Evaluation of Intersection Safety and Capacity Relevant to Signal Timing on Arizona's State Highway System

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16. Abstract

Traffic signal phase-change intervals are intended to provide a safe transition between two conflicting signal phases or a right-of-way transition between conflicting road-user movements. As a result, signal phase change (includes yellow change interval, red-clearance interval, and pedestrian intervals) has significant safety and operations implications at signalized intersections. Currently, there is no national standard for calculating these durations. Additionally, the current ADOT-recommended practice for calculating traffic signal intervals has resulted in two issues: (1) lengthy red-clearance intervals at interchanges with large conflict areas; and (2) yellow change interval durations with the potential of not meeting the needs of the driver population. The objectives of this research were to: (1) evaluate ADOT's current signal timing design guidelines; and (2) recommend an optimal signal timing design for the Arizona state highway system. A comprehensive evaluation of the effects of the current signal timing design guidelines and a thorough pilot study were used to inform a set of recommendations. These recommendations were used to draft a proposed version of the ADOT's Guidelines and Processes, which describes the interval duration calculation methods. Proposed changes to the methods include (1) an increase in the approach speed used to calculate left-turn yellow-change intervals; (2) an increase in the intersection speed used to calculate the red-clearance intervals at single-point urban interchanges; and (3) a decrease in the walk speed used to compute "DON'T WALK" interval durations at locations with a high volume of slower-moving pedestrians. These changes would yield increased yellow-change intervals, decreased red-clearance intervals, and longer "DON'T WALK" intervals.

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Acronyms, Abbreviations, and Symbols

ACIS	Arizona Crash Information System
ADOT	Arizona Department of Transportation
ARS	Arizona Revised Statute
DOT	department of transportation; ADOT's counterpart in another state
FHWA	Federal Highway Administration; joint sponsor with ADOT on many research studies
hr	hours
ITE	Institute of Transportation Engineers
MEV	million entering vehicles
min	minutes
MnDOT	Minnesota Department of Transportation
MOE	measure of effectiveness
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
ODOT	Oregon Department of Transportation
sec	seconds
SMRP	speed-measurement reference point
SPUI	single-point urban interchange
TGP	Traffic Guidelines and Processes
VMT	vehicle miles traveled
UDOT	Utah Department of Transportation

Introduction

Traffic signal phase-change intervals are used to provide a safe transition between two conflicting signal phases or a right-of-way transition between conflicting vehicular movements. The signal phase change has an important influence on the safety and operations of signalized intersections, and they consist of two elements: the yellow-change interval followed by the red-clearance interval. The yellow-change interval indicates to drivers that the current green indication has ended, and that a red indication will be shown immediately afterward. The red-clearance interval is intended to provide time for vehicles that entered the intersection during the yellow-change interval to clear the intersection prior to vehicles in the next phase entering the intersection.

Despite national research efforts conducted in this area, consensus has been difficult to reach on the most appropriate methodology to calculate the duration of yellow-change and red-clearance intervals. A national standard for calculating signal phase-change intervals is not available; instead, there are only recommended practices and agency guidelines available to assist traffic engineers in calculating the signal phase-change intervals.

The goal of this study was to evaluate safety conditions at a range of intersection signal light configurations on Arizona's state highway system for the purpose of identifying potential changes to the Arizona Department of Transportation (ADOT) guidelines for computing the yellow-change and red-clearance interval durations. Identified potential changes should focus on resolving the following two issues, listed in priority order:

1. **Current ADOT guidelines lead to lengthy red-clearance intervals at interchanges with large conflict areas (e.g., single-point urban interchange [SPUI]).** Can traffic safety be improved by reducing this interval's duration? If yes, can the current procedure for computing the interval duration be modified to provide an optimal level of safety for a specified location?
2. **ADOT guidelines give a standard calculation for yellow-change interval duration that may have unintended impacts on intersection safety for some conditions (e.g., left turns on high-speed approaches).** Can traffic safety be improved by changing the yellow-change interval slightly (to a value different from ADOT’s guideline calculation)? If yes, can the current procedure for computing the interval duration be modified to provide an optimal level of safety for a specified location?

The remaining three sections of this report describe the findings and recommendations of this study. The first section to follow summarizes the recommended methods for calculating the phase-change interval durations. The second section documents the findings from the analysis of crash and conflict data at several intersections in ADOT’s highway system. The third section describes the study approach and analysis methods.

Study Overview

The following list identifies the project tasks:

1. **Assessment of Sites with Potential for Improvement:** Yellow-change, red-clearance, and pedestrian-clearance interval durations were computed for 20 intersections in the state highway system. These were compared to the durations calculated by ADOT.
2. **Quantify Safety Effect of the Interval Formula Change:** In 2013, traffic engineers adopted a new formula for computing the red-clearance intervals for some intersections in the state highway system. Crash frequencies both before and after the update were calculated for both the updated intersections and other intersections that were used as experimental controls.
3. **Pilot Study: Planning, Designing, and Implementation:** This portion of the project was comprised of two parts:

    a. **Initial Data Collection and Analysis:** This portion of the project aimed to quantify the effectiveness of ADOT's current signal timing design guidelines and identify proposed changes for implementation in the pilot study. Data were collected at several sites, and data analysis was conducted to determine parameters for the pilot study.

    b. **Pilot Study Implementation:** The pilot study comprised a new phase of data collection and analysis. The purpose of the pilot study was to inform the development of final recommended revisions to ADOT's guidelines and processes.

State of the Practice

This section summarizes the current practices in Arizona for computing yellow-change and red-clearance intervals. An extended overview of the current state of the practice is in Appendix A. The comprehensive overview includes commonly used methods for computing yellow-change and red-clearance intervals, guidelines from other states' departments of transportation (DOTs), and the new 2020 Institute of Transportation Engineers' (ITE) recommended practice.

ADOT Traffic Guidelines and Processes

The *ADOT Traffic Guidelines and Processes* (TGP) provides traffic engineering guidance and information to be used on the state highway system, including traffic signals (TGP Section 600). TGP 621 (Signal Phase-Change Intervals) provides guidance on the calculation of yellow-change and red-clearance intervals for through movements. TGP 622 (Left Turn Signal Timing) provides guidance for protected left-turn movements.

Through Movements

The ADOT TGP follows the kinematic equation method for yellow-change interval calculation. The red-clearance interval is calculated using the ITE equation method without the 1.0-second (sec) subtraction for the conflicting approach start-up delay. The TGP equation for red-clearance interval is as follows (Eq. 1):

$$AR = \frac{w + l}{1.47v}$$

Eq. 1

Where:

AR = red-clearance interval (seconds)
w = intersection width (feet)
l = length of vehicle (20 feet)
v = speed (miles per hour)

ADOT updates the TGP periodically to improve its guidelines and processes. Prior to November 2013, TGP 621 stipulated that the intersection width (w) should be measured per Arizona Revised Statute (ARS) 28-601, which defines intersections as "…the area embraced within the prolongation or connection of the lateral curb lines…". Measurement of this width for the eastbound through movement is shown in Figure 1. TGP 621 was updated in November 2013 and was based on the 2013 proposed ITE guidelines, stipulating that the intersection width should be measured from the stop bar to the farthest conflicting lane. Figure 2 illustrates the measurement of intersection width for the eastbound through movement, per ARS 28-601 and per the November 2013 TGP revision.

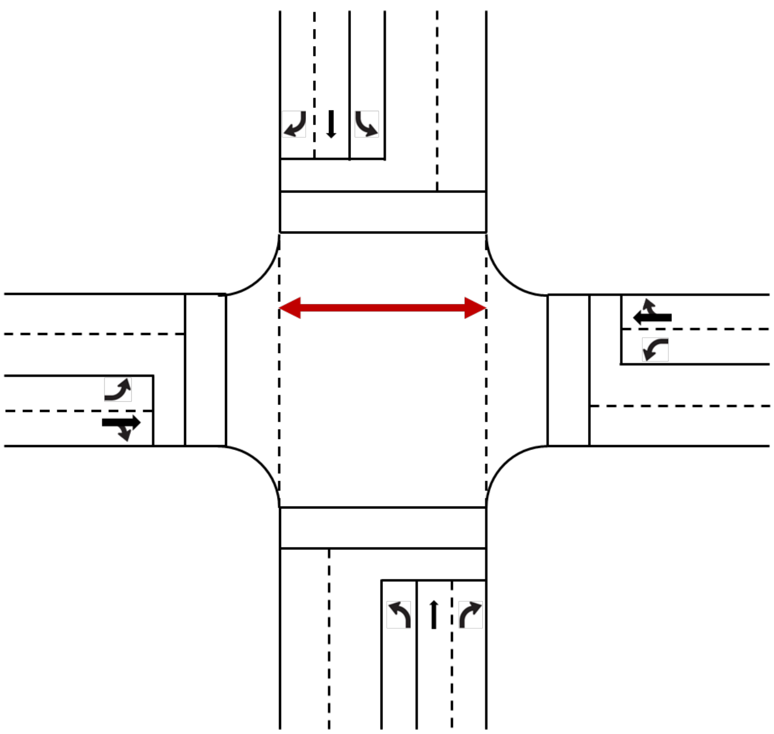

Figure 1. ADOT TGP 621 Intersection Width (w) Measurement Prior to November 2013

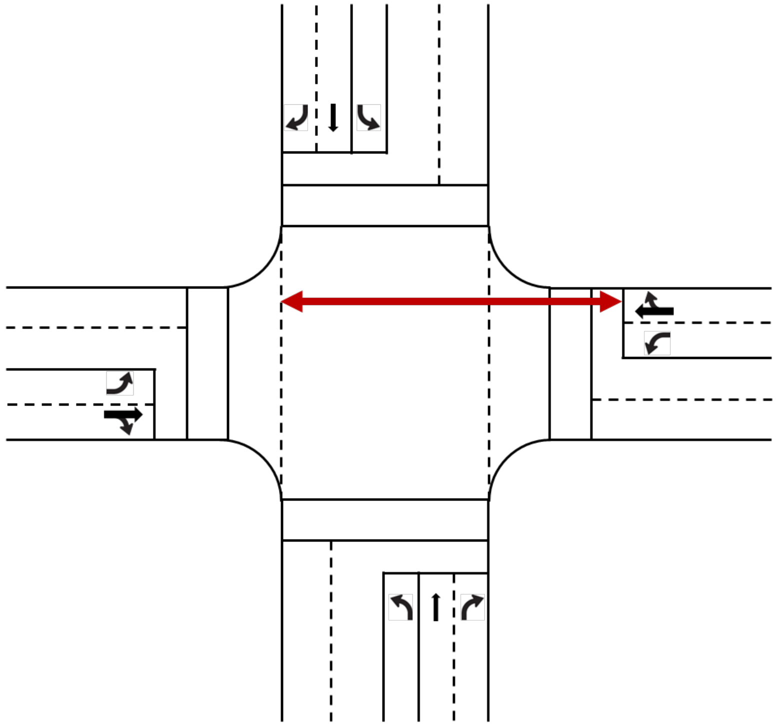

Figure 2. ADOT TGP 621 Intersection Width (w) Current Measurement

Left-turn Movements

TGP 622 recommends using the kinematic equation included in TGP 621 for calculating the yellow-change interval for left-turn movements. The calculation is conducted assuming a 25 miles per hour approach speed for turning vehicles.

Prior to December 2011, the ADOT TGP recommended a 1.0-sec red-clearance interval for protected left-turn movements at intersections in the state highway system. TGP 622 was added in December 2011, recommending 1.0 sec for the red-clearance interval for conventional intersections and the ITE equation method, as described in TGP 621, to determine intervals for complex intersections.

In November 2013, TGP 622 was updated to recommend using the ITE equation method for all intersections in the state highway system. This update recommended that an intersection's width be measured from the stop bar to the farthest conflicting lane, per the ITE's guidelines, and assumed left-turn speeds of 25 miles per hour (mph). Figure 3 illustrates the intersection width for left-turn movements.

Additional guidance in TGP 622 included recommendations for the length of the red-clearance interval – the minimum value shall be 1.0 sec but nor should it exceed 6.0 sec.

In January 2018, TGP 622 was updated to modify the guidance on measuring the intersection width. The new guidance recommends measuring the intersection width in a straight-line chord from stop bar to outside edge of conflicting travel lane, as shown in Figure 4 using the thick blue line.

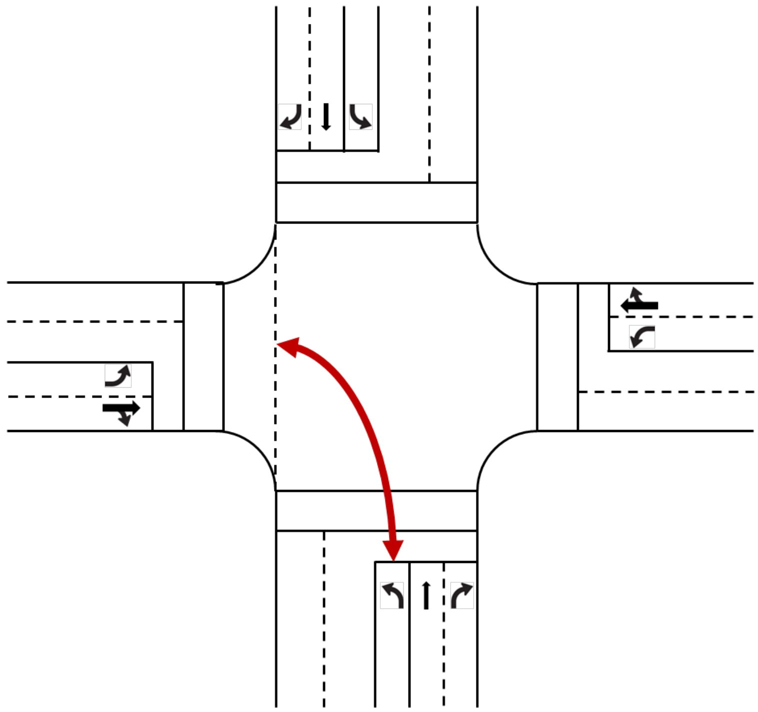

Figure 3. ADOT TGP 622 Intersection Width (w) Measurement, Dated November 2013

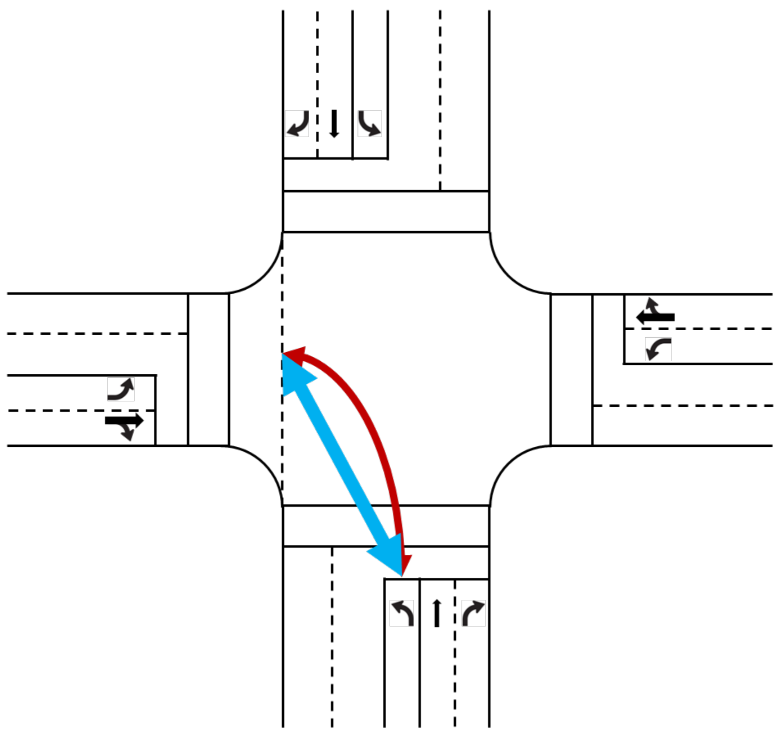

Figure 4. ADOT TGP 622 Intersection Width (w) Measurement, Dated January 2018

Arizona City and County Traffic Guidelines and Processes

To gain an understanding of current practice in Arizona for traffic signals' phase-change intervals, a multi-agency survey was conducted in 2019 to identify those practices that established yellow-change and red-clearance intervals as well as to identify operational or safety challenges encountered in recent years that might have been impacted by the guidelines for the signal-change and clearance interval timing. Information was collected from the following agencies:

- City of Mesa
- City of Peoria
- City of Phoenix
- City of Tucson
- Maricopa County
- Pima County
- Town of Gilbert

This multi-agency survey is included in Appendix A. Most of the agencies responded to the survey by providing their current documented guidance for yellow-change and red-clearance calculations. Only one agency responded to the survey by phone, while one other agency provided written responses on the provided survey. The following sections in this report summarize the timing methodologies used by these agencies. Since the survey responses were collected, only the Town of Gilbert has made changes to their interval calculation methods. The City of Phoenix is in the process of changing their methods. The methods for the remaining agencies have not changed.

Yellow Change Interval

In general, the surveyed agencies use the kinematic equation method to estimate yellow-change intervals for through movements. Minor differences—mostly in how the kinematic input and calculations are conducted—were identified in the collected information. For protected left-turn operations, most of the agencies provide 3.0 sec of yellow-change interval. However, some agencies calculate the yellow-change interval based on the kinematic equation, similar to how the kinematic equation is used to calculate timing for through movements. Table 1 and Table 2 present a summary of the collected yellow-change interval methods.

Table 1. Yellow-change Interval Calculation Method for Through Movements by Agency in 2019

Agency	Method	Speed	Min	Max	Notes
ADOT	Kinematic equation	Posted speed	3.0 sec	6.0 sec	N/A
City of Mesa	Kinematic equation[1]	Posted speed or 85th percentile speed	4.0 sec	6.0 sec	Interval ranges from 4.0 sec to 6.0 sec for posted or 85th percentile speeds between 40 mph and 65 mph. Uses the ITE minimum change formula for locations with posted speeds below 40 mph and wide crossings.
City of Peoria	Kinematic equation	Posted speed plus 7 mph	3.0 sec	6.0 sec	If necessary, the calculated interval will be rounded up to the next whole integer.
City of Phoenix	Kinematic equation	Posted speed	3.0 sec	5.0 sec[2]	If calculated time is longer than 5.0 sec, the remaining time will be added to the red-clearance interval (i.e., if the calculated time is 6 seconds, an extra 1 second will be added to the red-clearance interval).
City of Tucson	Kinematic equation	Posted speed	3.0 sec	N/A[3]	Rounded to 0.5 sec.
Maricopa County	Kinematic equation	Posted speed	3.0 sec	6.0 sec	Interval rounded to the next highest 0.1 sec after calculation.
Pima County	Kinematic equation	Posted speed	3.0 sec	N/A[3]	N/A
Town of Gilbert	Kinematic equation	Posted speed	3.0 sec	N/A[3]	N/A

1. For speeds between 40 mph and 65 mph.
2. Additional yellow-change interval can be assigned to red-clearance interval.
3. Maximum interval value was not provided. The Manual on Uniform Traffic Control Devices (MUTCD) recommends a maximum of 6 sec.

Table 2. Yellow-change Interval Calculation Method for Protected Left-Turn Movements by Agency in 2019

Agency	Method	Speed	Min	Max
ADOT	Kinematic equation	Typical: 25 mph	3.0 sec	6.0 sec
City of Mesa	Single left turn: 3.0 sec Dual left turn: 4.0 sec	Higher speeds might be used for wider intersections (e.g., SPUI, multi-lane)	N/A	N/A
City of Peoria	Kinematic equation	N/A	3.0 sec	6.0 sec
City of Phoenix	3.0 sec	Posted speed minus 5 mph	N/A	N/A
City of Tucson	3.0 sec	N/A	N/A	N/A
Maricopa County	3.0 sec	N/A	N/A	N/A
Pima County	3.0 sec	N/A	N/A	N/A
Town of Gilbert	Single left turn: 3.0 and Dual left turn: Kinematic	N/A	N/A	N/A

Red-clearance Interval

The survey also collected information on the methods used by agencies to estimate red-clearance intervals. Most of the surveyed agencies use the ITE equation for through movements with minor differences in the way the intersection width is measured (i.e., curb-to-curb and/or stop-line-to-farthest-conflict-lane) and vehicle length assumptions. Similar to the findings for the yellow-change interval, red-clearance interval methods vary for left-turn calculations. Table 3 and Table 4 summarize the information collected for red-clearance intervals.

Table 3. Red-clearance Interval Calculation Method for Through Movements

Agency	Method	Speed	Intersection Width	Length	Min	Max
ADOT	ITE equation[1] (AR=(w+l)/v)	Posted speed	Stop bar to the farthest conflict lane	20 ft	N/A	N/A
City of Mesa	2.0 sec[2]	N/A	N/A	N/A	N/A	N/A
City of Peoria	ITE equation[1] (1.0-sec subtraction for conflicting approach's start-up delay)	Posted speed plus 7 mph	Stop bar to the curb prolongation of the farthest conflict lane	20 ft	1.0 sec	2.0 sec
City of Phoenix	ITE equation[1]	Posted speed	Curb line to curb line	N/A	1.0 sec	2.0 sec
City of Tucson[3]	ITE equation[1]	Posted speed	Stop bar to the farthest conflict lane	20 ft	1.0 sec	3.0 sec
Maricopa County	ITE equation[1]	Posted speed	Stop bar to the farthest conflict lane	20 ft	2.0 sec	N/A
Pima County	ITE equation[1]	Posted speed	Stop bar to the farthest conflict lane	20 ft	N/A	6.0 sec[4]
Town of Gilbert	ITE equation[1]	Posted speed	Stop bar to the farthest conflict lane	20 ft	1.5 sec	N/A

1. ITE Traffic Engineering Handbook Equation
2. Yellow-change interval can be adjusted to account for extra red-clearance interval.
3. Tucson omits the red-clearance interval between the through and lagging left turns.
4. Maximum should not exceed 6.0 sec of yellow and red-clearance intervals.

Table 4. Red-clearance Interval Calculation Method for Protected Left-Turn Movements

Agency	Method	Speed	Intersection Width	Length	Min	Max
ADOT[2]	ITE equation[1]	25 mph	Straight-line chord from stop bar to the extension of the outside edge of the receiving lane intersects the curb line	20 feet	1.0 sec	6.0 sec
City of Mesa	1.0 sec	N/A	N/A	N/A	1.0 sec	1.0 sec
City of Peoria	ITE equation [1] (1.0-sec subtraction for conflicting approach start-up delay)	20 mph	Stop bar to curb extension	20 feet	1.0 sec	2.0 sec
City of Phoenix[3]	1.0 sec	N/A	N/A	N/A	1.0 sec	1.0 sec
City of Tucson[4]	2.0 sec	N/A	N/A	N/A	2.0 sec	2.0 sec
Maricopa County[5]	1.0 sec	N/A	N/A	N/A	1.0 sec	1.0 sec
Pima County	1.0 sec	N/A	N/A	N/A	1.0 sec	1.0 sec
Town of Gilbert	1.0 sec	N/A	N/A	N/A	1.0 sec	1.5 sec

1. ITE Traffic Engineering Handbook Equation
2. Maximum red-clearance interval should not exceed 6.0 sec.
3. Use of a red-clearance interval for protected-permissive left-turn operation is optional.
4. Tucson omits the red-clearance interval between the through and lagging left turns.
5. Unusual intersection geometry (i.e., a five-leg intersection) might require a longer interval.

Pedestrian Intervals

In addition to collecting information on yellow-change and red-clearance intervals, the survey gathered information on the methods used by the contacted agencies to calculate pedestrian intervals. In general, the surveyed agencies use a 3.5 feet per second (fps) walking speed to estimate the pedestrian-change interval. Minor differences were identified in the methods used by agencies to account for the yellow-change and red-clearance intervals in the pedestrian-clearance interval. Table 5 shows a summary of the collected pedestrian interval methods.

Table 5. Pedestrian Interval Calculation Method by Agency

Agency	WALK Interval	Pedestrian-Change Time (Flashing "DON'T WALK") Walking	Pedestrian-Change Time (Flashing "DON'T WALK") Crosswalk Length	Pedestrian-Clearance Time (Flashing "DON'T WALK") Subtractions
ADOT	At least 7.0 sec	3.5 feet per second (fps); 4.0 fps may be considered by Traffic Operations Engineer	Curb to curb or center of ramp to center of ramp	Yellow-change interval
City of Peoria	Guidance not identified	3.5 fps	Center of ramp to center of ramp	Yellow-change interval
City of Phoenix	4.0–8.0 sec	3.5 fps and 3.0 fps	Along crosswalk from pedestrian push button location to the far side	Calculation includes walk, yellow-change, and red-clearance interval
City of Tucson	8.0 sec is most common	3.5 fps; 3.0 fps at some locations	N/A	Yellow-change interval
Maricopa County	5.0–7.0 sec	3.5 fps	Curb to curb	Yellow-change and red-clearance intervals
Pima County	7.0 sec	3.5 fps	Along centerline of crosswalk	Yellow-change and red-clearance intervals

Recommendations

The findings within this study, specifically within the pilot-study portion of the project, have informed the following suggested changes to ADOT's TGP Section 600 Subsection 621 (Signal Phase-Change Intervals) and Subsection 622 (Left Turn Signal Timing). The suggested changes are presented with red text and a box outline within the existing TGP documents. The suggested changes aim to achieve the following:

- Synthesize the guidelines and processes documentation with the findings of the previous tasks.
- Improve comprehensive documentation by providing definitions and equations referenced by the documentation.
- Provide updated guidance in accordance with the 7th and most recent edition of the ITE's' *Traffic Engineering Handbook*. Note that while this handbook recommends the 85th percentile speed be used for the speed assumption, this does not align with the findings of the previous tasks. To better align the proposed changes with the pilot study's findings, the posted speed is recommended for use as the speed assumption in the ITE recommended equations. This is the only proposed change that deviates from the ITE *Traffic Engineering Handbook*.

621 SIGNAL PHASE-CHANGE INTERVALS

This guidance shall apply to all calculations of yellow and all-red timing, with the exception of those for protected-only left turn movements. For calculation of yellow and all-red timing for protected-only left-turn movements, see TGP 622.

These formulae shall be utilized for all applicable signal phase-change interval calculations performed on or after the date of approval of these guidelines.

621.1 PHASE CHANGE AND CLEARANCE INTERVALS

Vehicle phase change and clearance intervals are intended to provide a uniform and orderly transition between two conflicting phases. It consists of a yellow change interval and a red clearance interval.

The yellow vehicle-change interval should be followed by an all-red clearance interval of sufficient duration to permit the intersection to clear before cross traffic is released. **The length of the yellow vehicle-change interval and the all-red clearance interval shall be established on the basis of these guidelines and engineering judgment.**

ADOT uses the Institute of Transportation Engineers' (ITE) *Traffic Engineering Handbook (7th Edition)* formulas for phase change intervals; these formulas are general and should only be used as a guide. Other factors at an intersection (such as approach grades, visibility, truck traffic, and local traffic characteristics) should be considered. It is important that approach grades and truck traffic are considered in determining the yellow and red intervals. The yellow change interval must not be too short (causing quick stops and/or red violations) nor too long (encouraging vehicles to enter late in the yellow interval).

An engineering study may be used to determine the approach speed. The posted speed limit may be assumed to be the approach speed when an engineering study is not available.

Yellow Change Interval

The intent of the steady yellow interval is to warn traffic of an impending change in the right-of-way assignment. Yellow vehicle-change intervals should have a range of 3 to 6 seconds.

The following formula from the ITE *Traffic Engineering Handbook (7th Edition, Equation 10-1)* may be used to determine the yellow vehicle-change interval time.

Minimum yellow vehicle-change interval = $Y = t_1 + t_2$*, rounded to the nearest 0.1 second.*

Reaction time $t_1 = 1\,sec$

$$t_2 = \frac{1.47V}{(2a + 64.4g)}$$

where: t_1 = perception-reaction time; first component for computing length of yellow change interval

t_2 = time needed to comfortably decelerate to a stop; second component for computing length of yellow change interval; rounded to the nearest 0.1 second

g = % grade divided by 100 (downhill is negative grade)

a = deceleration rate of 10 feet per second per second

V = posted speed in miles per hour

Experience has shown that a perception-reaction time t_1 of one second (1 sec) is realistic. Also, deceleration rates of 8 and 12 feet per second per second are the lower and upper limits for establishing vehicle-change intervals. Typically, drivers in large urban cities will exhibit higher rates of deceleration than drivers in smaller towns or on rural highways. For typical applications, a deceleration rate (a) of 10 feet per second per second will be used in calculating the yellow vehicle-change interval. Note: While the 7th Edition of the ITE *Traffic Engineering Handbook* equation is referenced, the recommended velocity is the posted speed (mph) rather than the ITE Handbook's suggested 85th percentile approach speed (mph).

Red Clearance Interval

The red clearance interval is an interval at the end of yellow change interval during which the phase has a red-signal display before the display of green for the next phase.

The intent of this interval is to allow time for vehicles that entered the intersection during the yellow change interval to clear the intersection prior to the next phase.

The following formula from the ITE *Traffic Engineering Handbook (7th Edition, Equation 10-2)* may be used to determine the red time.

All-Red Clearance Interval

$$R = \frac{W + L}{1.47V}$$

where: R = red clearance interval length, to the nearest 0.1 second

V = posted speed in mile per hour

W = intersection width (ft), stop bar to far edge of the farthest conflicting lane

L = length of vehicle (ft), assumed to be 20 feet

Phase Change Interval

Total Phase Change Interval $= Y + R$

where: Y = length of the yellow vehicle-change interval

R = red clearance interval length, to the nearest 0.1 second

PEDESTRIAN INTERVALS

A. WALK Indication

The WALK indication should be at least 7 seconds in length so that pedestrians will have adequate opportunity to leave the curb or wheelchair ramp before their clearance interval is shown. A WALK interval of more than 7 seconds may be used for moderate to heavy pedestrian volumes.

B. DON'T WALK Indication

A flashing DON'T WALK indication shall always succeed the WALK indication to provide pedestrian clearance. The pedestrian clearance time shall be calculated from the following equation:

Pedestrian Clearance Time (rounded up to nearest whole second)

$$= \frac{P}{w} - Y$$

where: P = distance from curb to curb or center of wheelchair ramp radius to center of wheelchair ramp radius along center of crosswalk, in feet

w = normal walking speed, assumed to be 3.5 feet per second (fps)

Y = length of the yellow vehicle-change interval

Research verifies that 1/3 of all pedestrians cross streets at a rate slower than 4.0 fps and 15% walk at or below 3.5 fps. The timing of pedestrian signal indications near facilities that serve segments of the population with slower walking speeds should be calculated based on a slower walking speed. Such populations should be anticipated near shopping centers, convalescent or rest homes, therapy centers, elementary schools, etc. A walking speed of less than 3.5 fps (but no less than 3.0 fps) should be considered if senior citizens, pedestrians in wheelchairs, school children, or other slower-moving pedestrian populations are in the majority at a specific crosswalk (MUTCD Section 4E.06 Guidance 10). If an extended pushbutton press function has been installed to provide slower pedestrians with a longer pedestrian-clearance time, then walking speeds of 4.0 fps may be considered by the Traffic Operations Engineer.

On a street which has an island or median of 6 feet or greater width, the pedestrian-clearance time may be computed to provide only enough time to clear the crossing from the curb to the median. **In such cases, an additional detector shall be provided on the island.**

622 LEFT TURN SIGNAL TIMING

This guidance shall only be applicable to protected-only left turn movements. For the timing of all other movements, see TGP 621.

These formulae shall be utilized for all applicable signal phase change interval calculations performed on or after the date of approval of these guidelines.

622.1 PHASE CHANGE AND CLEARANCE INTERVALS

Vehicle phase change and clearance intervals are intended to provide a uniform and orderly transition between two conflicting phases. The full phase change and clearance interval cycle consists of a yellow change interval and a red clearance interval.

The yellow vehicle-change interval should be followed by an all-red clearance interval of sufficient duration to permit vehicles within the intersection to clear before cross traffic is released. **The length of the yellow vehicle-change interval and the all-red clearance interval shall be established on the basis of these guidelines and engineering judgment.**

ADOT uses the Institute of Transportation Engineers' (ITE) *Traffic Engineering Handbook (7th Edition)* formulas for phase change intervals; these formulas are general and should only be used as a guide. Other factors at an intersection (such as approach grades, visibility, truck traffic, and local traffic characteristics) should also be considered. It is important that approach grades and truck traffic are considered when determining the yellow and red intervals. The yellow change interval must not be too short (causing quick stops and/or red violations) nor too long (encouraging vehicles to enter the intersection late in the yellow interval).

An engineering study may be used to determine the approach speed. The posted speed limit may be assumed to be the approach speed when an engineering study is not available.

Yellow Change Interval

The yellow change interval*, Y, rounded to the nearest 0.1 second,* may be calculated using the ITE *Traffic Engineering Handbook* formula *(7th Edition, Equation 10-1)* to determine and sum the values of t_1 and t_2:

$$t_1 = 1\ sec$$

$$t_2 = \frac{1.47v}{(2a + 64.4g)}$$

where:

t_1 = perception-reaction time; first component for computing length of yellow change interval

t_2 = time needed to comfortably decelerate to a stop; second component for computing length of yellow change interval, rounded to the nearest 0.1 second

g = % grade divided by 100 (downhill is negative grade)

a = deceleration rate of 10 feet per second per second

v = posted speed in miles per hour (mph)

The minimum yellow change interval shall be 3.0 seconds but should not exceed 6.0 seconds. Note: While the 7th Edition ITE *Traffic Engineering Handbook* equation is referenced, the recommended velocity is the posted speed (mph), rather than the ITE Handbook's 85th percentile approach speed (mph).

Red Clearance Interval

In the case of a left-turning vehicle, the distance through the intersection is measured from the near-side stop line to the far edge of the last conflicting traffic lane along the left-turning vehicle path.

The typical intersection speed for left-turning vehicles is assumed to be 25 mph for conventional intersections and diamond interchanges. For single-point diamond interchanges, the typical intersection speed for left-turning vehicles is assumed to be 30 mph. A different speed may be used at complex intersections, such as at multi-legged intersections and at skewed intersections.

The following formula may be used to determine the red clearance interval, based on the ITE *Traffic Engineering Handbook* formula (7th *Edition, Equation 10-2*):

$$R = \frac{W + L}{1.47V}$$

where: R = red clearance interval length, to the nearest 0.1 second

W = travel distance of left-turning vehicle, in feet, measured along the left-turning vehicle path from the point where the near-side stop line intersects the outermost left turn lane line, directly to the point where the extension of the outside edge of the receiving lane for the outermost turning movement intersects the extension of the outside edge of the outermost conflicting traffic lane. When measuring W, consideration should be given to the crosswalk location in relationship to the edge of the receiving lane.

L = length of vehicle, assumed to be 20 feet; and

V = speed of left turning vehicle through the intersection, assumed to be 25 mph for conventional intersections and diamond interchanges, and 30 mph for single-point diamond interchanges.

The minimum value for red clearance intervals shall be 1.0 second but should not exceed 6.0 seconds.

These formulas are general and should only be used as a guide. Other factors at an intersection (such as approach grades, visibility, truck traffic, and local traffic characteristics) may be considered. Approach grades and truck traffic may also be considered in determining the yellow change and red clearance intervals.

The yellow change interval should not be too short (causing quick stops and/or red violations) nor too long (encouraging vehicles to enter late in the yellow interval).

Findings

Assessment of Sites with Potential for Improvement

The assessment process involved identifying 20 signalized intersections in the Phoenix area and comparing their operating signal phase-change intervals with those calculated using the equations in ADOT TGP 621 and TGP 622. Some of the intersections were located at an interchange crossroad-ramp terminal. The operating signal phase-change interval values were obtained from the signal-timing cards, which document the signal timing data from the traffic signal controllers. Details of this comparison are in Appendix B. The following observations were made:

- Calculated “DON’T WALK” intervals were similar to the intervals on the timing cards. The minor differences are likely due to the use of aerial photography to measure intersection widths. At Intersections One (SR 347 and Cobblestone Farms Drive) and Nine (I-17 and Anthem Way), pedestrian detection was provided in the medians and the length of “DON’T WALK” indications could be reduced to improve vehicular operations.
- Calculated yellow-change intervals were consistent with the intervals on the signal-timing cards. In some cases, differences were found at ramp terminals and at other complex intersection configurations where additional guidance might be useful to provide a more consistent assumption for approaching speeds at this type of intersection.
- Calculated red-clearance intervals sometimes varied from the intervals on the signal-timing cards. This is likely due to differences in assumed approach speed and intersection widths, as well as the use of aerial photography for the calculations.

Quantify Safety Effect of the Interval Formula Change

Crash frequency was evaluated at 100 intersections both before and after the 2013 implementation of a new red-clearance interval formula for through and left-turn movements to assess the safety effect of the formula change. While the new formula was introduced in 2013, implementation at the intersections varied from 2014 to 2017. The 100 intersections were categorized into three groups: updated left-turn clearance interval (Group 1), updated left-turn and through clearance intervals (Group 2), and a control group with no updates to the interval formulas (Group 3). For each intersection, three years’ worth of crash data prior to the formula change were compared to at least one year of post-implementation crash data. In total, the data-collection effort resulted in a database with 18,662 total crashes from 2008 to 2019 across the study of 100 intersections. The comparisons were analyzed for a combination of crash and intersection types:

- **All intersections:** Grouped into total, left-turn, angle, and rear-end collisions.
- **SPUIs:** Assessed by total, left-turn, and angle collisions.
- **Diamond interchanges:** Analyzed by total and left-turn crashes.
- **Four-leg intersections:** Analyzed by total and left-turn crashes.

Detailed analysis results are in Appendix C. Overall, the results of the crash frequency analysis provided ambiguous results to assess the direct effect of the red-clearance interval changes on crash frequency. The following trends were identified:

- From 2008 to 2019, each group experienced an increase in crash frequency. This could be the result of external factors, including human factors (age, attention, experience), vehicle factors (design, maintenance), roadway and environmental factors (geometric and traffic features, travel exposure/demand), and increased vehicle miles traveled (VMT). The state highway system's VMT rose 12.8 percent in five years, from 77,837 in 2013 to 87,816 in 2017.
- For Group 2, there was an increase in crash frequency before the formula change and a decrease after the formula change for all crashes, left-turn crashes, and angle crashes.
- Crash frequency trends for Group 2 intersections, from before to after, were not as steep as Group 1 intersection trends, meaning the Group 2 crash decreases did not decline as much as Group 1's did.
- For angle crashes at all intersections, Group 2 experienced no change in crash frequency after the clearance interval changes were implemented, whereas Group 1 *increased* by 67 percent. Therefore, the left-turn and through clearance interval modifications may have had a more positive effect in reducing angle crashes compared to the sites where only left-turn clearance interval modifications were implemented.
- As part of the analysis, 13 SPUIs were evaluated in more detail for left-turn and angle crash frequency. The modified SPUIs providing access to Interstate 17 (I-17) experienced a large variability in the number of crashes that occurred from year to year, even after the updated clearance interval change was implemented. As such, it is unclear if the updated intervals influenced the crash frequency at traffic interchanges where the distance from stop bar to stop bar is over 200 feet.

Pilot Study: Planning, Designing, and Implementation

Site Selection, Site Characteristics, and Traffic Characteristics

The purpose of the pilot study was to assess potential modifications to the ADOT guidelines for computing the yellow change and red-clearance intervals. Data were collected at 12 sites; an intersection approach is considered a site. A site includes the through phase and, if the left-turn operates as protected only, the left-turn phase serving the subject approach. Therefore, data were collected for the through and the protected left-turn movements. The selected sites provided a range of design, traffic, and operating conditions. The selected sites were located in urban environments and have leading left-turn phasing. The sites selected include the three most common intersection types within the state highway system: SPUI, diamond interchange, and conventional intersection. The sites selected include the following:

- **I-17 and Dunlap Avenue:** SPUI; northbound ramp terminal with frontage road.
- **U.S. Route 60 and 91st Avenue:** Conventional intersection; southbound approach.
- **Interstate 10 (I-10) and Warner Road:** Tight diamond interchange; southbound approach.
- **I-17 and Anthem Way:** Tight diamond interchange; northbound approach.
- **State Route 87 (SR 87) and Fort McDowell Road:** Conventional at-grade intersection; northbound approach.
- **SR 87 and Shea Boulevard:** Conventional at-grade intersection; eastbound approach.
- **I-10 and 7th Avenue:** SPUI; eastbound ramp terminal.
- **I-10 and 7th Street:** SPUI; eastbound ramp terminal.
- **I-10 and 7th Street:** SPUI; southbound cross-street.
- **I-17 and Camelback Road:** SPUI; northbound ramp terminal with frontage road.
- **I-17 and Camelback Road:** SPUI; westbound cross-street.
- **State Route 101 (SR 101) and Peoria Avenue:** Diamond interchange; westbound approach.

Site characteristics data were collected using current aerial photography and signal-timing cards provided by ADOT (Table 6). Traffic-characteristics data were collected using on-site video collection. Details on camera placement and which cameras collected which traffic elements are in Appendix D. Data were collected during a 5-hour period at each site, except at Site 1. At Site 1, I-17 at Dunlop Avenue, four hours of data were collected. This time period included at least one peak traffic hour and occurred during dry weather conditions. Up to five hours of data were extracted from the video. The Methods section details the data elements that were collected.

Table 6. Site Characteristics Data

Site No.	Speed Limit (mph)	Left-Turn Movement Yellow Change (sec)	Left-Turn Movement Red Clearance (sec)	Left-Turn Movement Clearance Distance (ft)	Through Movement Yellow Change (sec)	Through Movement Red Clearance (sec)	Through Movement Clearance Distance (ft)
1	NP	3.0	8.7	290	3.9	2.5	160
2	45	3.0	3.8	115	4.3	1.9	110
3	NP	3.9	1.9	105	None	None	None
4	NP	4.3	2.3	130	None	None	None
5	65	3.1	3.9	105	5.8	2.0	110
6	45	4.3	5.6	180	None	None	None
7	NP	3.9	4.3	220	None	None	None
8	NP	3.6	3.4	200	None	None	None
9	35	3.0	4.3	220	3.6	3.8	215
10	NP	3.0	8.5	275	3.9	2.1	140
11	35	3.0	8.6	280	3.6	6.8	370
12	40	3.9	4.0	120	3.9	1.0	115

NP – not posted.

Analysis of Site and Traffic Characteristics

At the 12 selected sites, key metrics were evaluated to assess the safety performance of the yellow-change and red-clearance intervals. The selected intersections reflect several common intersection types with a range of geometrics, traffic volumes, and vehicle operating speeds. The results obtained from this analysis guided the development of proposed modifications to be evaluated in the pilot study (Table 7). Further details on the analysis and results are provided in Appendix E.

Table 7. Results from Site and Traffic Data Analysis and Pilot Study Recommendations

Interval	Results	Pilot Study Recommendations
Left-turn Yellow-change Interval	At diamond interchanges and conventional intersections, applying a higher left-turn yellow-change interval than the ADOT TGP (Subsection 622, Year 2018) calculation may decrease the potential for red-light violations. At SPUIs, applying a higher left-turn yellow-change interval than the ADOT TGP calculation may increase the potential for rear-end crashes.	Increase the speed used to calculate left-turn yellow-change intervals from 25 mph to the posted speed on the intersection approach. This change will increase the yellow-change interval by up to approximately 2.8 sec.
Left-turn Red-clearance Interval	At SPUIs, utilizing a lower left-turn red-clearance interval than the ADOT TGP (Subsection 622, Year 2018) recommendation may reduce the potential for red-light violations and angle crashes. The entry speed data indicates that a higher speed (than the ADOT TGP recommended 25 mph) may be more appropriate when calculating red-clearance intervals at SPUIs.	At SPUIs, increase the entry speed to 30 mph for calculating the red-clearance interval. This change will reduce the interval by up to approximately 1.3 sec.
Through Yellow-change Interval	At diamond interchanges and conventional intersections, no correlation was found with the performance measures evaluated in this study.	No proposed changes.
Through Red-clearance Interval	The through movement entry speed data supports the use of the posted speed limit in calculating the red-clearance interval at conventional intersections. The use of a lower speed may potentially be considered at diamond interchanges and SPUIs.	No proposed changes.

Pilot Study Before-and-after Comparison

Based on the results of the site and traffic characteristic data analysis (Table 7), the yellow-change and red-clearance intervals were calculated for the pilot study. These calculated values were compared to the existing intervals on the timing cards. The change in total clearance time (sum of yellow-change intervals and red-clearance intervals) ranged from a reduction of 0.6 sec to an increase of 1.9 sec for the study sites. Details on this comparison are provided in Appendix F.

The pilot intervals were integrated in the field, then two months later data were collected, to allow enough time for drivers to adapt to the pilot study changes. There were 11 left-turn movements and seven through movements included in the before-and-after comparisons. The left-turn movement data were not successfully collected for the intersection at I-10 and Warner Road (Site 3) and, therefore, these data were not included in the pilot study. For the left-turn movement data collected at the intersection of I-17 and Dunlap Avenue (Site 1), data from before the pilot intervals were integrated came from four-hour observation periods, as opposed to the five-hour observation periods utilized later.

Three methods were used to perform the before-and-after comparison: the naïve approach, an approach accounting for changes in traffic flow and signaling cycle length and regression analysis of yellow and red-entry rate.

Naïve Approach

The naïve approach assumes that any observed changes were the result of changes to the signal-timing parameters. Details on the results of the naïve-approach comparison are in Appendix F. The volumes, observed yellow entries, and observed red entries for before-and-after periods were recorded for the 11 left-turn movement sites and seven through movement sites. In addition, the original and proposed intervals were compared. The following trends were observed in the left-turn movement site data:

- On average, the proposed changes in yellow and red intervals resulted in 18.11 percent longer yellow-change intervals, which corresponded to a 61 percent increase in yellow entries and 3.81 percent shorter red-clearance intervals compared to before.
- Both the increases in yellow-change intervals and decreases in red-clearance intervals for left-turn movements contributed to an 18.3 percent decrease in red entries.
- The increase in yellow entries at the intersection of I-17 and Dunlap Avenue was notably high, going from 27 yellow entries before integrating the pilot intervals to 348 yellow entries in the after period. However, this is partially due to the observations from before integration being only four-hour periods, while after integration the observation periods were five hours long. Moreover, the pre-integration data for this site were collected in late 2020, when traffic volumes were significantly impacted by the COVID-19 pandemic. For these reasons, this intersection is considered an outlier for left-turn-movement evaluation.

The following trends were observed in the through movement site data:

- On average, the proposed changes in yellow-change and red-clearance intervals resulted in no change (i.e., 0 percent) to the yellow-change interval duration and a 25.87 percent increase in the red-interval duration. This increase in red-interval duration is due to differences in the intersection width at some locations, as those distances were based on the legal definition of an intersection (i.e., before integration, the intersection width was measured from curb to curb, but measurement guidelines changed by the time of post-integration data collection).
- The observed total yellow entries were 1.22 percent higher after integration, while the observed total red entries were 30.95 percent lower.

Flow and Cycle Length Correction

Details on the results of the flow and cycle length correction comparison method are given in Appendix F. The following trends were observed:

- For left-turn movements, increases in red-clearance intervals correlated with an increase in the number of red entries. This interpretation applies to red-clearance interval changes between –1.7 and 1.7 sec. For through movements, increases in red clearance in the range of 0.0 to 0.9 sec did not significantly increase the frequency of red entries.
- For left-turn movements, increases in yellow-change intervals tended to decrease the number of red entries. This interpretation applies to changes in the yellow-change intervals of between –0.5 and 0.9 sec.
- Increases in yellow-change intervals tended to correlate with decreases in yellow entries. This interpretation applies to yellow-change intervals of between –0.4 and 1.3 sec.

Regression Modeling

Regression models for expected red-clearance entry frequency (number of vehicles observed when their front axle crossed the stop bar during red indication) and expected yellow-entry frequency (number of vehicles observed when their front axle crossed the stop bar during the yellow-change interval) were developed. All regression model coefficients (*b*) are in Appendix F. The *b* coefficients describe the change in an entry rate (yellow or red) due to changes in the interval (yellow change or red clearance) duration. The key results of the red-clearance entry frequency statistical analysis are the following:

- The b_0 coefficient of 0.64, which is lower than 1.0, indicates that the red-entry rate for lefts decreased by 36 percent from “before” to “after” periods due to factors other than the change in yellow-interval duration, red-interval duration, traffic volume, or signal-cycle length.
- The coefficient b_1 is statistically significant. Its value of 0.11 indicates that increases in red-clearance interval duration are expected to increase the red-entry rate during red-clearance. This interpretation applies to red-clearance interval changes between –1.7 and 1.7 sec.

- The positive coefficient b_2 indicates that increases in yellow time intervals tended to decrease entry rates during the red-clearance interval. However, the magnitude of this effect varies widely among the study sites and the value of the coefficient is not significant. This interpretation applies to yellow-interval changes between 0.1 and 1.6 sec. Note that Site 2 is the only site with a yellow change greater than 0.6 sec, which suggests a reversal of trend. This is possibly an outlier.
- The coefficient b_3 for through movements is statistically significant. This coefficient indicates that through movements have smaller entry rates during the red-clearance interval than left movements (probably due to left movements typically having higher delay than through movements).

The key results of the yellow-entry frequency statistical analysis are the following:

- The b_0 coefficient of 1.06, which is greater than 1.0, indicates that yellow-entry rates increased by 6 percent from "before" to "after" periods due to factors other than the change in yellow-interval duration, traffic volume, or signal-cycle length.
- The coefficient b_1, for the change in yellow-change interval duration, is insignificant. The coefficient value indicates that increases in yellow-interval duration tended to decrease the entry rate during the yellow interval, but the magnitude of the effect varies widely among sites. This interpretation applies to yellow-interval changes between –0.4 and 1.3 sec based on the study sites.

Conclusion

A pilot study was conducted to evaluate the effects of the proposed yellow-change and red-clearance interval changes. The major findings are the following:

- For left-turn movements, increases in the red-clearance interval tended to increase the red-entry frequencies (i.e., the frequency of vehicles crossing the stop line during the red-clearance interval).
- For through movements, increases in the red-clearance intervals between 0.0 and 0.9 sec did not appear to significantly increase the frequency of red entries.
- For left-turn movements, increases in the yellow-change intervals up to 1.3 sec appear to *decrease* the frequency of yellow entries.

Assessment of Sites with Potential for Improvement

The goal of this project component was to identify potential strategies to improve operational or safety challenges related to vehicular and/or pedestrian-clearance intervals. ADOT provided a list of 20 intersections experiencing operational challenges that were possibly related to their current yellow-change, red-clearance, or pedestrian-clearance intervals. For the selected 20 intersections, ADOT provided signal-timing cards and phasing diagrams. The 20 intersections were:

- John Wayne Parkway (State Route 347) and Cobblestone Farms Drive (4-legged intersection)
- I-10 and 67th Avenue (diamond interchange)
- I-10 and Queen Creek Road (diamond interchange)
- I-17 and Bell Road (diamond interchange)
- I-17 and 19th Avenue (diamond interchange)
- I-17 and Bethany Home Road (modified SPUI)
- I-17 and Deer Valley Road (diamond interchange)
- I-17 and Peoria Avenue (diamond interchange)
- I-17 and Anthem Way (diamond interchange)
- I-17 and Thunderbird Road (diamond interchange)
- Grand Avenue (State Route 60 [SR 60]) and 75th Avenue (6-legged intersection)
- Grand Avenue (SR 60) and Peoria Avenue (4-legged intersection)
- Grand Avenue (SR 60) and Myrtle Avenue (4-legged intersection)
- Grand Avenue (SR 60) and 51st Avenue (5-legged intersection)
- Grand Avenue and State Route 303 (folded diamond interchange)
- Agua Fria Freeway (SR 101) and Peoria Avenue (diamond interchange)
- Agua Fria Freeway (SR 101) and Camelback Road (SPUI)
- Agua Fria Freeway (SR 101) and Northern Avenue (diamond interchange)
- Superstition Freeway (US 60) and Kings Ranch Road (3-legged intersection)
- Superstition Freeway (US 60) and Goldfield Road (diamond interchange)

For each site, aerial photography was obtained and used to measure the clearance distances required for each intersection, including the phase movement as illustrated in the ADOT Traffic Signal Clearance Interval Sheet, which is included in Appendix B. Additionally, posted speed data and the presence or absence of pedestrian signals in the medians were collected for each approach of the 20 selected sites. At locations where speed limits were not posted, speed data were obtained from the field calculations documented in the ADOT Traffic Signal Clearance Interval Sheet.

Quantify Safety Effect of the Interval Formula Change

The goal of this project component was to quantify and evaluate the effects of the new red-clearance interval formula on intersection safety for both through and left-turn movements, adopted by ADOT in 2013 for signalized intersections. All signalized intersections in the state's highway system were considered for this evaluation, and information provided by ADOT was used to identify intersections where the clearance intervals were altered to reflect the new formula. Signalized intersections within the state's highway system that remained unchanged were used as experimental controls, as were signalized intersections located outside of the state's highway system that did not adopt and implement the new clearance interval formula. Intersections that installed red-light camera enforcement in 2010 or later were omitted from evaluation.

One hundred intersections were chosen for analysis. Crash data from both the three years preceding and the three years after the clearance interval adjustment was implemented were obtained from the Arizona Crash Information System (ACIS) for each of these 100 intersections. The implementation dates vary among the 100 intersections—some signal timing changes took place between 2013 and 2014, while other clearance interval changes took place between 2016 and 2017. Crashes that occurred during the years of implementation were not included in the evaluation. The crash data collected for this study were used to quantify the changes in safety that may have taken place. The 100 intersections represented four intersection types: SPUIs, modified SPUIs, diamond interchanges, and conventional intersections (both major-major roadway intersections and major-minor roadway intersections). The 100 intersections were categorized into three groups:

- **Group 1: Updated left-turn clearance intervals.** This group includes intersections where the red-clearance interval was adjusted for left-turn movements. The signal clearance modifications were implemented in 2013 and 2014. Group 1 includes 37 locations: nine SPUIs, 16 diamond traffic interchanges (TIs), and 12 conventional intersections.
- **Group 2: Updated left-turn and through clearance intervals.** This group includes intersections where the red-clearance interval was adjusted for left-turn and through movements. The signal clearance modifications were implemented in 2017 and 2018. Group 2 includes 22 locations: one SPUI, four diamond TIs, and 17 conventional intersections.
- **Group 3: Control group.** This group includes intersections where red and through clearance intervals remained unchanged for the last ten years. Group 3 includes 41 locations: three SPUIs, seven diamond TIs, and 31 conventional intersections.

Crash frequencies were evaluated both before and after the implementation of a new red-clearance interval formula for through and left-turn movements to assess the safety effect of the formula change. Intersection crash data was gathered from ACIS for all study intersections. Group 1 crash data were collected for 11 years, ranging from 2008 to 2018. Group 2 crash data were obtained for 2011 through the first six months of 2019. Group 3 crash data for intersections within the City of Phoenix, City of Mesa, City of Goodyear, City of Scottsdale, City of Tempe, and the City of Tucson were collected for the years from 2008 to 2018. For each intersection, three years' worth of crash data prior to the formula change were compared to at least one year of post-implementation crash data. The crash reports provide information including collision manner, lighting conditions, first harmful event, total units involved (motorists and non-motorists), total injuries and fatalities, highest injury severity, alcohol involvement, drug involvement, etc. Collision manner and number of crashes were the key elements used to perform the before-and-after study analysis.

Pilot Study: Planning, Designing, and Implementation

The goal of this project component was to plan, design, and implement a pilot study to inform final recommendations for future revisions of ADOT TGP documents, that they might address those issues caused or impacted by current documentation:

1. ADOT's guidelines lead to lengthy red-clearance intervals at interchanges with large conflict areas (e.g., SPUIs).
2. ADOT's guidelines give a standard calculation for the duration of the yellow-change interval that may have unintended impacts on intersection safety for some conditions (e.g., high-speed approaches).

This section discusses the data-collection and analysis methods used to evaluate safety at a range of intersection configurations for the purpose of identifying parameters to integrate in the pilot study. The key components of this step include selecting intersections, selecting data elements for collection, data-reduction methods, and data-analysis methods. This section also discusses methods that were used for integrating and monitoring the pilot study. The ultimate goal of the pilot study is to inform the development of a formal set of recommendations for changes to the ADOT interval calculation guidelines.

Site-selection Criteria

The first step was determining site-selection criteria. A site was defined as a single approach to an intersection. A list of site factors and the associated levels within each factor were identified. The goal of the site-selection process was to include at least one—or, preferably, more—site for each level of each factor. The candidates in both the sites assessment and before-and-after comparison were also considered for use in this part of the study. The following list identifies the site factors and associated levels within each factor:

- Area type (urban)
- Left-turn phase operation (protected, leading)
- Intersection type (SPUI, tight diamond interchange [<400 ft between ramps], at-grade intersection with multi-lane major street, intersection with a two-lane major street)
- Intersection leg location (minor street approach, major street approach, ramp approach)
- Speed limit (35–40, 45–50, ≥55 mph)

The study sites were selected based on their suitability for study and the need to control for (i.e., exclude) the effect of factors that are not directly relevant to the scope of this study. The following additional criteria were established to guide the selection of study sites:

- Adequate distribution of sites by the key site factors.
- Adequacy of the site for study equipment (e.g., camera) placement.
- Relatively straight intersection approaches.
- Good (or better) quality ratings of lane-line and stop-line markings.
- A lane or bay is available for the exclusive use of the left-turn movement.
- No signalized intersection within 0.5 miles of the selected intersection.

To ensure a wide geographic distribution of the sites, it was decided that no more than two sites (i.e., approaches) would be selected per intersection. Eventually, 12 sites were selected.

Data Elements for Collection

Site Characteristics

The five site characteristics identified for data collection at the 12 study sites are as follows:

- **Clearance distance:** Measured in a straight line from the stop line to the outside edge of the furthest conflicting vehicle travel lane. Measure for left-turn and through movements.
- **Left-turn travel distance:** Measured along the travel path from the stop line to the outside edge of the furthest conflicting (i.e., outside opposing through) vehicle travel lane. Measure for left-turn movements.
- **Stop line to conflict area distance:** Measured from the stop line to the curb line extension of the cross-street.
- **Approach speed limit:** Identified by review of the nearest posted speed limit sign located in advance of the intersection and in the subject direction of travel.
- **Duration of yellow-change interval and red-clearance interval:** Ability to observe the subject left-turn and through signal heads during the same hours of the day that traffic-characteristics data were collected.

The values of the yellow-change, red-clearance, and pedestrian-clearance intervals were provided by ADOT.

Site characteristic data that require measurement in the field by the research team were not measured on the same day as the traffic-characteristics data were collected. This restriction ensured that the behavior of the observed drivers was not affected by the researchers' presence.

Traffic Characteristics

The traffic characteristics identified for collection required the use of video. This subsection discusses camera placement and the data elements collected at each camera location.

Camera Locations

Traffic characteristic data were collected at each site using video. One video camera was located upstream of each intersection's stop line and pointed toward the intersection. The camera was positioned to allow for observation of (1) the vehicles traveling toward the intersection and (2) the signal indication. The location of this upstream camera is shown in Figure 5. The cameras were located 300 to 600 feet ahead of the intersection depending on specific site needs, with longer distances used for higher speeds. The cameras were mounted to provide an unobstructed view of all vehicles between the camera and stop line.

A second video camera was located at the intersection and pointed at the intersection, as shown in Figure 6. Also, at each SPUI location, a third video camera was used. The camera was positioned to allow for observation of the left-turn and through movements as they cross the stop line and travel through the intersection. The location of this downstream camera is shown in Figure 6. The cameras were mounted to provide an unobstructed view of the stop line and intersection conflict area.

The clocks associated with each video camera were synchronized to a common time prior to the start of the study. This action facilitated the tracking of vehicles as they traveled from the upstream cameras' field of view and into the field of view of the downstream cameras.

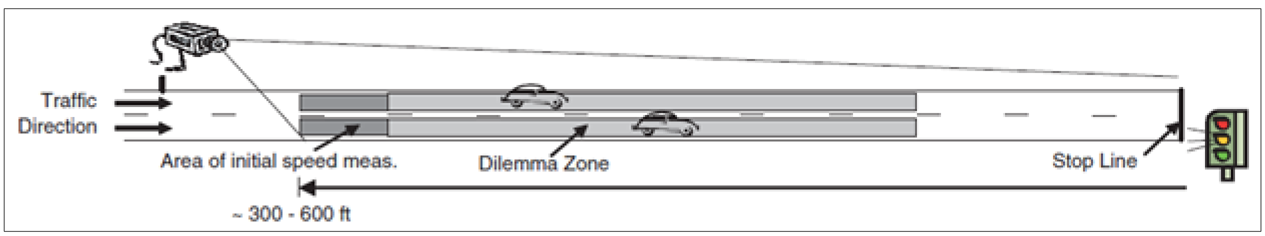

Figure 5. Upstream Video Camera Location and Field of View

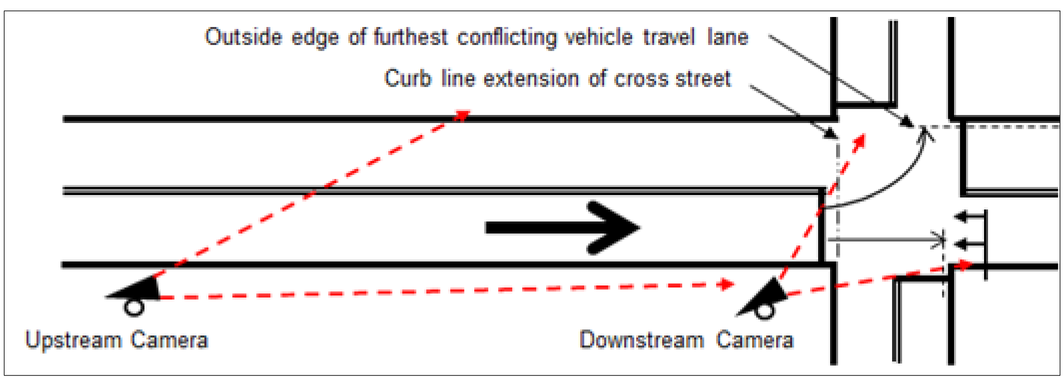

Figure 6. Upstream and Downstream Video Camera Locations and Fields of View

Upstream Camera Data

The speed of each vehicle on approach to the intersection was measured at the speed-measurement reference point (SMRP), which was located approximately 7.5 sec in travel time upstream from the stop line (based on the approach's speed limit).

All event data were measured to the one-hundredth of a second (i.e., HH:MM:SS.ss). The upstream video recording was used to extract the following traffic data for each vehicle that approached the intersection:

- Clock time (in HH:MM:SS.ss) at which the front axle of the vehicle crossed the SMRP.
- Clock time (in HH:MM:SS.ss) at which the front axle of the vehicle crossed the second reference point (2RP). Spot speed was then computed from the travel time between the SMRP and 2RP. Spot speed is defined as the instantaneous speed of the vehicle at the second reference point.

All upstream traffic data extracted from the video were recorded in a spreadsheet where one row in the spreadsheet represents one vehicle on the intersection approach. Signal-cycle event data extracted from the video were recorded in a spreadsheet where one row in the spreadsheet represents one signal cycle serving the intersection approach.

Downstream Camera Data

The downstream video recording was used to extract traffic data for left-turn and through vehicles that crossed the stop line. A vehicle was determined to have entered the intersection when its front axle crossed the stop line.

Data was not collected during the green signal indication. All downstream traffic data extracted from the video was recorded in a spreadsheet where one row in the spreadsheet represents one vehicle on the intersection approach.

Data-collection Period and Constraints

Data was collected during a 5-hour period at each site. This time included at least one hour of peak traffic. Data collection occurred during dry weather conditions and excluded periods when emergency vehicles were present.

Crash Characteristics

Crash data elements were intended to be collected and used to perform a crash analysis. However, there were not enough available crash data to perform an analysis and obtain reliable results. This was a limitation of the study.

Data-reduction Methods

The collected data were used to compute two categories of variables. Category One consisted of key variables that were used to compute the yellow-change interval and the red-clearance interval based on the procedures in ITE’s *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020). Category Two included measures that were used to evaluate the performance of the yellow-change intervals and red-clearance intervals at the studied locations. Each of these variables can be categorized as a computed variable, reduced variable, independent variable, or a performance measure. This process is summarized in Figure 7.

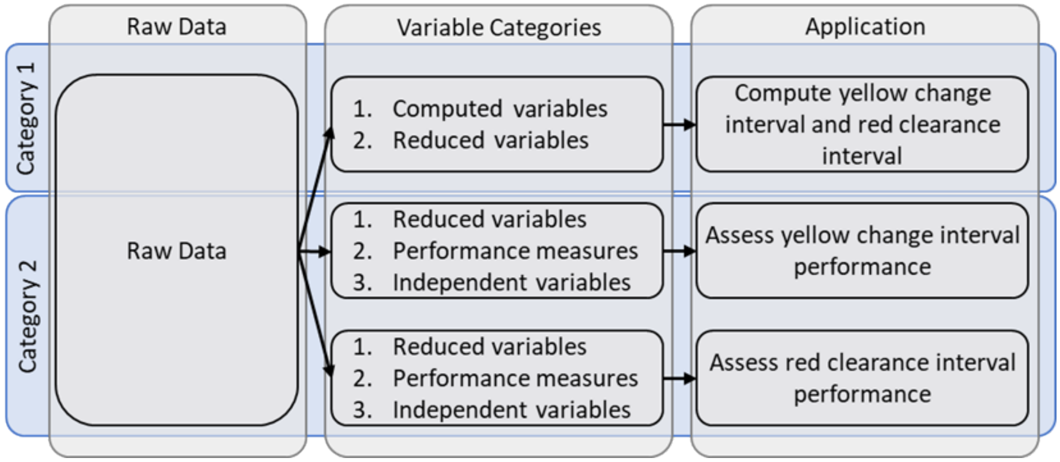

Figure 7. Flow from Raw Data to Reduced Data to Application

Category 1: Variables to Compute Yellow-change and Red-clearance Intervals

Reduced Variables

Vehicle speed is used to compute the yellow-change and red-clearance intervals. Specifically, approach speed and intersection-entry speed are needed for this purpose. Vehicle speeds were computed as percentile statistics that describe the traffic stream on the intersection approach. They included:

- 85th, median, and 15th percentile speed of free-flow vehicles at the SMRP (for vehicles that ultimately enter the intersection as a through movement).
- 85th, median, and 15th percentile speed of free-flow vehicles at the SMRP (for vehicles that ultimately enter the intersection as a left-turn movement).
- 85th, median, and 15th percentile through vehicle travel time through the conflict area.
- 85th, median, and 15th percentile left-turn vehicle travel time through the conflict area.

A free-flow vehicle is a vehicle that (1) has a headway of 8 sec or more to the vehicle ahead and 5 sec or more to the vehicle behind in the same traffic lane and (2) is not influenced (i.e., slowed) by traffic-control devices upstream (or downstream) of the SMRP.

Computed Variables

The speed measures identified in the previous section were used with the ITE's *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020) to compute the yellow-change interval and red-clearance interval for each left-turn and through movement at the studied sites. The yellow-change intervals and the red-clearance intervals computed in this manner are referred to as the ITE-based interval durations throughout this report.

Although not dependent on speed statistics, the procedure in the *ADOT Traffic Engineering Guidelines and Processes* (TGP 2018) document were used to compute the ADOT-based yellow-change interval and red-clearance interval for each left-turn and through movement for each of the studied sites.

Category 2: Variables to Assess Yellow-change Interval Performance

Reduced Variables

The performance measures needed to assess the level of safety afforded by the in-service yellow-change intervals were computed from the following variables:

- Count of left-turn vehicles entering the intersection during the yellow-change interval.
- Count of left-turn vehicles entering the intersection during the red-clearance interval.
- Count of left-turn vehicles entering the intersection during the green interval.
- Count of through vehicles entering the intersection during the yellow-change interval.
- Count of through vehicles entering the intersection during the red-clearance interval.
- Count of through vehicles entering the intersection during the green interval.
- Count of signal cycles (i.e., count of yellow-change intervals).
- Rear-end crash count associated with the left-turn movement.
- Rear-end crash count associated with the through movement.
- Red-light violation related crash count associated with the left-turn movement.
- Red-light violation related crash count associated with the through movement.

A vehicle is defined as having entered the intersection when its front axle crosses the stop line, as the stop line defines the near side of the intersection conflict area.

Performance Measures

These reduced variables were used to compute the following performance measures for both the left-turn movement and the through movement:

- Red-light violation rate (as violations per 1000 vehicles, per cycle, per 100 vehicle-cycles)
- Yellow-entry rate (as entries per 1000 vehicles, per cycle, per 100 vehicle-cycles)
- Rear-end crash rate
- Red-light violation related crash rate

Independent Variables

The following two independent variables were quantified and used as a basis for evaluating the yellow-change interval performance:

- Difference between the in-service yellow-change interval duration and the ITE-based yellow-change interval duration (i.e., in-service value – ITE-based value).
- Difference between the in-service yellow-change interval duration and the ADOT-based yellow-change interval duration (i.e., in-service value – ADOT-based value).

Intervals for the left-turn movement and through movement were separately evaluated.

Category 2: Variables to Assess Red-Clearance Interval Performance

Reduced Variables

Performance measures needed to assess the level of safety afforded by the in-service red-clearance intervals were also computed. These measures were computed from the following variables:

- Right-angle crash count associated with the left-turn movement.
- Right-angle crash count associated with the through movement.

The crash data gathered for each intersection was manually screened to determine which crashes were associated with the subject intersection approach. Each crash was also associated with a left-turn, through, or right-turn movement at the intersection.

Performance Measures

These reduced variables were used to compute the following performance measures for the left-turn movement and for the through movement:

- Right-angle crash rate.

Additionally, the following measures previously computed to assess yellow-change interval performance were also examined for their relationship to red-clearance interval performance:

- Red-light violation rate (as violations per 1000 vehicles, per cycle, per 100 vehicle-cycles).
- Red-light violation related crash rate.

Independent Variables

The following two independent variables will be quantified and used as a basis for evaluating the red-clearance interval performance:

- Difference between the in-service red-clearance interval duration and the ITE-based red-clearance interval duration (i.e., in-service value – ITE-based value).
- Difference between the in-service red-clearance interval duration and the ADOT-based red-clearance interval duration (i.e., in-service value – ADOT-based value).

Data-analysis Methods

The reduced data were used to assess the safety performance of the yellow-change intervals and red-clearance intervals at the intersections studied. Two analyses were undertaken. One analysis focused on the yellow-change interval. The second analysis focused on the red-clearance interval. Each analysis examined each performance measure, one at a time. Further details on these methods are given in Appendix E.

Yellow-change Interval Evaluation

The evaluation of yellow-change interval performance was based on two guideline documents. One is the ITE's *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020), which was used to compute the ITE-based interval durations. The second document is the *ADOT Traffic Engineering*

Guidelines and Processes (TGP 2018) document that was used to compute the ADOT-based interval durations. Each document was the basis for computing a difference in values that was used to serve as the independent variable in their respective performance evaluations.

Each performance variable was evaluated, one at a time, using the ITE-based interval duration and then using the ADOT-based interval duration. The insights obtained from this evaluation were used as a basis for developing proposed changes to the yellow-change interval calculation procedures in the ADOT signal timing design guidelines.

Red-clearance Interval Evaluation

The process outlined for evaluation of the yellow-change interval was repeated for the evaluation of the red-clearance interval. Each performance variable was evaluated (one-at-a-time) using the ITE-based interval duration and then using the ADOT-based interval duration. The insights obtained from this evaluation were used as a basis for developing proposed changes to the red-clearance interval calculation procedures in the ADOT signal timing design guidelines.

Speed Analysis

Speed data collected at study sites included approach speed, speed of left-turning vehicles within the intersection, and speed of through vehicles within the intersection. The collected data were intended to provide insight into potential changes to the speed used in the current ADOT TGP guidelines to calculate the yellow-change and red-clearance intervals. Where feasible, approach speeds were collected approximately 600 feet upstream of the stop line and included vehicles that were operating at free flow, where their speed was not impeded by a vehicle in front.

Pilot Study Methods

A pilot study was conducted to evaluate the proposed changes to the yellow-change, red-clearance, and pedestrian-clearance intervals. The effects of the proposed changes were evaluated based on the two following selected surrogate safety measures:

- **Yellow entry:** When the front axle of a vehicle crossed the stop bar during the yellow-change interval.
- **Red entry:** When the front axle of a vehicle crossed the stop bar during red indication.

Data collection during the pilot study (i.e., the data collected after the interval changes were integrated) followed the same procedures used to collect data from before integration. These data were collected two months after integration to allow drivers enough time to adapt to the changes. Three methods were used to analyze and compare the data from both before and after integration: the naïve approach, an approach accounting for changes in traffic flow and signal-cycle length, and a regression analysis based on yellow and red vehicle entry rate.

Naïve Approach

A naïve-approach analysis was conducted to assess any changes in safety that might have occurred after the signal-timing parameters (i.e., yellow-change and red-clearance intervals) were integrated, in comparison to safety data from before the interval changes were integrated. This approach assumed that any observed changes were the result of those signal-timing parameter changes. However, this assumption can only work if other contributing factors—such as traffic volumes, number of cycle lengths, weather conditions, road-user demographics, and types of vehicles comprising the vehicle fleet—stay the same in both periods. In reality, however, this is seldom the case. Therefore, comparisons made with the naïve-approach analysis method cannot distinguish between the effect of signal timing changes and other potential contributing factors (e.g., traffic volumes, number of cycles, etc.) that may have also changed.

Flow and Cycle-length Correction

This section compares the before-and-after measures of effectiveness (MOE) while accounting for the changes in traffic volumes and cycle lengths. The MOEs selected for the before-and-after evaluation include:

- Change in yellow-entry frequency, related to change in yellow-change interval duration.
- Change in red-entry frequency, related to change in yellow-change interval duration.
- Change in red-entry frequency, related to change in red-clearance interval duration.

The red-entry frequency MOE is used as an example to explain the analysis methodology.

Step 1: Predict the expected number of red entries for the "after integration" condition:

$$\hat{\pi} = Expected\ Entry_{aft} = Entry_{bef} \times \frac{Red_{aft}}{Red_{bef}} \times r_{ft}$$

Eq. 2

Where:

$\hat{\pi}$ = The estimated "after integration" red-entries expectation when π is the "after integration" observed red entries

$\frac{Red_{aft}}{Red_{bef}}$ = The correction factor of different red-clearance intervals for both "before integration" and "after integration" conditions.

r_{ft} = The correction factor of different traffic volumes for both "before integration" and "after integration" conditions, i.e.,

$$\frac{Volume_{aft}}{Volume_{bef}}$$

Eq. 3

Step 2: Estimate the variance (*Var*) of red entries for the "after integration" condition:

$$Var(\pi) = (\hat{\pi})^2 * \left(\frac{1}{Entry_{bef}} + \frac{Var\, r_{ft}}{r_{ft}^2}\right)$$

Eq. 4

Where:

$v^2\{Volume_{bef}\}$ = Coefficient of variation for volumes

Step 3: Estimate the expected change in red entries as a ratio:

$$\hat{\theta} = \frac{\frac{Entry_{bef}}{\hat{\pi}}}{1 + \frac{Var(\pi)}{\hat{\pi}^2}}$$

Eq. 5

The expected changes for entries observed in yellow change can be estimated following the same methodologies.

Regression Modeling

A regression model for the expected entry frequency during red-clearance intervals (Eq. 6) was estimated by including the changes in all red and yellow intervals and through movements as independent variables.

$$Expected\ Red\ Clearance\ entry\ frequency = b_0 + b_1 \times (\Delta R) + b_2 \times |\Delta Y - 0.6| + b_3 \times (Thru)$$

Eq. 6

Where:

ΔR = "after integration" minus "before integration" red-clearance interval in seconds

ΔY = "after integration" minus "before integration" yellow interval in seconds

Thru = 1 for through movement, or 0 otherwise

A regression model for the expected entry frequency for left-turn movements during yellow intervals (Eq. 7) was developed by including the changes in yellow intervals as the independent variables.

$$Expected\ Yellow\ Entry\ Frequency = b_0 + b_1 \times (\Delta Y)$$

Eq. 7

Where:

ΔY = "after"–"before" yellow interval in seconds

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