15.09 (0.7)	14.77 vs. 14.80 (1)

* P-value of T-test

6.2.2 Incremental Sites:

The average RLR frequency per day for the four incremental sites is provided in Table 6.11. As described in Chapter 5, the yellow change intervals at the incremental sites gradually increased until they reached the updated yellow change intervals in Period 5. The data indicates that except for Period 6 at Intersection #4, where the average RLR frequency was higher than the baseline, there was a decrease in RLR frequency in the later periods compared to the baseline. However, after normalizing the average RLR rate, it was found that the average RLR rate was lower in Period 6 compared to the baseline at Intersection #4. To ensure impartiality in the analysis and maintain fairness in comparison, the RLR rate was calculated, and a statistical T-test was performed to determine the statistical significance of the difference in the average RLR rate at a 95% confidence level. Table 6.12 shows the T-test results.

Table 6.11 Average of RLR Frequency Per Day for Left-Turn Movements at Incremental Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #1	-	-	-	-	-	-	-
Intersection #2	24	12	12	10	10	8	11
Intersection #4	37	31	29	12	27	24	42
Intersection #9	157	138	130	61	128	50	-

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

Table 6.12 presents the statistical T-test outcomes for the RLR rate at the incremental sites. It is evident from the comparison of Periods 3, 4, 5, and 6 with the baseline that the average RLR rate decreased at all treated intersections. 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 to the baseline, but the difference was not statistically significant at a 95% confidence level. Similar results were found for Period 4 at Intersection #9 and Intersection #4 for Period 6. Overall, the study found that the incremental increase in yellow change intervals for left-turn movements significantly reduced red-light violations.

Table 6.12 Statistical T-Test Results of RLR Rate (RLR Per 1000 Vehicles Per Day) for Left-Turn Movements at Incremental Sites

Intersections	Baseline vs. Period 1	Baseline vs. Period 2	Baseline vs. Period 3	Baseline vs. Period 4	Baseline vs. Period 5	Baseline vs. Period 6
Intersection #1	-	-	-	-	-	-
Intersection #2	5.13 vs. 2.36** (0.03)*	5.13 vs. 3.10 (0.01)	5.13 vs. 2.26 (0.1)	5.13 vs. 2.15 (0.00)	5.13 vs. 1.58 (0.00)	5.13 vs. 2.39 (0.00)
Intersection #4	4.93 vs. 3.71 (0.07)	4.93 vs. 4.17 (0.4)	4.93 vs. 1.92 (0.00)	4.93 vs. 3.33 (0.01)	4.93 vs. 2.65 (0.00)	4.93 vs. 4.41 (0.4)
Intersection #9	16.13 vs. 14.92 (0.6)	16.13 vs. 17.16 (0.8)	16.13 vs. 6.97 (0.00)	16.13 vs. 12.75 (0.3)	16.13 vs. 5.07 (0.00)	-

* P-value of T-test
** Cells with green color means that the difference is statistically significant at a 95% confidence level

NCHRP Report 731, released in 2012, provides recommendations for determining yellow change and red clearance intervals at signalized intersections (NCHRP, 2012). The study recommends using "Speed Limit + 7" as the 85th percentile approach speed for through movements, aligning with the recommendations provided in the ITE 2020 guidelines. However, the NCHRP report 731 recommends using "Speed Limit - 5" as the 85th percentile approach speed for left-turn movements, resulting in a shorter yellow interval than the ITE 2020 guidelines. The yellow change intervals implemented at the incremental sites during Period 3 closely matched the recommended intervals from NCHRP report 731. The findings suggest that adopting the NCHRP yellow change intervals can be effective, making it unnecessary to fully implement the ITE 2020 guidelines for calculating yellow change intervals. However, additional research is necessary to establish a definitive and robust conclusion.

6.2.3 Long-term Sites:

Table 6.13 displays the average daily frequency of RLR for left-turn movements at four long-term sites. In Period 1, the yellow change interval was increased to the new updated amount and remained constant for the subsequent periods. The data indicates that the RLR frequency decreased after the new intervals were implemented in Period 1. Furthermore, the RLR frequency did not return to baseline conditions when comparing the latest periods to the baseline. Previous studies have suggested that drivers may adapt to the new timings over time, but this does not negate the benefits of the intervention. To explore this further, extending the study to additional periods and performing statistical tests to compare the baseline with later periods is important.

Table 6.13 Average of RLR Frequency Per Day for Left-Turn Movements at Long-Term Sites

Intersections	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Intersection #6	23	5	8	5	4	-	9
Intersection #7	11	7	9	6	6	7	7
Intersection #10	25	4	5	4	7	8	-
Intersection #11	148	82	95	78	99	88	-

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

In order to ensure a fair comparison and avoid bias in the analysis, it is important to consider traffic volume. To achieve this, the study calculated the RLR rate (RLR per 1000 vehicles per day) and conducted a statistical T-test. Table 6.14 shows the results of the T-test for the RLR rate of left-turn movements at the long-term sites. The results indicate a significant decrease in the average RLR rate during Period 1 when the new yellow change intervals were implemented compared to 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.

Table 6.14 Statistical T-Test Results of RLR Rate (RLR Per 1000 Vehicles Per Day) for Left-Turn Movements at Long-Term Sites

Intersections	Baseline vs. Period1	Baseline vs. Period 2	Baseline vs. Period 3	Baseline vs. Period 4	Baseline vs. Period 5	Baseline vs. Period 6
Intersection #6	**4.00 vs. 0.84** (0.00)***	**4.00 vs. 2.10 (0.03)**	**4.00 vs. 0.97 (0.00)**	**4.00 vs. 0.87 (0.00)**	**-**	**4.00 vs. 1.41 (0.01)**
Intersection #7	**3.87 vs. 2.73 (0.04)**	**3.87 vs. 3.47 (0.5)**	**3.87 vs. 2.30 (0.00)**	**3.87 vs. 2.15 (0.00)**	**3.87 vs. 2.48 (0.00)**	**3.87 vs. 2.21 (0.00)**
Intersection #10	**4.10 vs. 0.76 (0.00)**	**4.10 vs. 1.09 (0.00)**	**4.10 vs. 0.72 (0.00)**	**4.10 vs. 1.18 (0.00)**	**4.10 vs. 1.23 (0.00)**	**-**
Intersection #11	**17. 59 vs. 9.14 (0.00)**	**17.59 vs. 12.10 (0.00)**	**17.50 vs. 9.06 (0.00)**	**17.59 vs. 10.69 (0.00)**	**17.59 vs. 8.27 (0.00)**	**-**

* P-value of T-test
** Cells with green color means that the difference is statistically significant at a 95% confidence level

Chapter 7

Conclusion & Recommendations (Phase 1)

7. CONCLUSION & RECOMMENDATIONS (Phase 1)

7.1 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. In the Phoenix metropolitan area, there were 113 RLR-related fatalities and 9,320 injuries from 2014 to 2020. To address this issue and ensure the safety of all road users, it is essential to investigate RLR behavior at local intersections, evaluate the impact of different signal timing parameters (such as yellow change and red clearance intervals) on the frequency of RLR violations, and develop effective countermeasures. To this end, this project aims to evaluate whether implementing the updated ITE guidelines for calculating traffic signal timing (released in March 2020) can improve safety at signalized intersections. Various factors were considered to select the study sites, including the number and severity of RLR-related crashes and infrastructure feasibility. Smart sensors were installed at each intersection, and a before-and-after analysis was conducted to examine the relationship between signal timing parameters and red-light violations.

Phase 1 of this study evaluated the impact of increasing yellow change intervals on drivers' compliance behavior. According to the statistical analysis (using a 95% confidence level), the results for both through movements and left-turn movements are summarized below.

1. For the control sites, there was no significant reduction in the average rate of RLR (measured as RLR per 1000 vehicles per day) for through movements when comparing the latest periods with the baseline period. The same results were observed for the left-turn movements.
2. For the incremental sites (yellow change intervals were gradually increased), the average rate of RLR (measured as RLR per 1000 vehicles per day) for through movements showed a significant reduction when comparing the latest periods with the baseline period. However, during the initial stages of implementation, where yellow change intervals were only increased by 0.1~0.2 seconds, the evaluation results were inconclusive. Similarly, the average rate of RLR for the left-turn movements showed a significant reduction when comparing the latest periods with the baseline period. However, the results during the initial

stages of implementation, where yellow change intervals were only increased by 0.3~1.1 seconds, were inconclusive.

3. For the periodical sites (yellow change interval was modified every period), the average rate of RLR (measured as RLR per 1000 vehicles per day) for through movements significantly decreased during periods with the ITE 2020 yellow change intervals compared to periods with old yellow change intervals.
4. For the long-term sites, the average rate of RLR (measured as RLR per 1000 vehicles per day) for both through and left-turn movements significantly reduced compared to the baseline.

7.2 Recommendations

Based on the findings and results of Phase 1 in this study, the project team has proposed several recommendations to the City of Phoenix to improve safety at signalized intersections by better understanding road users' compliance behavior with the traffic signal. These recommendations include:

1. Based on the data collected at the incremental sites, the findings indicate that fully implementing ITE 2020 guidelines for the calculations of yellow change intervals may not be necessary. This conclusion is supported by the significant decrease in RLR frequencies observed after Period 3 at the incremental sites.
2. For calculating through-movement yellow change intervals, "Speed Limit +7" as the 85th percentile approach speed is recommended when field-measured speed data is unavailable. For left-turn movements, it is recommended to use "Speed Limit - 5" as an estimation for the 85th percentile left-turn approach speed according to the NCHRP report 731, leading to shorter yellow change intervals.
3. In order to obtain a more comprehensive understanding of the effects of implementing the ITE 2020 guidelines on RLR violations, it is recommended to explore the utilization of other advanced technologies as an alternative approach. By employing such technologies,

it would be possible to compare and analyze the outcomes obtained from various systems and locations, facilitating a more profound comprehension of the matter.

4. The current study focused solely on analyzing the effect of yellow change intervals on driver compliance behavior. Further research is currently being conducted to investigate the impact of red clearance intervals, both individually and in conjunction with yellow change intervals, to gain a more comprehensive understanding of their combined effects on intersection safety.

PHASE 2

Red Clearance Intervals Study

Chapter 8

Experimental Design (Phase 2)

8. EXPERIMENTAL DESIGN (Phase 2)

8.1 Red Clearance Intervals Calculation Based on ITE 2020

The current ITE-recommended equation for calculating the red clearance intervals is shown below:

$$R = \left[\frac{W + L}{1.47V_E}\right] - t_s \qquad \text{(Equation 4)}$$

Where:

R = red clearance interval (seconds).

V_E= intersection entry speed (mph); the speed at which a "reasonable" driver is assumed to cross the stop line of the intersection.

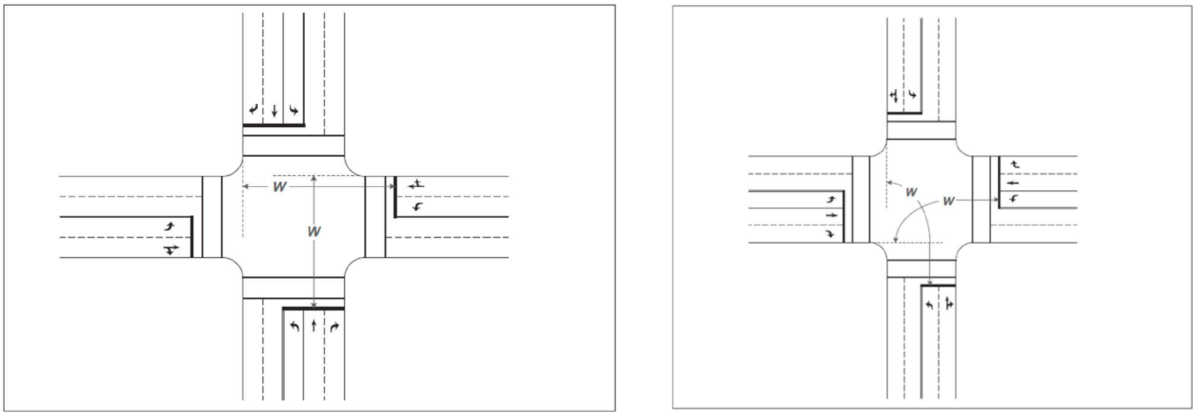
L = length of vehicle (ft.); 20 ft is often used as the representative length for vehicles entering the intersection.

W = distance to traverse the intersection (width); stop line to far side no-conflict point along the vehicle path (ft.).

t_s = conflicting vehicular movement start-up delay (seconds); an optional parameter with an initial value set at 0.0 seconds. Values may be used based on engineering judgment or a study's support.

In this study, the start-up delay for conflicting vehicular movements (t_s) was set at 0.0 seconds. Figures 8.1 (a) and (b) illustrate intersection widths for through and left-turn movements, respectively. The aerial images from Google Maps were used to measure the intersection width for through movements and left-turn movements.

The following sections provide the details of red clearance interval calculation at twelve selected study sites for through and left-turn movements.



(a) (b)

Figure 8.1 Diagram of intersection width measurement for a) through movements, and b) left-turn movements

8.1.1 Through Movements

Due to the absence of field-measured speed data at the selected study sites, in this study, the "speed limit+7" was used in lieu of through movement's intersection entry speed. The start-up delay (t_s) was assumed to be 0.0 seconds. The 20 ft was used as the representative length for vehicles entering the intersection (L). Thus, for this study, the red clearance interval for through movement was measured using Equation 8:

$$R = \left[\frac{W + 20}{1.47(SL + 7)}\right] \quad \text{(Equation 8)}$$

Where:

R = red clearance interval (seconds).

SL = posted speed limit (in mph).

W = distance to traverse the intersection (width), stop line to far side no-conflict point along the vehicle path (ft.) for through movements.

Table 8.1 contains the width of each intersection for through movements and the speed limit of each approach at twelve selected study sites.

Table 8.1 Study Sites Posted Speed Limit and Intersection Width for Through Movements

Intersection	Speed Limit (MPH)				Intersection Width (ft)			
	EB	NB	WB	SB	EB	NB	WB	SB
Intersection #1	35	35	35	35	93	103	100	100
Intersection #2	35	35	35	35	66	77	66	80
Intersection #3	30	40	30	40	78	62	78	62
Intersection #4	35	35	35	35	134	109	138	108
Intersection #5	30	40	30	40	84	67	85	70
Intersection #6	45	40	45	40	93	95	93	92
Intersection #7	45	25	45	25	80	100	90	97
Intersection #8	45	40	45	40	108	91	110	102
Intersection #9	45	40	45	40	115	115	117	117
Intersection #10	40	40	40	40	86	89	80	86
Intersection #11	40	35	40	40	150	103	150	100
Intersection #12	40	40	40	40	107	120	105	113

The red clearance intervals are calculated for through movements at each study site using the speed limit and the intersection width, and the calculations are shown in Table 8.2. Table 8.2 includes the COP policy's red clearance intervals and the difference between the newly measured and COP policy's intervals. Comparing the COP policy's intervals and the newly measured intervals, the differences range from -0.2 to 0.2 seconds for the red clearance intervals.

Table 8.2 Calculated Red Clearance Intervals for Through Movements

Intersections	Red Clearance Interval (ITE 2020)		Red Clearance Interval (COP Policy)		Delta Δ (ITE – COP)	
	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB
#1	2	2	2	2.2	0	-0.2
#2	1.4	1.7	1.4	1.6	0	0.1
#3	1.9	1.2	1.9	1.1	0	0.1
#4	2.6	2.1	2.6	2.2	0	-0.1
#5	2	1.4	2	1.3	0	0.1

#6	**1.5**	**1.7**	**1.6**	**1.5**	**-0.1**	**0.2**
#7	**1.5**	**2.6**	**1.4**	**2.7**	**0.1**	**-0.1**
#8	**1.8**	**1.8**	**1.7**	**1.7**	**0.1**	**0.1**
#9	**1.8**	**2**	**1.8**	**2**	**0**	**0**
#10	**1.6**	**1.6**	**1.5**	**1.5**	**0.1**	**0.1**
#11	**2.5**	**2**	**2.6**	**2**	**-0.1**	**0**
#12	**1.9**	**2.1**	**1.9**	**2.1**	**0**	**0**

8.1.2 Turning Movements

According to the ITE 2020 guidelines, the intersection entry speed would be equal to the general value of 20 mph for left turns in the lack of field-measured speed data. Thus, for this study, the red clearance interval for left-turn movements was measured using Equation 9:

$$R = \left[\frac{W + 20}{1.47 \times 20}\right] \qquad \text{(Equation 9)}$$

Where:

R = red clearance interval (seconds).

W = distance to traverse the intersection (width); stop line to far side no-conflict point along the vehicle path (ft.) for left-turn movements.

Table 8.3 contains the width of each intersection for left-turn movements.

Table 8.3 Study Sites Intersection Width for Left-Turn Movements

Intersection	Intersection Width (ft)			
	EB	NB	WB	SB
Intersection #1	**85**	**-**	**93**	**-**
Intersection #2	**62**	**72**	**69**	**60**
Intersection #4	**116**	**123**	**125**	**115**
Intersection #6	**80**	**89**	**87**	**82**
Intersection #7	**84**	**82**	**90**	**65**
Intersection #8	**86**	**90**	**90**	**91**
Intersection #9	**103**	**108**	**97**	**105**

Intersection #10	71	72	71	76
Intersection #11	122	127	137	125
Intersection #12	103	101	102	96

The red clearance intervals for left-turn movements are calculated at each study site and are shown in Table 8.4. Table 8.4 includes the COP policy's red clearance intervals and the difference between the newly measured and COP policy's intervals. Comparing the COP policy's and newly measured intervals, the differences range from 1.5 to 4.4 seconds.

Table 8.4 Calculated Red Clearance Intervals for Left-Turn Movements

Intersections	Red Clearance Interval (ITE 2020)		Red Clearance Interval (COP Policy)		Delta Δ (ITE – COP)	
	EB/WB	NB/SB	EB/WB	NB/SB	EB/WB	NB/SB
#1	3.9	-	1	-	2.9	-
#2	3.1	3.2	1	1	2.1	2.2
#4	5	4.9	1	3.3	4	1.6
#6	3.7	3.8	1	1	2.7	2.8
#7	3.8	3.5	1	1	2.8	2.5
#8	3.8	3.8	1	1	2.8	2.8
#9	4.2	4.4	1	1	3.2	3.4
#10	3.1	3.3	1	1	2.1	2.3
#11	5.4	5	1	3.5	4.4	1.5
#12	4.2	4.2	1	1	3.2	3.2

8.2 Experimental Design Details for Red Clearance Intervals

The proposed study design included several periods. For each period, a new traffic signal change interval was implemented, and the data collected from the smart sensors was used for further exploratory data analysis. Figure 8.2 shows the proposed timeline for the study design. Among all study sites, some of the intersections were used as the control sites, and the rest were selected as the treatment sites. No modifications were made to the yellow change and red clearance intervals at the control sites. The control sites were used to eliminate the effects of traffic volume and pattern variation during the holiday seasons in our statistical analysis. The succeeding sections outline the specifics of the yellow change and red clearance intervals that were put into practice for through and turning movements.

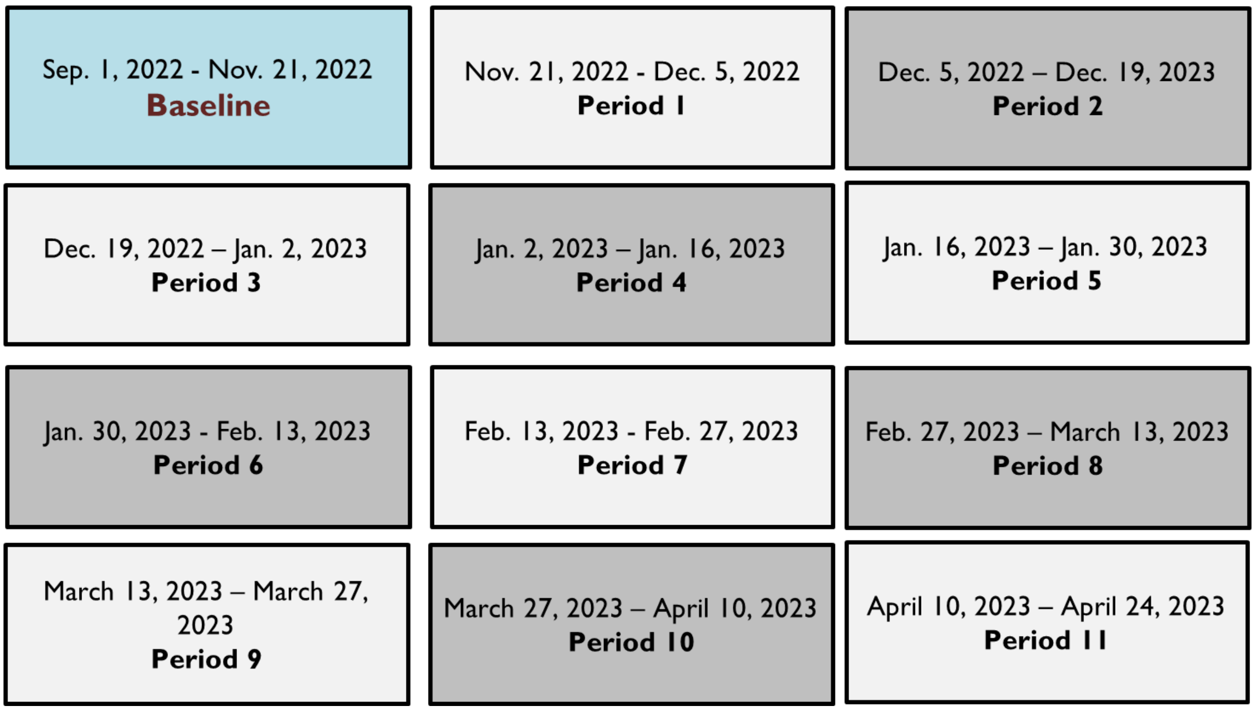


Figure 8.2 Periods of experimental study design

8.2.1 Through Movements

After comparing the red clearance intervals specified by COP policy with the newly measured intervals based on ITE 2020 guidelines, it was found that the differences range from -0.2 to 0.2 seconds. In order to gain a deeper understanding of driver behaviors and the effects of updating red clearance intervals, both individually and in conjunction with updated yellow change intervals, a comprehensive experiment was conducted. The current study on red clearance intervals was done in conjunction with the Phase 1 study on yellow change intervals. The Phase 1 study carefully considered various types of study sites, including incremental, periodical, and long-term sites, to thoroughly understand the individual and combined impacts of yellow change intervals.

Since the disparity between COP policy and ITE 2020 red clearance intervals was minimal for through movements, the updated red clearance intervals were implemented at the start of Period

10, and data was collected during Periods 10 and 11. In order to investigate the effects of updated red clearance intervals, the study sites were categorized into four groups based on the signal timing implemented in Periods 10 and 11:

1. In order to study the compound effect of updated yellow change and red clearance intervals, the following study sites were selected to implement the ITE 2020 yellow change and red clearance intervals.
   - Intersections #2, #4, and #10
2. In order to study the individual long-term effect of yellow change intervals, the following study sites' yellow change intervals were kept at the updated ITE 2020 guidelines from Phase 1, and the red clearance intervals remained unchanged.
   - Intersections #7, #9, and #11
3. In order to study the individual effect of updated red clearance intervals, the following study sites' yellow change intervals returned to COP policy, and the red clearance intervals updated to ITE 2020 guidelines.
   - Intersections #1, #5, and #6
4. Control sites continued with COP policy's yellow change and red clearance intervals.
   - Intersections #3, #8, and #12

Table 8.5 provides detailed information about the specific yellow change and red clearance intervals implemented at the selected study sites. The yellow change intervals at the periodical sites were reduced to meet COP policy at the beginning of Period 8, and the red clearance intervals were updated to ITE 2020 guidelines in Period 10 to understand the individual effects of updated red clearance intervals. Two incremental sites (Intersections #1 and #4) and one long-term site (Intersection #10) were selected to assess the combined effects of updated yellow change and red clearance intervals. At these study sites, the red clearance intervals were updated to align with ITE 2020 guidelines, while the yellow change intervals had already been updated at the start of Period 10. Additionally, one incremental site (Intersection #9) and two long-term sites (Intersections #7 and #11) were selected to investigate the long-term impact of increasing yellow change intervals on drivers' compliance behavior. Importantly, the red clearance intervals at these sites were kept unchanged throughout the study.

Table 8.5 Implemented Experimental Design for the Through Movements

Intersections	Type of Intersections in Yellow Change Interval Study	Type of Intersections in Red Clearance Interval Study	Periods 10 and 11 Signal Timing Parameters
#1	Periodically Site	Changing in One Step	Yellow is Baseline Red Clearance is ITE 2020
#2	Incrementally Site	Changing in One Step (compound effect)	Yellow is ITE 2020 Red Clearance ITE 2020
#3	Control Site	Remain Unchanged	Yellow is Baseline Red Clearance is Baseline
#4	Incrementally Site	Changing in One Step (compound effect)	Yellow is ITE 2020 Red Clearance ITE 2020
#5	Periodically Site	Changing in One Step	Yellow is Baseline Red Clearance is ITE 2020
#6	Periodically Site	Changing in One Step	Yellow is Baseline Red Clearance is ITE 2020
#7	Long-term Site	Remain Unchanged	Yellow is ITE 2020 Red Clearance is Baseline
#8	Control Site	Remain Unchanged	Yellow is Baseline Red Clearance is Baseline
#9	Incrementally Site	Remain Unchanged	Yellow is ITE 2020 Red Clearance is Baseline
#10	Long-term Site	Changing in One Step (compound effect)	Yellow is ITE 2020 Red Clearance ITE 2020
#11	Long-term Site	Remain Unchanged	Yellow is ITE 2020 Red Clearance is Baseline
#12	Control Site	Remain Unchanged	Yellow is Baseline Red Clearance is Baseline

8.2.2 Turning Movements

A comprehensive experiment was conducted to thoroughly examine the impact of updated red clearance intervals for left-turn movements, both individually and in conjunction with updated yellow change intervals. Comparing the COP policy’s red clearance intervals and the newly measured intervals, the differences range from 1.5 to 4.4 seconds for the left-turn movements. In order to investigate the effects of updating red clearance intervals and yellow change intervals for left-turn movements, the study sites were divided into five groups based on the signal timing implemented during Periods 8, 9, 10, and 11:

1. In order to study the individual short-term effect of red clearance intervals, the following study sites' yellow change intervals returned to COP policy, and the red clearance intervals were increased incrementally in Periods 8 and 9, followed by an incremental decrease in Periods 10 and 11.
    - Intersections #4, and #9
2. In order to study the individual long-term effect of red clearance intervals, the following study sites' yellow change intervals returned to COP policy, and the red clearance intervals were updated to ITE 2020 guidelines in Period 8.
    - Intersections #1, and #2
3. In order to study the individual long-term effect of yellow change intervals, the following study sites' yellow change intervals were kept at the updated ITE 2020 guidelines from Phase 1, and the red clearance intervals remained unchanged.
    - Intersections #7, and #11
4. In order to study the compound effect of updated yellow change and red clearance intervals, the following study sites were selected to implement the ITE 2020 yellow change and red clearance intervals.
    - Intersections #6, and #10
5. Control sites continued with COP policy's yellow change and red clearance intervals.
    - Intersections #8, and #12

Table 8.6 provides detailed information about the specific yellow change and red clearance intervals implemented at the selected study sites. The yellow change intervals at the incremental sites were reduced incrementally during Periods 6 and 7 to meet COP policy at the beginning of Period 7. Then, the incremental sites were categorized into two groups to investigate the impact of red clearance intervals individually in the long and short term. The red clearance intervals were increased incrementally during Periods 8 and 9 and reduced incrementally during Periods 10 and 11 at Intersections #4 and #9. In addition, the red clearance intervals were increased at the start of Period 8 and remained unchanged at Intersections #1 and #2 to study the long-term effect of increasing red clearance intervals.

Furthermore, the long-term sites were divided into two groups. The red clearance intervals remained unchanged at Intersections #7 and #11 to study the long-term effect of yellow change intervals. The red clearance intervals were increased in Period 8 at Intersections #6 and #10 to study the combined effect of updated yellow change and red clearance intervals.

Table 8.6 Implemented Experimental Design for the Left-Turn Movements

Intersections	Type of Intersections in Yellow Change Interval Study	Type of Intersections in Red Clearance Interval Study	Periods 8 and 9 Signal Timing Parameters	Periods 10 and 11 Signal Timing Parameters
#1	Incremental Site	Increasing in One Step	Yellow is Baseline Red Clearance is ITE 2020	Yellow is Baseline Red Clearance is ITE 2020
#2	Incremental Site	Increasing in One Step	Yellow is Baseline Red Clearance is ITE 2020	Yellow is Baseline Red Clearance is ITE 2020
#4	Incremental Site	Increasing in Two Steps (Periods 8 and 9) Decreasing in Two Steps (Periods 10 and 11)	Yellow is Baseline Red Clearance Increasing Incrementally	Yellow is Baseline Red Clearance Decreasing Incrementally
#6	Long-term Site	Increasing in One Step (compound effect)	Yellow is ITE 2020 Red Clearance is ITE 2020	Yellow is ITE 2020 Red Clearance is ITE 2020
#7	Long-term Site	Remain Unchanged	Yellow is ITE 2020 Red Clearance is Baseline	Yellow is ITE 2020 Red Clearance is Baseline
#8	Control Site	Remain Unchanged	Yellow is Baseline Red Clearance is Baseline	Yellow is Baseline Red Clearance is Baseline
#9	Incremental Site	Increasing in Two Steps (Periods 8 and 9) Decreasing in Two Steps (Periods 10 and 11)	Yellow is Baseline Red Clearance Increasing Incrementally	Yellow is Baseline Red Clearance Decreasing Incrementally
#10	Long-term Site	Increasing in One Step (compound effect)	Yellow is ITE 2020 Red Clearance is ITE 2020	Yellow is ITE 2020 Red Clearance is ITE 2020
#11	Long-term Site	Remain Unchanged	Yellow is ITE 2020 Red Clearance is Baseline	Yellow is ITE 2020 Red Clearance is Baseline
#12	Control Site	Remain Unchanged	Yellow is Baseline Red Clearance is Baseline	Yellow is Baseline Red Clearance is Baseline

Chapter 9

Results
(Phase 2)

9. RESULTS (Phase 2)

9.1 Through Movements

Please refer to Chapter 8, where a detailed explanation of how the twelve study sites were classified into four distinct groups to investigate the impact of updated red clearance intervals, both individually and in conjunction with updated yellow change intervals.

9.1.1 Incremental Sites

As discussed in Chapter 8, the incremental sites were categorized into two groups. Intersections #2 and #4 were selected to study the combined effect of updated yellow change and red clearance intervals. Therefore, the ITE 2020 guidelines for yellow change and red clearance intervals were implemented during Periods 10 and 11 at these study sites. While Intersection #9 was selected to study the individual impact of the updated yellow change interval. Thus, the red clearance intervals at this study site remained unchanged during Periods 10 and 11.

Table 9.1 displays the average daily RLR frequency for the three incremental sites. The data suggests no significant change in RLR frequency comparing Periods 10 and 11 with prior periods.

Table 9.1 Average of RLR Frequency per Day for Through Movements at Incremental Sites

Intersections	Phase 1						Phase 2					
	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #2	**188**	**193**	**195**	**123**	**127**	**128**	**143**	**121**	**115**	**119**	**121**	**113**
Intersection #4	**226**	**192**	**176**	**157**	**163**	**157**	**157**	**154**	**147**	**142**	**149**	**178**
Intersection #9	**156**	**104**	**97**	**84**	**70**	**93**	**-**	**-**	**84**	**89**	**112**	**97**

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

The results of the statistical T-test conducted on the RLR rate at the incremental sites are presented in Table 9.2. By comparing Periods 5 to 11 with the baseline, it can be observed that the average RLR rate was significantly reduced. However, it was found that the difference between the RLR rate in Periods 5 to 11 was not statistically significant (refer to Appendix B). The results showed that updating yellow change intervals effectively reduced the RLR, while updating the red clearance intervals based on ITE 2020 guidelines did not significantly impact drivers' compliance behavior.

Table 9.2 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements at Incremental Sites

Intersections	Baseline	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #2	5.49	3.66*	3.99	3.25	3.36	3.33	3.42	3.18
Intersection #4	9.09	5.95	5.66	5.26	5.20	5.24	5.31	6.11
Intersection #9	4.99	2.45	-	-	2.13	2.39	2.81	2.53

* Green-highlighted cells show a statistically significant decrease in the RLR rate compared to the baseline at a 95% confidence level

9.1.2 Periodical Sites

Table 9.3 contains the average daily RLR frequency for the three periodical sites. As explained in Chapter 8, at the start of Period 8, the yellow change intervals at the periodical sites were shortened to align with COP policy. Then, in Period 10, the red clearance intervals were updated based on ITE 2020 guidelines to assess the impact of updating red clearance intervals. Upon analyzing the data across Periods 8, 9, 10, and 11 compared to Periods 1, 3, 5, and 7, it becomes evident that implementing COP policy's yellow change intervals led to an increase in RLR frequency. However, the data suggests no significant change in RLR frequency when evaluating Periods 10 and 11 against Periods 8 and 9.

Table 9.3 Average of RLR Frequency per Day for Through Movements at Periodical Sites

Intersections	Phase 1						Phase 2					
	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #1	234	-	-	-	-	-	-	80	231	234	225	221
Intersection #5	353	202	339	199	339	212	327	209	275	303	319	340
Intersection #6	223	91	192	78	140	-	167	102	199	195	227	219

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

The statistical T-test results for the RLR rate at the periodical sites are presented in Table 9.4. These results indicate a significant increase in the average RLR rate during periods where the COP policy's yellow change intervals were implemented (Periods 8, 9, 10, and 11), compared to the periods with the ITE 2020 intervals (Periods 5 and 7). Nevertheless, no statistically significant difference was observed when comparing the RLR rates between Periods 10 and 11 and Periods 8 and 9 (refer to Appendix B). The findings indicate that the updates made to the red clearance intervals following ITE 2020 guidelines did not significantly reduce RLR violations.

Table 9.4 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements at Periodical Sites

Intersections	Baseline	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #1	9.47	-	-	3.41	9.27	9.48	8.53	8.62
Intersection #5	9.94	6.07	9.25	5.49	8.00	8.42	8.76	9.43
Intersection #6	8.89	-	-	4.02	7.88	7.64	8.39	8.26

* Green-highlighted cells show a statistically significant decrease in the RLR rate compared to the baseline at a 95% confidence level

9.1.3 Long-term Sites

Table 9.5 contains the average daily RLR frequency for the three long-term sites. As explained in Chapter 8, at the start of Period 1, the yellow change intervals at the long-term sites were increased to comply with ITE 2020 guidelines. In order to examine the long-term impact of increasing the yellow change intervals, the red clearance intervals remained unchanged at two long-term sites (Intersections #7 and #11). Additionally, to investigate the impact of updating the yellow change and red clearance intervals, the red clearance intervals at Intersection #10 were updated at the beginning of Period 10. The data indicates a decrease in RLR frequency following the implementation of ITE 2020 yellow change intervals in Period 1, and this reduction persisted until Period 11. However, no significant change was observed when comparing the average RLR frequency in the last two periods with the preceding periods at Intersection #10.

Table 9.5 Average of RLR Frequency per Day for Through Movements at Long-term Sites

Intersections	Phase 1						Phase 2					
	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #7	110	52	51	50	49	59	65	53	63	62	67	64
Intersection #10	216	82	106	73	113	102	-	-	122	123	126	126
Intersection #11	244	114	144	110	143	124	-	-	110	137	135	128

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

Table 9.6 presents the results of the statistical T-test conducted on the RLR rate at the long-term sites. These findings show a significant decrease in the average RLR rate after implementing ITE 2020 yellow change intervals. However, no statistically significant difference was observed when comparing the RLR rates between Periods 10 and 11 and Periods 8 and 9, specifically at Intersection #10 (refer to Appendix B). Therefore, the findings suggest that the updates made to the red clearance intervals in alignment with ITE 2020 guidelines did not significantly reduce RLR violations.

Table 9.6 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements at Long-term Sites

Intersections	Baseline	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #7	5.42	2.84	2.92	3.00	2.86	2.75	2.94	2.77
Intersection #10	5.17	2.30	-	-	2.65	2.94	2.91	2.97
Intersection #11	6.80	3.33	-	-	2.81	3.94	3.55	3.72

* Green-highlighted cells show a statistically significant decrease in the RLR rate compared to the baseline at a 95% confidence level

9.2 Turning Movements

This section covers the results of implementing ITE 2020 guidelines for left-turn movements. In the following sections, a statistical analysis will be discussed, examining the effects of the updated red clearance intervals both individually and in combination with updated yellow change intervals.

For a comprehensive understanding of how the study sites were categorized into four distinct groups and the updated signal timing parameters, please refer to Chapter 8.

9.2.1 Incremental Sites

In Chapter 8, it was explained that the yellow change intervals at the four incremental sites were reduced during Periods 6 and 7 in order to reach COP policy's intervals at the beginning of Period 8. Subsequently, at the start of Period 8, the red clearance intervals at Intersections #1 and #2 were increased to align with the ITE 2020 guidelines. This adjustment aimed to study the individual impact of increasing red clearance intervals for left-turn movements. Furthermore, the red clearance intervals at Intersections #4 and #9 were incrementally increased during Periods 8 and 9, reaching the updated ITE 2020 guidelines at the beginning of Period 9. These intervals were then incrementally reduced during Periods 10 and 11 to align with COP policy at the start of Period 11.

Table 9.7 contains the average daily RLR frequency for the four incremental sites. Upon analysis, it was observed that the RLR frequency increased with the increase in red clearance intervals. This observation highlights the correlation between increasing red clearance intervals and the corresponding increase in RLR frequency.

Table 9.7 Average of RLR Frequency Per Day for Left-Turn Movements at Incremental Sites

Intersections	Phase 1						Phase 2					
	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #1	5	-	-	-	-	-	-	4	7	7	10	11
Intersection #2	24	12	12	10	10	8	11	18	63	52	67	53
Intersection #4	37	31	29	12	27	24	42	36	51	35	42	37
Intersection #9	157	138	130	61	128	50	-	-	355	327	266	170

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

Table 9.8 presents the results of the statistical T-test conducted on the RLR rate at the incremental sites. Compared to the baseline, the average RLR rate significantly decreased in Period 5, where the yellow change intervals based on ITE 2020 guidelines were implemented. The significant reduction in RLR rate also dissipated by reducing the yellow change intervals incrementally during Periods 6 and 7. It can be observed that increasing red clearance intervals in Period 8 resulted in an increase in the RLR rate at four incremental sites. The increase in RLR rate at Intersections #1 and #4 was not statistically significant. However, the increase in the RLR rate at Intersections #2 and #9 was statistically significant compared to the baseline.

Furthermore, comparing Periods 10 and 11 with the baseline, it can be seen that increasing red clearance intervals resulted in a statistically significant increase in RLR rate at Intersections #1 and #2. In addition, by looking into the results from Intersection #9, it can be observed that the RLR rate increased significantly with the increase of red clearance interval and then reduced significantly by reducing red clearance intervals during Periods 10 and 11. Upon comparing Periods 8, 9, 10, and 11 with Period 7, it can be seen that the average RLR rate increased significantly at Intersections #1 and #2 (refer to Appendix B). Therefore, the findings suggest that the updates made to the red clearance intervals in alignment with ITE 2020 guidelines increased RLR violations significantly for left-turn movements.

Table 9.8 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Left-Turn Movements at Incremental Sites

Intersections	Baseline	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #1	0.97	-	-	0.65	1.31	1.33	1.7	1.98
Intersection #2	5.13	1.58	2.39	4.53	12.49	10.86	13.37	10.85
Intersection #4	4.93	2.65	4.41	4.07	5.30	4.30	4.55	4.22
Intersection #9	16.13	5.07	-	-	33.12	34.00	25.31	16.02

* Green-highlighted cells show a statistically significant decrease in the RLR rate compared to the baseline at a 95% confidence level
** Red-highlighted cells show a statistically significant increase in the RLR rate compared to the baseline at a 95% confidence level

9.2.2 Long-term Sites

Table 9.9 contains the average daily RLR frequency for the four long-term sites. As explained in Chapter 8, at the start of Period 1, the yellow change intervals at the long-term sites were increased to comply with ITE 2020 guidelines. In order to examine the long-term impact of increasing the yellow change intervals, the red clearance intervals remained unchanged at two long-term sites (Intersections #7 and #11). Additionally, to investigate the impact of updating the yellow change and red clearance intervals, the red clearance intervals at Intersections # 6 and #10 were increased at the beginning of Period 8. The data shows a decrease in RLR frequency following the implementation of ITE 2020 yellow change intervals in Period 1. However, it can be observed that increasing the red clearance intervals at intersections # 6 and #10 resulted in an increase in RLR frequency.

Table 9.9 Average of RLR Frequency Per Day for Left-Turn Movements at Long-term Sites

Intersections	Phase 1						Phase 2					
	Baseline	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #6	23	5	8	5	4	-	9	14	12	14	22	23
Intersection #7	11	7	9	6	6	7	7	7	9	5	8	8
Intersection #10	25	4	5	4	7	8	-	-	25	16	23	19
Intersection #11	148	82	95	78	99	88	-	-	94	88	101	89

* The tables have been color-coded to help visually detect patterns and trends, with lighter shades representing cells with lower values and bolder shades indicating higher values.

The statistical T-test results for the long-term sites' RLR rate are presented in Table 9.10. The data shows a significant decrease in the RLR rate after implementing the ITE 2020 yellow change intervals. This decrease persisted until Period 11 at Intersections #7 and #10, where the red clearance intervals remained unchanged to observe the long-term effects of increased yellow change intervals. However, Intersections #6 and #10 experienced an increase in the RLR rate after increasing the red clearance intervals. Upon comparing the most recent periods with the baseline, it is evident that the average RLR rate in Periods 10 and 11 at Intersection #6 is not significantly different from the baseline.

Similarly, the average RLR rate is not significantly different when comparing Periods 8 and 10 with the baseline at Intersection #10. Moreover, compared to Period 7, the RLR rate in Periods 10 and 11 increased significantly at Intersection #6. Therefore, the findings suggest that increasing red clearance intervals based on ITE 2020 guidelines did not significantly reduce RLR violations.

Table 9.10 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Left-Turn Movements at Long-term Sites

Intersections	Baseline	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #6	**4.00**	**-**	**1.41**	**1.87**	**2.02**	**2.23**	**3.95**	**3.70**
Intersection #7	**3.87**	**2.48**	**2.21**	**2.27**	**2.78**	**1.81**	**2.46**	**2.41**
Intersection #10	**4.10**	**1.23**	**-**	**-**	**3.49**	**2.79**	**3.59**	**3.18**
Intersection #11	**17.59**	**8.27**	**-**	**-**	**9.06**	**9.71**	**10.14**	**9.54**

* Green-highlighted cells show a statistically significant decrease in the RLR rate compared to the baseline at a 95% confidence level

Chapter 10

Conclusion

&

Recommendations

(Phase 2)

10.CONCLUSION & RECOMMENDATIONS (Phase 2)

10.1 Conclusion

Red-light running (RLR) behavior poses a significant risk at signalized intersections and has become one of the leading causes of intersection-related crashes. Addressing this critical issue and ensuring the safety of all road users necessitates a comprehensive investigation into RLR behavior at local intersections. The primary objective of this study is to assess whether implementing the updated ITE 2020 guidelines for determining yellow change and red clearance intervals, released in March 2020, can significantly enhance safety at signalized intersections. Phase 1 of this study focused on the individual impact of implementing updated yellow change intervals on drivers' compliance behavior. The results found that increasing the yellow change intervals could effectively reduce the frequency of RLR violations.

In Phase 2, the research was conducted to investigate the impact of red clearance intervals, both individually and in conjunction with yellow change intervals. Additionally, the long-term effects of implementing updated yellow change intervals were also investigated. Similar to Phase 1, a rigorous before-and-after analysis was conducted to examine the relationship between signal timing parameters and RLR violations through a comprehensive experimental design.

According to the statistical analysis (using a 95% confidence level), the results for both through movements and left-turn movements are summarized below.

1. The updating of red clearance intervals in accordance with the ITE 2020 guidelines had an insignificant impact on drivers' compliance behavior for through movements. It is worth noting that the red clearance intervals recommended by the ITE 2020 guidelines are closely aligned with the COP policy for through movements.
2. Increasing red clearance intervals based on the ITE 2020 guidelines showed limited effectiveness in reducing RLR violations for left-turn movements. Notably, at certain study sites, where red clearance intervals were increased to meet the ITE 2020 guidelines, a significant increase in RLR violations was observed for left-turn movements.

3. It was observed that the significant decrease in RLR violations following the implementation of longer yellow change intervals persisted throughout the study at the designated long-term sites where the red clearance intervals were left unchanged to assess the long-term effects of increased yellow change intervals.

10.2 Recommendations

Based on the findings and results of Phase 2 of this study, the project team has proposed several recommendations to the City of Phoenix to improve safety at signalized intersections by better understanding road users' compliance behavior with the traffic signal. These recommendations include:

1. Considering the minimal disparity between the calculation of red clearance intervals according to the ITE 2020 guidelines and the COP policy’s calculation, and the lack of significant reduction in RLR violations for through movements observed after updating the red clearance intervals, it is recommended to maintain the current practices for red clearance intervals instead of adopting the ITE 2020 guidelines for through movements.
2. Based on the observations regarding the implementation of increased red clearance intervals for left-turn movements, it was found that adhering to the ITE 2020 guidelines showed limited effectiveness in reducing RLR violations. Also, it was observed the adoption of these increased intervals led to an increase in RLR violations for left-turn movements. As a result, it is recommended to maintain the current practices for red clearance intervals for left-turn movements instead of implementing the ITE 2020 guidelines.
3. Further study is strongly recommended to draw more robust conclusions. Particularly, due to the permissive-protected nature of left-turn movements at certain study sites and the difficulty in capturing RLR violations during transitions between phases, it is crucial to conduct additional research using a new system and an alternative algorithm for RLR detection. This will enable more comprehensive analysis and provide valuable insights into optimizing RLR mitigation strategies.

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Appendix A
Sample RLR/YLR Data

APPENDIX A

Table A.1 Sample of Turning Movement Count (TMC) Data

Local Datetime Bin (start)	Classification	Direction	Movement	Total TMCs
10/1/2022 6:00	ArticulatedTruck	NB	THRU	2
10/1/2022 6:00	PickupTruck	NB	THRU	14
10/1/2022 6:00	SingleUnitTruck	NB	THRU	1
10/1/2022 6:00	WorkVan	NB	THRU	1
10/1/2022 6:00	Bus	NB	THRU	1
10/1/2022 6:00	PickupTruck	SB	LT	1
10/1/2022 6:00	WorkVan	SB	THRU	3
10/1/2022 6:00	SingleUnitTruck	SB	THRU	2
10/1/2022 6:00	ArticulatedTruck	SB	THRU	2
10/1/2022 6:00	Car	SB	THRU	94
10/1/2022 6:00	PickupTruck	SB	U-TURN	1
10/1/2022 6:00	PickupTruck	WB	THRU	1
10/1/2022 6:15	PickupTruck	EB	LT	1
10/1/2022 6:15	ArticulatedTruck	EB	RT	1
10/1/2022 6:15	PickupTruck	EB	RT	6

Table A.2 Sample Of Traffic Signal Phase Data

Direction	Movement	Red Start	Red End	Red Duration (ms)	Green Start	Green End	Green Duration (ms)	Yellow Start	Yellow End	Yellow Duration (ms)
EB	THRU	8/1/2022 00:00:19.449	8/1/2022 00:01:32.376	72927	8/1/2022 00:01:32.376	8/1/2022 00:02:19.294	46918	8/1/2022 00:02:19.294	8/1/2022 00:02:23.583	4289
WB	THRU	8/1/2022 00:00:19.449	8/1/2022 00:01:35.177	75728	8/1/2022 00:01:35.177	8/1/2022 00:02:19.294	44117	8/1/2022 00:02:19.294	8/1/2022 00:02:23.583	4289
SB	LTProtected	8/1/2022 00:00:33.658	8/1/2022 00:08:21.385	467727	8/1/2022 00:08:21.385	8/1/2022 00:08:27.985	6600	8/1/2022 00:08:27.985	8/1/2022 00:08:30.986	3001
NB	LTProtected	8/1/2022 00:00:33.858	8/1/2022 00:02:25.292	111434	8/1/2022 00:02:25.292	8/1/2022 00:02:32.176	6884	8/1/2022 00:02:32.176	8/1/2022 00:02:35.176	3000
NB	THRU	8/1/2022 00:01:20.473	8/1/2022 00:02:25.292	64819	8/1/2022 00:02:25.292	8/1/2022 00:03:16.469	51177	8/1/2022 00:03:16.469	8/1/2022 00:03:20.469	4000
SB	THRU	8/1/2022 00:01:20.473	8/1/2022 00:02:36.176	75703	8/1/2022 00:02:36.176	8/1/2022 00:03:16.469	40293	8/1/2022 00:03:16.469	8/1/2022 00:03:20.469	4000
WB	LTProtected	8/1/2022 00:01:31.375	8/1/2022 00:03:22.169	110794	8/1/2022 00:03:22.169	8/1/2022 00:03:31.468	9299	8/1/2022 00:03:31.468	8/1/2022 00:03:34.469	3001
EB	LTProtected	8/1/2022 00:01:34.176	8/1/2022 00:19:22.290	1068114	8/1/2022 00:19:22.290	8/1/2022 00:19:33.286	10996	8/1/2022 00:19:33.286	8/1/2022 00:19:36.294	3008
EB	THRU	8/1/2022 00:02:23.583	8/1/2022 00:03:35.477	71894	8/1/2022 00:03:35.477	8/1/2022 00:04:15.170	39693	8/1/2022 00:04:15.170	8/1/2022 00:04:19.471	4301
WB	THRU	8/1/2022 00:02:23.583	8/1/2022 00:03:22.169	58586	8/1/2022 00:03:22.169	8/1/2022 00:04:15.170	53001	8/1/2022 00:04:15.170	8/1/2022 00:04:19.471	4301

Table A.3 Sample of RLR/YLR data

Track Datetime	Cycle Green Start	Cycle Green End	Cycle Yellow Start	Cycle Yellow End	Cycle Red Start	Cycle Red End	Direction	Track Movement	Phase Movement	Classification	Track Light Colour
1/10/2022 00:53:06.271	1/10/2022 00:52:39.217	1/10/2022 00:53:05.517	1/10/2022 00:53:05.517	1/10/2022 00:53:09.110	1/10/2022 00:51:12.715	1/10/2022 00:52:39.217	WB	THRU	THRU	Car	Yellow
1/10/2022 00:53:08.042	1/10/2022 00:52:50.510	1/10/2022 00:53:05.517	1/10/2022 00:53:05.517	1/10/2022 00:53:09.110	1/10/2022 00:51:12.715	1/10/2022 00:52:50.510	EB	THRU	THRU	Car	Yellow
1/10/2022 00:53:19.258	1/10/2022 00:54:41.013	1/10/2022 00:54:56.014	1/10/2022 00:54:56.014	1/10/2022 00:54:59.614	1/10/2022 00:53:09.110	1/10/2022 00:54:41.013	EB	THRU	THRU	Car	Red
1/10/2022 00:54:24.957	1/10/2022 00:53:31.817	1/10/2022 00:54:24.112	1/10/2022 00:54:24.112	1/10/2022 00:54:27.722	1/10/2022 00:52:37.009	1/10/2022 00:53:31.817	SB	THRU	THRU	Car	Yellow
1/10/2022 00:56:31.330	1/10/2022 00:56:12.316	1/10/2022 00:56:28.226	1/10/2022 00:56:28.226	1/10/2022 00:56:31.818	1/10/2022 00:54:59.614	1/10/2022 00:56:12.316	WB	THRU	THRU	PickupTruck	Yellow
1/10/2022 00:56:31.841	1/10/2022 00:57:46.420	1/10/2022 00:58:04.021	1/10/2022 00:58:04.021	1/10/2022 00:58:07.622	1/10/2022 00:56:31.818	1/10/2022 00:57:46.420	WB	THRU	THRU	Car	Red
1/10/2022 00:57:45.630	1/10/2022 00:58:25.230	1/10/2022 00:59:25.624	1/10/2022 00:59:25.624	1/10/2022 00:59:29.232	1/10/2022 00:57:44.228	1/10/2022 00:58:25.230	NB	THRU	THRU	PickupTruck	Red
1/10/2022 00:58:19.775	1/10/2022 00:58:10.230	1/10/2022 00:58:18.929	1/10/2022 00:58:18.929	1/10/2022 00:58:21.922	1/10/2022 00:55:10.915	1/10/2022 00:58:10.230	SB	LT	LTProtected	Car	Yellow
1/10/2022 00:58:27.417	1/10/2022 00:58:10.230	1/10/2022 00:58:27.029	1/10/2022 00:58:27.029	1/10/2022 00:58:30.029	1/10/2022 00:56:45.018	1/10/2022 00:58:10.230	NB	LT	LTProtected	Car	Yellow

Appendix B
Statistical Analysis Results

APPENDIX B

Table B.1 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements compared to **Period 8**

Intersections	Intersection type	Period 8	Period 9	Period 10	Period 11
Intersection #2	Incremental	3.36	3.33	3.42	3.18
Intersection #4	Incremental	5.20	5.24	5.31	6.11
Intersection #9	Incremental	2.13	2.39	2.81	2.53
Intersection #1	Periodical	9.27	9.48	8.53	8.62
Intersection #5	Periodical	8.00	8.42	8.76	9.43
Intersection #6	Periodical	7.88	7.64	8.39	8.26
Intersection #7	Long-term	2.86	2.75	2.94	2.77
Intersection #10	Long-term	2.65	2.94	2.91	2.97
Intersection #11	Long-term	2.81	3.94	3.55	3.72

* Red-highlighted cells show a statistically significant increase in the RLR rate compared to Period 8 at a 95% confidence level

Table B.2 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Through Movements compared to **Period 9**

Intersections	Intersection type	Period 9	Period 10	Period 11
Intersection #2	Incremental	3.33	3.42	3.18
Intersection #4	Incremental	5.24	5.31	6.11
Intersection #9	Incremental	2.39	2.81	2.53
Intersection #1	Periodical	9.48	8.53	8.62
Intersection #5	Periodical	8.42	8.76	9.43
Intersection #6	Periodical	7.64	8.39	8.26
Intersection #7	Long-term	2.75	2.94	2.77
Intersection #10	Long-term	2.94	2.91	2.97
Intersection #11	Long-term	3.94	3.55	3.72

* Green-highlighted cells show a statistically significant decrease in the RLR rate compared to Period 9 at a 95% confidence level

** Red-highlighted cells show a statistically significant increase in the RLR rate compared to Period 9 at a 95% confidence level

Table B.3 Statistical T-Test Results Of RLR Rate (RLR Per 1000 Vehicles Per Day) for Left-turn Movements compared to **Period 7**

Intersections	Intersection type	Period 7	Period 8	Period 9	Period 10	Period 11
Intersection #1	Incremental	0.65	1.31	1.33	1.7	1.98
Intersection #2	Incremental	4.53	12.49	10.86	13.37	10.85
Intersection #4	Incremental	4.07	5.30	4.30	4.55	4.22
Intersection #9	Incremental	-	33.12	34.00	25.31	16.02
Intersection #6	Long-term	1.87	2.02	2.23	3.95	3.70
Intersection #7	Long-term	2.27	2.78	1.81	2.46	2.41
Intersection #10	Long-term	-	3.49	2.79	3.59	3.18
Intersection #11	Long-term	-	9.06	9.71	10.14	9.54

* Red-highlighted cells show a statistically significant increase in the RLR rate compared to Period 8 at a 95% confidence level