Traffic Signal Change and Clearance Interval Pooled Fund Study: Synthesis Report

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16. Abstract

Traffic signal controllers use yellow change and red clearance intervals at signalized intersections to alert drivers to impending changes in the right-of-way assignment between conflicting traffic movements. Determining appropriate change and clearance intervals (CCIs) is important at signalized intersections to ensure safe transfer of the right-of-way while minimizing lost time and therefore reducing intersection delay. To improve documentation and consistent implementation of CCI calculation methods in State and local agencies, the Federal Highway Administration is leading the Traffic Signal Change and Clearance Interval Pooled Fund Study. The pooled fund study sponsored a phase I study to develop a synthesis of knowledge on CCIs. The phase I study included a literature review and an agency benchmarking plan to synthesize existing research and agency practices and identify research gaps. Based on the review findings, this synthesis report presents eight research studies and the data needs to execute the research. The eight research studies include proposed methods for determining the CCIs and the CCI performance assessment.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS AND ACRONYMS

a	acceleration
AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
aacc	constant acceleration until vehicles reach the speed vmax when the signal turns green
adec	constant deceleration following the trajectory that, if uninterrupted, brings vehicles to a standstill at the stop line
ATSPM	automated traffic signal performance measure
Bp	indicator variable for back plate presence
BSM	basic safety message
C	cycle length
CAN	controller area network
CCI	change and clearance interval
CV	connected vehicle
D	length of free path
di	deceleration implied by speed limit and change interval duration
E	extension of effective green
FHWA	Federal Highway Administration
ft	foot
ft/s2	foot per second squared
g	approach grade
GPS	global positioning system
Hz	hertz
I	index of the exiting movement
IIHS	Insurance Institute for Highway Safety
IRB	institutional review board
ITE	Institute of Transportation Engineers
j	index of the entering movement
L	length of vehicle
l1	start-up lost time
Lp	clearance path length
lt	phase lost time
mph	miles per hour
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
NCUTLO	National Committee on Uniform Traffic Laws and Ordinances
NDS	naturalistic driving study
NHTSA	National Highway Traffic Safety Administration
NRC	predicted fatal and injury red-light-violation-related crash frequency for the subject approach
NRV	predicted average red light violation frequency
P	width of intersection
PET	postencroachment time
Q	approach flow rate

Qd	intersection leg annual average daily traffic
R	red clearance interval
Rc	red clearance interval duration
RCUT	restricted-crossing U-turn intersection
RLR	red light running
Rp	platoon ratio
RSU	roadside unit
s	second
S	minimum safe stopping distance
sec	second
sexit	distance a vehicle in the exiting movement must travel from the stop line to fully clear the conflicting zone
SGA	solid green arrow
SHRP 2	Second Strategic Highway Research Program
sPaT	signal phase and timing
SPUI	single-point urban interchange
SQL	Structured Query Language
SU	single unit
SUV	sport utility vehicle
SYA	solid yellow arrow
t	perception-reaction time
TAP	technical advisory panel
Tc	clearance time deviation
tclearance	red clearance interval, where i is the index of the exiting movement and j is the index of the entering movement
tentrance	entrance time for the entering movement
texit	exit time for the exiting movement
TOD	time of day
TRB	Transportation Research Board
ts	conflicting vehicular movement start-up delay
TTC	time to collision
UVC	Uniform Vehicle Code
v	approach speed
V	average running speed
V	speed of clearing vehicle
V	85th-percentile approach speed
V0	initial speed
v/c	volume-to-capacity ratio
Vc	speed of conflicting vehicle
VE	intersection entry speed
veh/h	vehicles per hour
V85	85th-percentile approach speed
vexit	speed of a vehicle in the exit movement that crosses the stop line at the last moment of the yellow signal
vmax	maximum speed
Vmph	average running speed

Vsl	approach speed limit
w	intersection width
W	distance to traverse the intersection width
W	intersection width
Y	minimum yellow change interval
Yc	yellow change interval duration

EXECUTIVE SUMMARY

Traffic signal controllers use yellow change and red clearance intervals (CCIs) at signalized intersections to alert drivers of an impending change in the right-of-way assignment between conflicting traffic movements. Appropriately determining the CCIs is important at signalized intersections to ensure the safe transfer of the right-of-way while minimizing lost time. The lost time during the CCI is the time between conflicting signal intervals when no vehicles can pass through an intersection. Change intervals minimize lost time, thereby reducing intersection delay while maintaining safe operations. Although shorter CCIs may not provide sufficient time for safe phase termination, longer CCIs can reduce intersection capacity and lead to high delays. Due to the importance of the subject, the industry has been discussing the CCI for 70 years. Even though researchers have studied the CCI over several decades, they hold contradictory opinions. The profession has not achieved consensus on how to determine CCI durations under a variety of operational conditions (e.g., approach speeds and lane configurations). Local laws that inconsistently define restrictive and permissive yellow intervals may exacerbate the contradictory opinions and lack of consensus. Local laws may also prevent agencies from using red clearance intervals for restrictive yellows, depending on how agencies apply the law.[1] As a result, the practice of how to calculate and apply CCIs varies. Most agencies either use a version of the kinematic equation to calculate the CCIs or apply an engineering judgment to define CCIs (McGee et al. 2012).

The Institute of Transportation Engineers (ITE) recently published *Guidelines for Determining Traffic Signal Change and Clearance Intervals: An ITE Recommended Practice* (ITE 2020). The ITE document introduces a new equation, defined as the extended kinematic equation, for computing the CCIs. The extended kinematic equation includes a new variable to address the limitations of the original equation for turning movements. The original equation assumes intersection approach and entry speeds for turning vehicles are the same as through vehicles. ITE’s recent nonregulatory guidance addressed some industry concerns about change interval timing and generated research questions about yellow change intervals for turning vehicles, resulting from introducing new variables that could significantly increase yellow change intervals under some conditions.

In coordination with stakeholders in State and local agencies, the Federal Highway Administration (FHWA) commissioned a pooled fund study to address research needs prompted by publication of *An ITE Recommended Practice* (ITE 2020). The desired outcome of the pooled fund study is to improve documentation and consistent implementation of traffic signal CCI calculation methods. The pooled fund study enables participants to identify and pursue research needs that extend the existing knowledge about the interaction between human factors and traffic signal CCIs. The pooled fund study findings will research methodologies to address the design and implementation of traffic signal CCIs.

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[1]Under a restrictive yellow law, drivers may not enter the intersection during the yellow indication unless they can entirely clear the intersection prior to the onset of the red indication. Under a permissive yellow law, drivers may enter the intersection during the entire duration of the yellow change interval and legally be in the intersection while the signal is red (National Committee on Uniform Traffic Laws and Ordinances (NCUTLO) 2021).

The pooled fund study sponsored a phase I study to develop this synthesis report of knowledge on traffic signal CCIs. The phase I study included the following activities:

- Conducting a literature review and a benchmarking survey to document the existing research and the state of the practice for the CCIs
- Identifying research gaps related to calculating and applying the CCIs
- Developing a research plan to study research gaps
- Evaluating potential data collection alternatives for conducting the research

This synthesis report provides a foundation for a subsequent phase II study. The phase II study may partially or fully execute the research and data collection plans outlined in this synthesis report.

This synthesis report details the project's motivation (chapter 1), background on the CCIs (chapter 2), state-of-the-practice synthesis (chapter 3), phase II research plan (chapter 4), phase II data collection plan (chapter 5), and summary of findings (chapter 6). This report identifies findings and gaps related to (1) the available methods for determining CCIs and (2) the CCI performance assessment.

SUMMARY OF METHODS FOR DETERMINING CHANGE AND CLEARNACE INTERVALS

This section provides the following summary of methods for determining the CCIs:

- The kinematic model originally developed by Gazis, Herman, and Maradudin (1960) was based on a simple analytical model developed for through vehicles. The objective of that research was to provide insights into the problem of determining the proper duration of the yellow change interval rather than developing guidance for practitioners. However, today, most agencies use some form of kinematic equation even though the kinematic model has limitations. The limitations include that the model follows a mostly deterministic approach, assuming ideal or reasonable driving behavior characteristics. Additionally, the model was developed for through vehicles and not for turning vehicles. The model thus assumes a uniform intersection approach and entry speed even though these speeds differ between through and turning movements.

- Researchers developed the stopping probability model as an alternative to the kinematic model. The research that produced the stopping probability model focused on driver behavior and defined stopping probability functions at the onset of the yellow interval. The research found that a yellow interval duration between 4 and 5 seconds allowed 95 percent of the "going" vehicles to reach the stop line regardless of the approach speed (Chang, Messer, and Santiago 1985; Wortman and Fox 1986). Although these findings may support using a uniform yellow interval, it may still pose risks without conducting additional research, as the suggested yellow interval varied from one study intersection to another even though it was mostly in the 4- to 5-second range.

- The extended kinematic equation, introduced in *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020), modified the kinematic equation by adding variables to address speed variations for turning vehicles. The new variables are based on assumptions of driver behavior and vehicle trajectory for turning movements that still need to be validated by research. The extended kinematic equation generates yellow change intervals for high-speed turning movements that are longer than limits established by the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009).

SUMMARY OF CHANGE AND CLEARANCE INTERVAL PERFORMANCE ASSESSMENT

This section provides the following summary for CCI performance assessment:

- Recent research efforts have developed safety surrogate and crash-based measures to assess CCI performance. Safety surrogate measures for assessing CCIs include the rate of red light violations and the rate of late exits (i.e., the proportion of approach vehicles that exit the intersection after the end of the clearance interval). Common crash-based measures are frequencies and rates of rear-end crashes, opposing left-turn crashes, and right-angle crashes.

- Research studies that evaluated the relationship between the duration of the yellow change interval and red light violation suggests that an increase in the yellow change interval is associated with a reduction in red light violation frequency. However, the tendency is to examine the safety effect of an increase in change interval duration. The research team identified no studies that examine the safety effect of a decrease in yellow change interval duration. The surrogate-based safety studies focus on measures associated with the through driver and the driver’s conflicting movements (including the opposing left-turn movement). The research team identified no studies that examine conflicts associated with the left-turn or right-turn movements related to change interval of the subject approach.

- Limited information exists about the effect of the yellow change interval duration on crash frequency. The relevant literature does not agree on which crash types are sensitive to change interval duration modifications or about the magnitude of the change in crashes associated with the modification.

CHAPTER 1. INTRODUCTION

This document is a synthesis report of the Traffic Signal Change and Clearance Interval Pooled Fund Study led by the Federal Highway Administration (FHWA). The pooled fund study is seeking to improve documentation and consistent implementation of traffic signal change and clearance interval (CCI) calculation methods within State and local agencies. The pooled fund study provides a forum for participants and interested observers to identify and pursue research needs that extend existing knowledge about the interaction between human factors and traffic signal CCIs.

The pooled fund study sponsored a phase I study to develop a synthesis of knowledge on traffic signal CCIs, identify research gaps, develop a research plan, and evaluate potential data collection alternatives. The synthesis report lays the foundation for the subsequent phase II study, which may partially or fully execute the research and data collection plans outlined here.

The specific objective of the synthesis report is to characterize the current state of knowledge and practices related to development and implementation of traffic signal CCIs. To prepare for developing this report in phase I of the pooled fund study, the research team first gathered information related to the development, implementation, and monitoring of traffic signal CCIs through a literature review and benchmarking of current methods, practices, and policies. Using key findings from the literature review and benchmarking, the team developed the research plan and the data collection analysis and alternative methods plan. This report summarizes the findings of work published in North America outside of peer reviewed and public sector sources phase I reports and provides suggestions for the forthcoming phase II effort.

PROBLEM DEFINITION

Traffic signal controllers use CCIs at signalized intersections to warn traffic on an impending change in the right-of-way assignment between conflicting traffic movements.[1] In many jurisdictions in the United States, a red clearance interval follows the yellow change interval. The signal controllers use the yellow change interval as a warning of the change in right-of-way assignment. The red clearance interval provides additional time before the controller grants a green interval to a conflicting movement.

The appropriate determination of the CCIs is key at signalized intersections to ensure safe transfer of the right-of-way while minimizing lost time (and therefore maximizing intersection capacity). While shorter CCIs may not provide sufficient time for safe phase termination, longer CCIs can reduce intersection capacity and lead to high delays. (Anecdotal information by traffic engineers also suggests that longer change intervals will increase crash frequency and promote driver disrespect for the traffic control signal; however, the literature is not definitive on this issue.)

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[1]Sometimes referred to as the minimum time required for a driver to make a decision to come to a safe stop or proceed before the beginning of a conflicting phase; also known as type I dilemma zone or decision zone.

To date, research on this topic has typically focused on the following areas:

- Physics of vehicle motion at the onset of the yellow indication (as described using a kinematic equation) for the appropriate determination of the CCIs
- Safety and capacity effects of CCIs at signals with varying operating conditions and intersection types (e.g., approach speed profiles for through and left-turn movements, approach vertical grade, intersection width, movement type, and vehicle length)
- Driver behavior related to the duration of the CCIs

Although many publications provide information for computing the CCI duration, most methods follow some form of a kinematic equation (Institute of Transportation Engineers (ITE) 1999; McGee et al. 2012; Urbanik 2015), which originates from the analytical solution developed by Gazis, Herman, and Maradudin (1960). Other studies have researched driving behavior and stopping probability at the onset of a yellow signal. These studies highlighted the kinematic equation limitations and suggested the potential use of a uniform duration for the yellow interval (Wortman and Matthias 1983; Wortman, Witkowski, and Fox 1985). Research studies that extend back 70 years have not resulted in consensus on a standard approach for computing CCI. A complicating factor is how agencies design CCIs in the United States; based on interpretation of laws that define restrictive or permissive yellows. (NCUTLO 2021). As a result, the applied CCIs vary in practice. Most agencies either use a version of the kinematic equation or apply an engineering judgment to define CCIs (McGee et al. 2012).

ITE recently published nonregulatory *Guidelines for Determining Traffic Signal Change and Clearance Intervals: An ITE Recommended Practice* (ITE 2020) to overcome the challenges related to lack of a national standard to determine CCIs and to leverage more-recent research that had used changes in technology and availability of new data sources. The ITE document introduces a new equation (defined as the extended kinematic equation) for computing the CCI and includes a new variable to address the limitations of the original equation for turning movements, as the original equation assumes intersection approach and entry speeds for turning vehicles are the same as through vehicles.

While the ITE document is an advancement of the previous concept, it has also generated the following concerns among practitioners and researchers:

- Yellow change intervals for left-turn movements (and protected right turns) based on the new ITE information are longer than the accepted limits some local agencies use.
- The calculated yellow change intervals sometimes conflict with the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009), which says the yellow change should have a minimum duration of 3 seconds and a maximum duration of 6 seconds. The extended kinematic equation assumes that turning drivers maintain their approach speed during the perception-reaction time. This assumption is questionable and would benefit from further research because, anecdotally, practitioners believe that turning drivers start decelerating to the intersection entry speed (i.e., turning speed) well before the onset of the yellow indication and use a much gentler deceleration than what is assumed in the extended kinematic equation while slowing down from intersection approach speed to intersection entry speed. As a result, the extended kinematic equation may overestimate duration of the yellow change interval.

These concerns along with the contradictory findings documented in the past research and the permissive versus restrictive yellow laws (NCUTLO 2021) in the United States are some of the primary motivations for this research. Additionally, with the expanding use of automated enforcement of red light running, improving the understanding of CCIs will allow agencies to properly apply such techniques for safety without unnecessary misunderstanding and inconsistency of CCIs.

ORGANIZATION OF THIS SYNTHESIS REPORT

To characterize the current state of knowledge and practices related to traffic development and implementation of traffic signal CCIs, the research team has organized the remainder of this report as follows:

- **Chapter 2: Background** provides an overview of existing calculation methods for CCIs and an overview of applicable language in vehicle codes. The chapter also summarizes information in the MUTCD and discusses the relation between CCIs and automated enforcement.

- **Chapter 3: State-of-the-Practice Review** presents details of existing calculation methods for CCIs. The chapter divides these methods into those that involve kinematic equations and those that follow behavioral methods. The chapter discusses CCI performance assessment via several types of performance measures. The chapter also provides key findings from the phase I agency benchmarking data collection effort.

- **Chapter 4: Phase II Research Plan** synthesizes research gaps and needs for traffic signal CCI calculation methods. The chapter describes discrete research study candidates based on factors known to affect driver behavior at traffic signals, plus research studies suggested by stakeholders. The chapter also presents the research team's recommended prioritization of the discrete research studies.

- **Chapter 5: Phase II Data Collection and Analysis** provides detail about the known data collection alternatives and their characteristics. The chapter provides criteria for evaluating the likely cost-effectiveness of these data collection alternatives. The chapter also aligns recommended data collection approaches with the prioritized research studies from chapter 4.

- **Chapter 6: Summary of Findings** summarizes the findings of phase I and discusses gaps and research needs that the phase II research effort may address.

CHAPTER 2. BACKGROUND

This chapter presents background information on CCI research and practice. The chapter provides an overview of the calculation methods agencies typically use.[1] Next, the chapter presents an overview of the definitions of CCIs as defined by the vehicle codes and relevant content from the MUTCD. Finally, the chapter presents an overview of issues related to automated enforcement, which have increased the attention on the accuracy and applicability of various calculation methods.

OVERVIEW OF CALCULATION METHODS

The history of determining CCIs spans many decades. While these historical methods often have roots in kinematic equations from physics, researchers have developed other methods based on driving behavior, stopping probability, or a combination of multiple methods.

The review of the literature revealed the following major calculation methods for CCIs:

- **Kinematic equation method:** The kinematic equation method is the most common method for determining CCI durations and ITE has used it since 1965 (ITE 2020). The equation originates from the analytical work conducted by Gazis, Herman, and Maradudin (1960). In this method, the yellow change interval calculation uses perception-reaction time, vehicle approach speed, an assumed deceleration, and the grade of the approach. The red clearance interval (to clear the intersection) is based on the entry speed (which until recently the method had assumed to be the same as the approach speed), width of the intersection, and length of a vehicle. The kinematic equation is the only method presented here that considers the grade of the approach in the calculation of the yellow interval duration.

- **Rule-of-thumb method:** The rule-of-thumb method is a simplified method for yellow change intervals when perception-reaction time and deceleration are unavailable. Some engineers use the approach speed in miles per hour (mph) divided by 10 to determine the length of the yellow change interval (FHWA 1975), subject to the 3-second minimum yellow change interval guidance provided by the MUTCD (FHWA 2009).

- **Uniform duration method:** Some jurisdictions use a uniform duration for CCIs across all intersections, which, depending on the duration, some research (Chang, Messer, and Santiago 1985) suggests may be appropriate regardless of approach speed due to driver behavior.

- **Stopping probability method:** The stopping probability method determines the yellow interval based on how drivers respond at the onset of a yellow phase. Using field observations, some research estimated the probability of stopping at the onset of a yellow phase as a function of distance to an intersection. Researchers then converted this calculation to the time to clear the intersection using the reported speed of each vehicle

[1] See chapter 3 for details on various calculation methods.

(Olson and Rothery 1972). Yellow duration can then be determined based on a certain percent of vehicles (e.g., 95 percent) that would stop for the yellow indication.

- **Combined kinematic model and stopping probability method:** This method combines the kinematic model with the stopping probability method to determine the yellow interval. Researchers developed the resulting equation using observational data from one intersection. They factored in the 85th-percentile approach speed, 85th-percentile deceleration, and the distance and acceleration of conflicting traffic.

- **Modified kinematic model for protected left-turn movements:** The modified kinematic model for a left turn alters the kinematic equation model by accounting for the time it takes for a vehicle to slow down to a comfortable speed for making a left-turn movement. This model typically produces longer yellow times for left-turn movements than for through movements. However, field observations of the calculated intervals from this method indicated that such calculated intervals may not be appropriate for all intersections (Yu et al. 2003). The duration of the red clearance interval is determined using an estimate for the length of the curve traversed by a left-turning vehicle based on the angle of intersection of the crossing roadways.

- **Extended kinematic equation model:** The extended kinematic equation incorporates elements of the kinematic equation and the modified kinematic model, producing the minimum yellow interval for left- and right-turning vehicles arriving at the minimum stopping distance when the yellow interval begins (Beeber 2020)[2]. This model also incorporates the time it takes for a vehicle to decelerate to a comfortable turning speed. A benefit of this model is that it accounts for the same critical distance for stopping or proceeding through the intersection, thereby eliminating the type II dilemma zone. This model is also the method proposed in *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020).

- **Conflict zone and rational model methods:** The conflict zone and rational model methods calculate durations for red intervals based on the time for a vehicle to clear the intersection from the near side to far side conflict point and the time required for conflicting traffic to cross paths with the clearing traffic (Muller, Dijker, and Furth 2004). The main difference between the two models is that the conflict zone method considers the perception-reaction time, or start-up delay, of conflicting drivers to the onset of green, while the rational model method does not factor in the start-up delay.

An inherent consideration in most of these methods is whether to use an approach speed or posted speed limit, and if the constants used for perception-reaction time and deceleration are appropriate for all drivers.[3] If an agency decides to select a model that uses these parameters, for each of these durations, driver behavior produces probability curves, and the question arises of

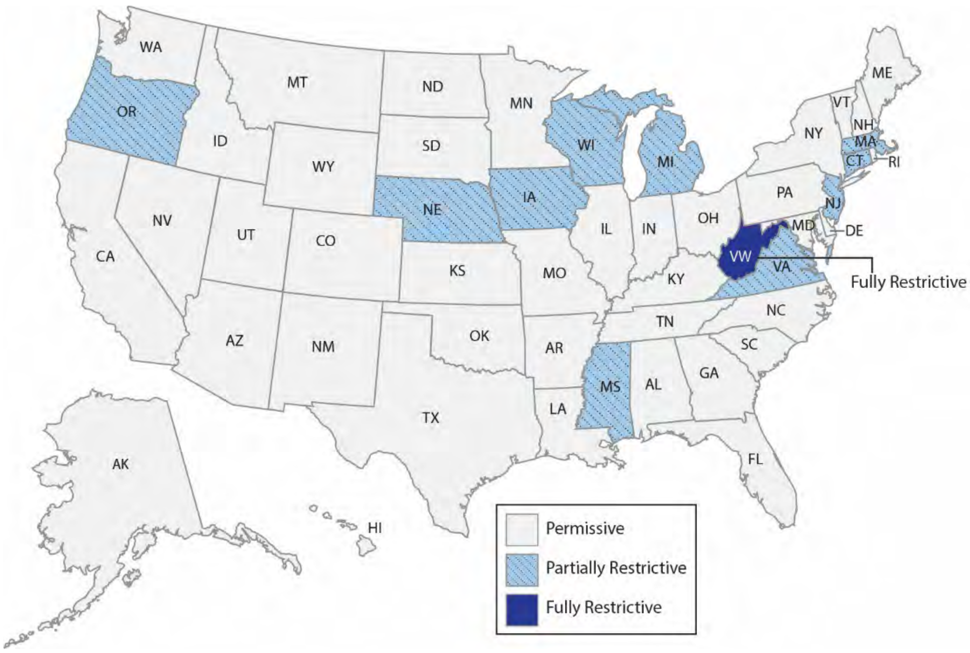
[2]Järlström, M. 2020. June 28. *An Extended Kinematic Equation*. Beaverton, OR:
[3]See chapter 3 for details.

which percentile value to use. These considerations may have a large impact on the duration of CCIs.

OVERVIEW OF VEHICLE CODES

States have the sole legal authority to adopt rules of the road within their jurisdictions. They can also follow the *Uniform Vehicle Code* (*UVC*) (NCUTLO 2021), which promotes uniformity in definitions and practices across the United States. NCUTLO published the latest version of the UVC in 2000 and has since disbanded; however, the National Committee on Uniform Traffic Control Devices has explored reactivation of a national effort under its committee structure focused on uniform code related to traffic control devices.

The 2000 UVC describes the purpose of a yellow indication is to warn drivers that the signal controller will display a red indication immediately upon termination of the yellow interval. The code does not specify if vehicles can enter the intersection on yellow or be within an intersection upon the start of a red indication, as such specifications vary by State. The review of the State vehicle codes showed that 39 States use a permissive yellow indication law, where vehicles may enter an intersection during a yellow indication and be present within the intersection during a red indication if the vehicle had entered the intersection on yellow. The remaining 11 States have restrictive yellow indication laws with two variations in practice: partially restrictive and fully restrictive. Ten of these 11 States allow vehicles to enter the intersection on a yellow indication if the vehicle is unable to safely stop before entering the intersection, also allowing the vehicle to be within the intersection during a red indication. This report defines these as partially restrictive States. One State (West Virginia) does not allow vehicles to be inside the intersection during a red indication; vehicles can enter an intersection on yellow only if it is unsafe to stop and the vehicle can clear the intersection during the yellow interval. This report defines West Virginia as a fully restrictive State. Figure 1 shows a map of permissive, partially restrictive, and fully restrictive States.



Source: Federal Highway Administration.

Figure 1. Map. Yellow signal vehicle laws for permissive, partially restrictive, and fully restrictive States.

Gaining consensus on standard practices to set CCIs may hinge on a parallel effort to harmonize how State vehicle codes define permissive or restrictive yellow intervals. A key action item outside of this research effort would be to develop an appropriate outreach, engagement, and implementation strategy to seek such uniformity.

MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES

The latest edition of the MUTCD (FHWA 2009) provides information on the use of traffic control signals, including CCIs. While the MUTCD does not provide equations for calculating the duration of these intervals, the purpose of the intervals is "to warn traffic of an impending change in the right-of-way assignment" and "to provide additional time before conflicting traffic movements, including pedestrians, are released" (FHWA 2009) for CCIs, respectively. The MUTCD Section 4D.26 describes the sequence that yellow intervals shall follow circular green or green arrow indications but does not require red clearance intervals.

The MUTCD does not provide calculation methods for CCIs, deferring to engineering practices. The MUTCD directs users to *Traffic Control Devices Handbook* (ITE 2013) and *Manual of Traffic Signal Design* (ITE 1998) as support for these engineering practices. The language regarding engineering practices and ITE resources did not exist in MUTCD prior to the 2009 edition.

The MUTCD includes the following provisions:

- A series of definitions related to CCI, including:

- “Yellow Change Interval—the first interval following the green or flashing arrow interval during which the steady yellow signal indication is displayed” (FHWA 2009, Section 1A.13, 258)
- “Red Clearance Interval—an interval that follows a yellow change interval and precedes the next conflicting green interval” (FHWA 2009, Section 1A.13, 171)

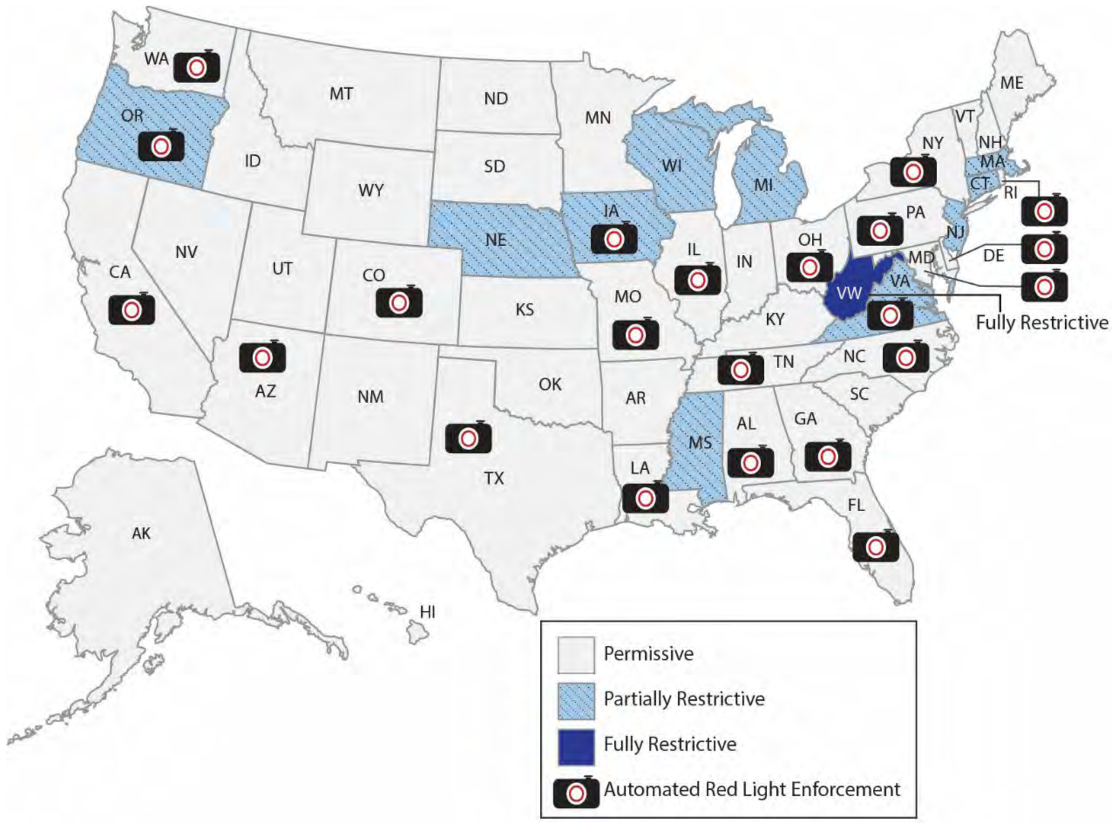
- “The duration of the yellow change interval shall be determined using engineering practices” (FHWA 2009, Section 4D.26, pg. 485). It provides as guidance “that the duration of the yellow change interval should have a minimum of 3 seconds and a maximum duration of 6 seconds. The longer intervals should be reserved for use on approaches with higher speeds” (FHWA 2009, Section 4D.26, pg. 489).

- “When indicated by the application of engineering practices, the yellow change interval should be followed by a red clearance interval to provide additional time before conflicting traffic movements, including pedestrians, are released.” The MUTCD also provides as a standard that “when used, the duration of the red clearance interval shall be determined using engineering practices” (FHWA 2009, Section 4D.26, pg. 485).

- The MUTCD does not allow the signal controller to reduce or omit the red clearance interval on a cycle-by-cycle basis, with the exception of a specific case of lagging permissive/protected signal operations. However, the MUTCD allows the controller to extend the red clearance interval from its predetermined duration for a given signal cycle based on detection of a vehicle predicted to violate the red signal indication and to vary in different signal timing plans for the same controller unit (FHWA 2009, Section 4D.26, pg. 489).

AUTOMATED ENFORCEMENT

In many jurisdictions, transportation agencies have deployed cameras that record red light running (RLR) violations as deterrents (Eccles et al. 2012). According to the Insurance Institute for Highway Safety (IIHS), 15 States and the District of Columbia allow automated enforcement statewide or districtwide, 10 additional States allow automated enforcement in specific jurisdictions, six States prohibit or generally prohibit automated enforcement, and 17 States have no laws regarding automated enforcement of RLR (IIHS 2021). IIHS estimates that at least 340 communities were using red light cameras as of August 2021. Figure 2 shows a map of States that use automated red light enforcement.



Source: FHWA.

Figure 2. Map. Yellow signal vehicle laws and States that use automated enforcement.

Federal guidance for CCI computation with red light systems has generally deferred to the ITE recommendations for the calculations of the CCIs (FHWA and National Highway Traffic Safety Administration 2005). As an example, FHWA and National Highway Traffic Safety Administration (NHTSA) published an update in 2005 to operational guidelines on the use of red light camera systems (FHWA and NHTSA 2005).

Automated enforcement requires establishing a specific point in time on or after the onset of the red interval to engage an enforcement action. In recent years, this requirement has led to scrutiny of the time between onset of the red indication and the point at which enforcement is engaged, and of the underlying model assumptions associated with calculating yellow change intervals. *ITE Recommended Practice* (ITE 2020) states "actions to enforce red light violations, either through traditional or automated means, with zero tolerance are not appropriate." Another research effort may be necessary to address this topic that stakeholders often conflate with the topic of CCIs.

CHAPTER 3. STATE-OF-THE-PRACTICE REVIEW

This chapter provides a summary of the state-of-the-practice review related to the CCIs. The review starts with an examination of work published on CCIs in peer reviewed research journals; Federal, State, and local agency reports; and reports of international research bodies and transportation agencies and organizations. Chapter 3 begins with a detailed review of CCI computational methods documented in peer reviewed journals and reports developed by public sector institutions. The chapter also explains calculation methods, the model components and variables (e.g., approach speed) included in the methods, and the motivation for change from prior methods. Additionally, the review of peer reviewed, and public sector work synthesizes the information describing the safety and operational effectiveness of the CCI. Then, this chapter discusses the benchmarking effort and provides key findings from the benchmarking survey. Finally, this chapter summarizes work published in North America outside of peer reviewed and public sector sources to ensure comprehensive coverage of the topic that has contributed to the body of knowledge on the topic of traffic signal change and clearance intervals.

PEER REVIEWED AND PUBLIC SECTOR DOCUMENTED METHODS FOR CALCULATING CCIS

The available peer reviewed and public sector work indicates two main methods for determining CCIs: (1) methods that follow some form of a kinematic equation originally derived by Gazis, Herman, and Maradudin (1960) and (2) behavioral studies that analyze driving behavior and stopping probability at the onset of a yellow signal. For the first method, some of the literature assumed that the kinematic equation originally developed by Gazis, Herman, and Maradudin (1960) is the correct form and focused only on the variables used in the kinematic equation. Other literature explored the form of the equation to address limitations of the original equation (e.g., the extended kinematic equation). For the second method, behavioral studies tended to focus less on the underlying physics of stopping behavior, as is the case for the kinematic behavior, and looked more closely at the observed behavior of drivers at intersections relative to the change in signal status. Because much of the existing research focuses heavily on the kinematic equation, the mix of sources in this literature review may appear skewed toward the kinematic approach. The research team selected the year 2000 for the organization of this chapter because *A History of the Yellow and All-Red Intervals for Traffic Signals* (Eccles and McGee 2001) included a comprehensive review of published research sources developed through 2000.

Research Through the Year 2000

Practitioners have used many methods to determine CCIs. These methods have also changed over the years in both the calculation of the appropriate interval durations and their application in the field. Most methods developed before 2000 use the form of a standard kinematic equation for calculation of the CCI.

Methods That Follow a Kinematic Equation

Table 1 overviews the kinematic equation methods. The equations have changed little over the years, especially after the introduction of a standard equation in 1965. In 1982, the standard equation incorporated grade effects on the deceleration of vehicles approaching a signal. Also, the equation divided into two terms that respectively correspond to the CCIs. The recommended practice developed by ITE (1985) proposed alternate distances for calculating the red interval and incorporated pedestrian crossing effects for the first time. Most methods suggest caution in the use of long yellow intervals and suggest a maximum of 5 seconds due to the notion that local drivers tend to use more of the change interval when they know it is long. This notion is anecdotal, however, and the literature is not definitive.

Table 1. Methods developed through the year 2000.

Year	Source	Equations	Motivation for Change From Prior Methods
1941	ITE, *Traffic Engineering Handbook*, first edition	$y_1 = 0.8 + 0.04V(0.682) + \frac{0.7W}{V(0.682)}$ $y_2 = \frac{(W+S)}{V} - \frac{D}{V_c}$	Not applicable; this was the first attempt to provide information on yellow clearance interval. Note that the ITE document refers to this equation as the yellow clearance interval and does not differentiate between yellow change and red clearance interval (ITE 1941, page 129)
1950	ITE, *Traffic Engineering Handbook*, second edition	Same equations as 1941	Provides discussion on all-red intervals and describes the equation as “the minimum time required for a vehicle to clear the intersection” (ITE 1950, page 226)
1965	ITE, *Traffic Engineering Handbook*, third edition	$y_1 = t + \frac{1}{2}\frac{V}{a}$ $y_2 = t + \frac{1}{2}\frac{V}{a} + \frac{W+L}{V}$	Based on work by Gazis, Herman, and Maradudin (1960), the calculation took on the form of a standard kinematic equation (rather than the time needed for an approaching vehicle to decelerate to a stop)
1976	ITE, *Transportation and Traffic Engineering Handbook*, first edition	Same equations as 1965	Similar to 1965, except the definition and purpose of the yellow interval change from “advise the motorist that the green was about to end” to “advise the motorist that the red interval is about to commence” (ITE 1976, page 814); also, the second equation (y_2) is now called the nondilemma yellow
1982	ITE, *Transportation and Traffic Engineering Handbook*, second edition	Same equations as 1965 and 1976	Discusses vehicle codes for the first time and states that the first equation is for permissive States, and the second equation is for restrictive States

Table 1. Methods developed through the year 2000. (continuation)

Year	Source	Equations	Motivation for Change From Prior Methods
1982	ITE, *Manual of Traffic Signal Design*	$y_1 = t + \frac{1}{2}\frac{V}{a} + \frac{W+L}{V}$ $y_2 = t + \frac{V}{2a + 64.4g} + \frac{W+L}{V}$	The first equation is the same as the equation presented in 1976, but called nondilemma change period; the second equation time incorporates the effect of grade (first time) on stopping ability
1985	ITE, *Determining Vehicle Change Intervals: A Proposed Recommended Practice*	$y = t + \frac{V}{2a + 64.4g}$ $r_1 = \frac{W+L}{V}$ $r_2 = \frac{P}{V}$ $r_3 = \frac{P+L}{V}$	The 1982 equation is divided into two intervals: the first for the yellow change interval and the second for the red clearance interval; the 1982 equation was modified to account for the effect of approach grade based on research by Parsonson and Santiago (1981)
1992	ITE, *Traffic Engineering Handbook*, fourth edition	Same equations as 1985	No change from the 1985 methods
1994	ITE, *Determining Vehicle Signal Change and Clearance Intervals*, Technical Council Task Force	For the kinematic model: $y = t + \frac{V}{2a + 64.4g}$ Also suggests using the following term to allow a vehicle to clear the intersection: $\frac{W+L}{V}$	This report provided additional alternatives to determine change interval length
1999	ITE, *Traffic Engineering Handbook*, fifth edition	$y = t + \frac{V}{2a + 64.4g} + \frac{W+L}{V}$	This edition returns the third term to the equation (similar to the 1982 edition)

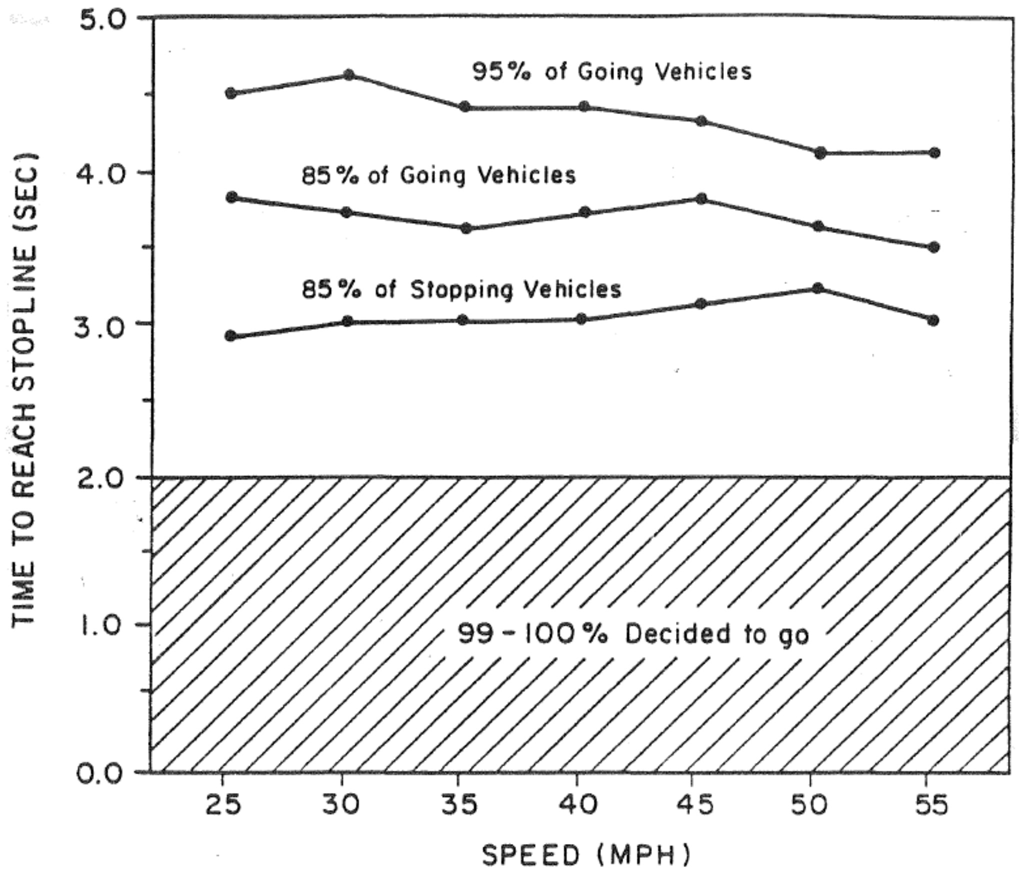
Adapted from © 2001 Eccles and McGee.

a = deceleration, in feet per second squared (ft/s^2); *D* = length of free path, in feet (ft), to conflict point with clearing traffic; *g* = grade of approach, in decimal form; *L* = length of vehicle, in ft; mph = miles per hour; *P* = width of intersection, in ft, measured from the nearside stop bar to the far side of the farthest conflicting pedestrian crosswalk along the path of clearing traffic; *S* = minimum safe stopping distance, in ft; *V* = speed of clearing vehicle, in mph; *Vc* = speed of conflicting vehicle, in mph; *W* = width of intersection, in ft; *t* = perception-reaction time, in seconds.

Methods Based on Behavioral Studies

Since 1965, all the proposed ITE methods have descended from the kinematic model originally developed by Gazis, Herman, and Maradudin (1960). However, the kinematic model is inherently limited because it follows a mostly deterministic approach (except for the approach speed) and assumes ideal or reasonable driving behavior characteristics with specific preset values of perception-reaction time and acceptable deceleration when a driver faces a yellow signal. Additionally, Gazis, Herman, and Maradudin (1960) considered only through movements and did not consider a range of possible speeds. Subsequent implementation and adaptation of this deterministic approach mostly ignored the effects of different contexts or vehicle types. Another limitation of the kinematic model is that it assumes a constant or uniform deceleration, which simplifies the calculation and makes it easier to adjust the equation for special cases. However, field data suggest that when drivers face a yellow signal, they do not necessarily follow the constant or uniform deceleration model. Research conducted in Arizona using data collected from five intersections found that only about 30 percent of the stopping vehicles had deceleration profiles that approximated the constant rate condition, and the remaining 70 percent displayed nonuniform deceleration (Wortman and Matthias 1983; Wortman, Witkowski, and Fox 1985).

To overcome the limitations of the kinematic model, several researchers investigated driver behavior, stopping probability function, and the potential use of a uniform duration for the yellow interval. Using data collected at seven intersections (three in Virginia and four in Texas), Chang, Messer, and Santiago (1985) studied driver responses to the change intervals and examined interval timing as a function of driver behavior (figure 3). The results show that it took less than approximately 4.5 seconds for 95 percent of the “going” vehicles to reach the stop line regardless of their approach speed. This finding contradicts the methods that use the kinematic equation to estimate yellow duration, since these methods suggest using a lower yellow interval with lower approach speeds and increasing yellow duration for higher speeds. The results shown in figure 3 also support the potential use of a constant yellow interval regardless of approach speed ranges.

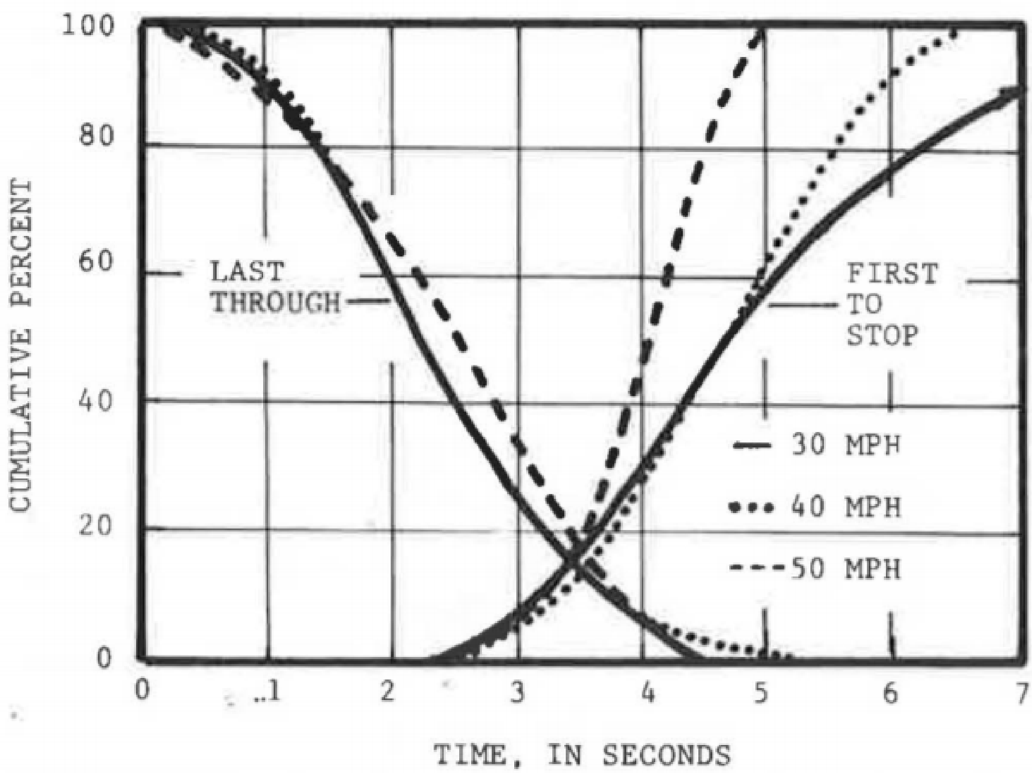


Source: Chang, Messer, and Santiago.

mph = miles per hour; sec = seconds.

Figure 3. Chart. Driver's decision to stop or go, by time and approach speed.

Wortman and Fox (1986) reinforced the notion that yellow interval needs are independent of the approach speed. This study analyzed driver behavior of the last vehicle through the intersection and the first vehicle to stop after the onset of the yellow interval using field data collected from intersections in Arizona with 30-, 40-, and 50-mph approach speeds. Figure 4 shows the cumulative distribution functions for the time from the intersection at the onset of the yellow interval for the first vehicle to stop and the last vehicle to proceed through the intersection for approach speeds of 30, 40, and 50 mph. The research found that approximately 95 percent of the last vehicles through the intersection are 4 seconds or less from the intersection at the onset of yellow. One could interpret these findings as supporting the use of a uniform yellow interval because driver behavior seems to remain the same regardless of approach speed. The findings also suggest that the current yellow change interval calculation methodology may pose risks for lower speed approaches (e.g., speed below 40 mph), as the methodology typically results in yellow change intervals that are less than 4.0 seconds.



Source: Wortman and Fox.

mph = miles per hour.

Figure 4. Graph. Time from intersection at onset of yellow interval by cumulative percentage of stopping or going vehicles: 30-, 40-, and 50-miles-per-hour approach speeds.

Lin, Cooke, and Vijayakumar (1987) explored whether a constant yellow interval can be effective and whether the ITE equations (1985) can realistically reflect driver behavior. The analysis found that the 95th-percentile yellow interval requirements (that would lead to only 5 percent of vehicles entering the intersection after the onset of yellow) varied from about 3 to 5 seconds. While the analysis sites did not have so much variation in approach speeds, the analysis also found no positive correlation with the approach speed and the required yellow interval. To the contrary, the results indicated the left-turn movement with an approach mean speed of 21.9 mph resulted in similar yellow interval requirements as the through movement with an approach mean speed of 32.5 mph, using the 95th-percentile yellow requirement (5.0 seconds for the left-turn movement versus 4.5 seconds for the through movement). A detailed analysis of the field observations for the left-turn movement revealed that residual queues from previous cycles and short green intervals to discharge queued vehicles in one cycle resulted in aggressive driving behavior where vehicles often continued entering the intersection long after the yellow interval (which was set as 3.9 seconds).

Shanteau (1983) summarized the minimum yellow intervals that can come from using the stopping probability curves based on the 90th-percentile probability of stopping as the criterion. The stopping probability method is based on the first stopping vehicle, while Lin, Cooke, and Vijayakumar (1987) and Wortman and Fox (1986) are based on the last clearing vehicle. This is an important distinction because some researchers believe that yellow change interval should be determined based on clearing vehicles rather than stopping vehicles, as the real safety concern is applicable to clearing vehicles instead of stopping vehicles.

Research After the Year 2000

Through the year 2000, many agencies adopting the kinematic equation expressed concerns that drivers did not conform to the model and assumptions. As a result, in the past 20 years, researchers have continued to investigate CCIs, leading to additional research. Since the year 2000, the National Highway Traffic Safety Administration (NCHRP) and ITE have investigated CCIs in two comprehensive studies: *NCHRP Report 731: Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections* (McGee et al. 2012) and *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020). This section reviews these reports and incorporates other research from peer-reviewed publications.

Methods and Variables Following the Kinematic Equation

Methods that use a kinematic equation have three parameters that directly relate to its use: (1) perception-reaction time, (2) deceleration, and (3) approach speed. This section provides key findings from the literature in the past 20 years regarding these three parameters.

Perception-reaction time strongly affects the calculation of the yellow change interval. Several recent studies have investigated the value of perception-reaction time within the kinematic equation. Table 2 summarizes this research.

Recent research on deceleration in the kinematic equation has focused on the factors influencing deceleration (e.g., approach speed, grade, and driver's age). Researchers have studied the suggested deceleration of 10 ft/s^2 given in the ITE equation to explore its validity. Table 3 summarizes the recent research on through vehicle deceleration at the onset of yellow.

Approach speed is a key variable in the kinematic equation, and selecting an appropriate value is a common question for agencies. While both the original and extended ITE equations recommend using the 85th-percentile approach speed, agencies often do not have the staff to collect speed data in the field. Moreover, turning-vehicle approach speeds typically differ from through vehicles (and for turning vehicles, approach speed often differs from the entry speed). To overcome these challenges, recent studies have developed approach speed recommendations in lieu of an 85th-percentile speed, which requires collecting field data. Table 4 summarizes the research on the approach speed for the through vehicles and the recommendation for the 85th-percentile approach speed as an alternative to field-calculated speeds. Table 5 summarizes the research on the turning vehicles and the recommendation for approach speed and entry speed for left-turning movements, as the geometry of the turning movement limits the entry speeds for turning vehicles, leading to different approaches and entry speeds.

Table 2. Research that studied perception-reaction time.

Research Title	Key Findings	Recommended Perception-Reaction Time
NCHRP Report 731 (McGee et al. 2012)	• Mean brake-response time of 1.0 second observed • 85th-percentile brake-response time estimated as 1.33 seconds • Brake-response time decreased as approach speed increased • Brake-response time increased as deceleration increased and as travel time to the intersection at the start of yellow increased	1.0 second for the perception-reaction time in the kinematic equation
Guidelines for Determining Traffic Signal Change and Clearance Intervals (ITE 2020)	The review of the state of the practice and literature found that 1.0 second is sufficient for most users	1.0 second for the perception-reaction time in the kinematic equation; however, if local conditions, driving population age, or a supporting engineering study suggests a value higher than 1.0 second is appropriate, analysts may apply engineering judgment
"Characterizing Driver Behavior on Signalized Intersection Approach at the Onset of a Yellow-Phase Trigger" (Rakha, El-Shawarby, and Setti 2007)	• Median of 0.7 second for the perception-reaction time identified • No significant differences found between the perception-reaction time of men and women or younger and older drivers • A small but significant difference for the upgrade (0.70 second) and downgrade (0.63 seconds) • When travel time to intersection at the onset of yellow was 5.6 seconds, median perception-reaction time was longer than times observed for shorter travel times to intersection	The authors did not recommend a specific value but concluded that the 1.0-second perception-reaction time is valid and consistent with the field observations
"The Effect of Yellow Light Onset Time on Older and Younger Drivers' Perception-Response Time and Intersection Behavior" (Caird et al. 2007)	• Mean perception-response time of 0.96 second identified; 85th-percentile response time estimated as 1.22 seconds • Consistent with the other studies, mean perception-response time (for the stopped vehicles) increased as time to intersection increased (e.g., 0.93 second at 3.1 seconds travel time to intersection versus 1.03 seconds at 3.53 seconds travel time to intersection) • No difference observed in perception-response time between younger and older drivers	The authors did not recommend a specific value but concluded that the 1.0-second perception-reaction time is valid and consistent with the field observations

Table 3. Research that studied deceleration.

Research Title	Key Findings	Recommended Deceleration
NCHRP Report 731 (McGee et al. 2012)	• Mean deceleration was 10.08 ft/s^2 with an 85th-percentile of 12.89 ft/s^2 • Travel time to stop line at start of yellow, approach speed, and perception-reaction time were significant • Approach speed largely influenced deceleration	10 ft/s^2 for deceleration in the kinematic equation
Guidelines for Determining Traffic Signal Change and Clearance Intervals (ITE 2020)	The literature and agency practices revealed that 10 ft/s^2 is appropriate for most users	10 ft/s^2, although analysts may apply engineering judgment
"Evaluation of Driver Deceleration Behavior at Signalized Intersections" (El-Shawarby et al. 2007)	• Decelerations are influenced by travel time to stop • No significant differences in mean deceleration for uphill and downhill conditions • Male drivers had slightly higher decelerations than female drivers • Young and old drivers had greater decelerations than middle-aged drivers	No specific recommendation
"The Effect of Yellow Light Onset Time on Older and Younger Drivers' Perception-Response Time and Intersection Behavior" (Caird et al. 2007)	• A significant relationship between deceleration and time to stop line and driver age was found • Mean deceleration ranged from 8.2 to 18.0 ft/s^2 as a function of time to stop line	No specific recommendation
"Analysis of Driver Behavior in Dilemma Zones at Signalized Intersections" (Gates et al. 2007)	• Researchers observed 7.2, 9.9, and 12.9 ft/s^2 for the 15th-, 50th-, and 85th-percentile deceleration, respectively • Drivers use greater decelerations from higher speeds • 10 ft/s^2 recommended in the ITE formula corresponds to the 31st percentile for speeds >40 mph and the 74th percentile for speeds <40 mph	Use greater design deceleration for high-speed approaches

Table 4. Research that studied approach speed for through vehicles.

Research Title	Key Findings	Approach Speed Recommendation in Lieu of 85th-Percentile Speed
NCHRP Report 731 (McGee et al. 2012)	• Mean speeds for through vehicles typically exceed the speed limits of 35 mph and below and were approximately equal to the speed limit at speed limits between 40 and 55 mph • For lower speed limits (e.g., 25 mph), 85th-percentile speeds were 10 mph higher than the speed limit; when averaged across all sites, the 85th-percentile speed is about 7 mph greater than the speed limit	• For sites with speed limits higher than 25 mph, the 85th-percentile approach speed for through vehicles can be approximated to the speed limit plus 7 mph; at speed limits of 25 mph, the speed limit plus 10 mph is recommended for approach speed • Suggests the speed for the red clearance calculation for through vehicles should be the same as that for yellow change interval
NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices (Fitzpatrick et al. 2003)	A greater percentage of vehicles on rural roads (37–64 percent) traveled at or below the posted speed limit compared with vehicles on suburban or urban roads (23–52 percent)	Researchers developed a linear regression model to estimate 85th-percentile speed, which is approximately 7 mph greater than the posted speed limit; the research also developed individual regression models for each functional class
"Evaluation of Driver Behavior in Type II Dilemma Zones at High-Speed Signalized Intersections" (Hurwitz, Knodler, and Nyquist 2011)	85th-percentile approach speeds were found to be approximately 5 mph higher than the posted speed limit for high-speed approaches	No specific recommendation
Guidelines for Determining Traffic Signal Change and Clearance Intervals (ITE 2020)	Based on the review of the agency practices, the authors found that 80 percent of the surveyed agencies that use approach speed in the change interval calculation use either the posted speed limit or the 85th-percentile approach speed	Measure 85th-percentile approach speed, determined under free-flow conditions, on the intersection approach, upstream of the area of influence of the intersection operations; if 85th-percentile speed is unavailable, estimate 85th-percentile approach speed for through movements by adding 7 mph to the posted speed limit

Table 5. Research that studied approach speed for turning vehicles.

Research Title	Key Findings	Approach and Entry Speed Recommendation in Lieu of 85th-Percentile Speed
NCHRP Report 731 (McGee et al. 2012)	Left-turning-vehicle speeds on high-speed approaches were 10.6 mph lower than the posted speed limit; 85th-percentile left-turn speeds were 4.9 mph lower than the posted speed limit	• For left-turning 85th-percentile approach speeds, analysts can use approach speed minus 5 mph • Turn movement geometry limits left-turning-vehicle entry speeds; use 20 mph for the left-turn and the 85th-percentile entry speed for the red clearance interval calculation
Guidelines for Determining Traffic Signal Change and Clearance Intervals (ITE 2020)	Focuses on through-moving vehicles for the approach speed and references *NCHRP Report 731* (McGee et al. 2012) for turning vehicles	• The extended equation accounts for differences in turning-vehicle entry and approach speeds • Turning approach speed is the 85th-percentile value under free-flow conditions measured from a speed study; where data are unavailable, use the speed limit for approach speed • For turning-vehicle entry speeds, analysts can use the actual 85th-percentile intersection entry speed; where speed data are unavailable, analysts can use 20 mph

New Methods Developed After the Year 2000

To address limitations of the well-known ITE formula (i.e., the traditional kinematic equation), researchers have developed new methods. This section discusses these methods and compares the calculated CCIs with the new methods and the well-known ITE formula.

NCHRP Report 731 Method

The findings of this study suggest traffic engineers use the equation in figure 5 for the yellow change interval, and the equation in figure 6 for the red clearance interval.

$$Y = t + \frac{1.47V}{2a + 64.4g}$$

Source: McGee et al.

Figure 5. Equation. Yellow change interval calculation recommended in *NCHRP Report 731*.

Where:

t = perception-reaction time (second)
V = 85th-percentile approach speed (mph)
a = deceleration (ft/s^2)
g = approach grade (percent divided by 100, negative for downgrade)

$$R = \frac{W + L}{1.47V} - 1$$

Source: McGee et al.

Figure 6. Equation. Red clearance interval calculation recommended in *NCHRP Report 731*.

Where:

V = 85th-percentile approach speed (mph)
W = intersection width measured from the back edge of the approaching movement stop line to the far side of the intersection as defined by the extension of the curb line or outside of the farthest travel lane (ft)
L = length of vehicle (ft)

The yellow calculation reflects the first two terms of the ITE 1999 equation. For the figure 6 calculation, *NCHRP Report 731* (McGee et al. 2012) subtracted 1 second from the red interval to account for intersection entry delay. Field data found an average of 1.1 seconds of start-up lost time and an average of 4.1 seconds of total intersection entry delay. For rolling vehicles (the most conservative scenario), the research found a start-up delay of 0 seconds. Based on the findings, *NCHRP Report 731* (McGee et al. 2012) recommended a 1-second reduction for red clearance calculation. While they are not directly mentioned in the equations, the report recommends using different approach and entry speeds for left-turning vehicles.

Extended Kinematic Equation Adopted by Institute of Transportation Engineers

Guidelines for Determining Traffic Signal Change and Clearance Intervals (ITE 2020) introduced a new equation based on Järlström's extended kinematic equation (Beeber 2020)[1]. The motivation for this new equation was to address the oversimplification of the original equation for turning vehicles. The 2020 ITE recommended practice extended the traditional equation to turning movements and recognized that the approach speed (used to calculate the

[1] Järlström, M. 2020. June 28. *An Extended Kinematic Equation*. Beaverton, OR

yellow change interval) and entry speed (used to calculate the red clearance interval) for turning vehicles are different, since drivers must decelerate within the critical distance. Figure 7 and figure 8 show the extended kinematic equation.[2]

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

Source: Institute of Transportation Engineers.

Figure 7. Equation. Extended kinematic equation for the minimum yellow change interval.

Where:

Y = minimum yellow change interval (seconds)
t = perception-reaction time (seconds)
V_{85} = 85th-percentile approach speed (mph)
a = deceleration (ft/s^2)
g = approach grade (percent divided by 100, negative for downgrade)

$$R = \frac{W + L}{1.47V_E} - t_s$$

Source: Institute of Transportation Engineers.

Figure 8. Equation. Extended kinematic equation for the red clearance interval.

Where:

V_E = intersection entry speed (mph)
R = red clearance interval (seconds)
W = distance to traverse the intersection width (ft)
L = length of vehicle (ft)
t_s = conflicting vehicular movement start-up delay (seconds)

For the calculation in figure 7, when the 85th-percentile approach speed equals entry speed (considered generally true for through vehicles), the second term in the equation becomes 0, and the extended equation is equivalent to the traditional equation. Additionally, for restrictive yellow laws, the yellow interval should also include the red interval calculation.

While the new guidance that uses the principles of the extended kinematic equation represents an advancement, it also resulted in the following new concerns among practitioners and researchers:

- *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020) sometimes results in yellow intervals for left turns (and protected right turns) that exceed the accepted limits used by some agencies. Additionally, the calculated intervals sometimes conflict with the MUTCD (FHWA 2009), which constrains the yellow duration to between 3 and 6 seconds. The notion of acceptable limits on CCI calculations

[2]In July 2021, ITE published errata and issued an updated release. This equation is from that release.

highlights a research gap as to whether either of these common procedures is indeed appropriate.

- The extended equation assumes turning drivers maintain their approach speed during perception-reaction time. Anecdotally, traffic engineers believe turning drivers decelerate to entry speed (i.e., turning speed) well before the onset of yellow. As a result, the extended equation may overestimate the yellow interval duration. Further research on the approach vehicle speed trajectories can help to better understand turning drivers' behavior before and at the onset of yellow.

- The extended equation requires entry speed estimates. When applied to a turn movement, *Guidelines for Determining Traffic Signal Change and Clearance Intervals* advises the analyst to compute this speed from data at the intersection or, if unavailable, assume 20 mph for left turns. However, the 20 mph may not accurately represent many left turns. Left- and right-turn entry speeds may reflect site characteristics (e.g., turn radius, approach speed, and cross street entrance width). The *Guidelines for Determining Traffic Signal Change and Clearance Intervals* does not provide guidance to estimate approach speeds for turning vehicles as a function of site characteristics (ITE 2020). If this procedure were to be the appropriate method for determining CCIs, research efforts to establish these parameters for various intersection characteristics may be helpful.

- The extended equation assumes turning drivers have fixed deceleration and perception-reaction times for all roadways; research shows deceleration and perception-reaction times are correlated and influenced by approach speed and travel time to stop line.

North Carolina Equation for the Red Clearance Calculation

In North Carolina, calculation of the red clearance interval is based on the third term of the traditional kinematic equation. However, practitioners expressed concern about excessive red intervals for left turns at large intersections. To address this concern, an alternative equation (Click 2008) adjusted ITE's red interval equation (ITE 1999). One adjustment removed vehicle length from the formula (figure 9). A second adjustment recalculated the red interval when the figure 9 equation computes a value above 3 seconds (figure 10).

$$R = \frac{w}{v}$$

Source: Click.

Figure 9. Equation. North Carolina's modification of the red clearance interval equation to remove vehicle length.

Where:
R = red clearance interval (seconds)
w = intersection width (ft) calculated from the stop line to the far edge of the conflict zone
v = approach speed

$$R = \frac{1}{2}\left(\frac{w}{v} - 3\right) + 3$$

Source: Click.

Figure 10. Equation. North Carolina's modification to reduce the red clearance interval when the calculated red clearance interval is greater than 3 seconds.

Where:

R = red clearance interval (seconds)
w = intersection width (ft) calculated from the stop line to the far edge of the conflict zone
v = approach speed

This adjustment intends to increase intersection efficiency and reduce non-compliance of drivers for long red intervals. (Despite a general perception that long red clearance intervals encourage disrespect for drivers, the literature is not definitive on this issue.) The equation in figure 10 takes the average of the calculated value and 3 seconds (e.g., if the initial calculation resulted in 5 seconds, this adjustment would reduce it to 4 seconds).

Red Clearance Intervals Using the Conflict Zone Method

A red interval method considered required clearance times for conflicting movements depending on the distance of entering and exiting movements (Muller, Dijker, and Furth 2004). The method requires that before the start of green for a given traffic movement, clearance intervals for all proceeding conflicting traffic streams must be satisfied. Therefore, the controller needs red times $t_{clearance}\,(i, j)$ for every proceeding conflicting traffic movement. Therefore, phase sequence and the next phase become key during the calculation of the red interval.

For a given pair of conflicting movements, figure 11 calculates the clearance interval length. Determination of exit time is the same as traditional clearance interval calculations, shown in figure 12.

$$t_{clearance}(i,j) = t_{exit}(i) - t_{entrance}(j) \ \mid \ \geq 0$$

Source: Muller, Dijker, and Furth.

Figure 11. Equation. Red clearance interval calculation using the conflict zone method based on the ordered pair of conflicting movements.

Where:

$t_{clearance}\,(i,j)$ = red clearance interval (seconds) where i is the index of the exiting movement and j is the index of the entering movement
$t_{exit}\,(i)$ = exit time (seconds) for the exiting movement
$t_{entrance}\,(j)$ = entrance time (seconds) for the entering movement

$$t_{exit} = \frac{s_{exit}}{v_{exit}}$$

Source: Muller, Dijker, and Furth.

Figure 12. Equation. Exit time calculation for the conflict zone method.

Where:

s_{exi} = the distance a vehicle in the exiting movement must travel from the stop line to fully clear the conflicting zone (including the vehicle length, suggested as 40 ft to represent a truck)

v_{exit} = the speed of a vehicle in the exit movement that crosses the stop line at the last moment of the yellow signal

t_{exit} = exit time (seconds) for the exiting movement

Determination of entrance time is more complicated and considers both fully stopped vehicles and rolling vehicles (i.e., an approaching vehicle starts to decelerate because the signal is red and starts accelerating again before coming to a standstill, since the signal turns green and enters the intersection at some speed). Using an analytical approach and vehicle trajectories obtained from field data, the researchers derived the figure 13 equations for entrance time.

$$t_{entrance} = t_r + \sqrt{\frac{2s_{entrance}}{a_{acc} - a_{dec}}} \qquad if\ s_{entrance} \leq s_{critical}$$

$$t_{entrance} = t_r + \quad \frac{s_{entrance}}{v_{max}} + \frac{v_{max}}{2(a_{acc} - a_{dec}}) \qquad if\ s_{entrance} > s_{critical}$$

Source: Muller, Dijker, and Furth.

Figure 13. Equations. Entrance time calculation for the conflict zone method.

Where:

a_{dec} = constant deceleration following the trajectory that, if uninterrupted, brings vehicles to a standstill at the stop line

a_{acc} = constant acceleration until vehicles reach the speed v_{max} when the signal turns green

v_{max} = maximum speed

$s_{entrance}$ = distance from the stop line of the entering movement to the conflict zone

$s_{critical}$ = critical distance travelled from the stop line corresponding to the minimum entrance time for the entering movement

$t_{entrance}$ = entrance time (seconds) for the entering movement

t_r = reaction time (seconds)

Using the equations in figure 11, figure 12, and figure 13, red interval calculation using the conflict zone method was compared with ITE’s equation (the third term). Since the conflict zone method is sensitive to phase sequence, researchers performed the comparison for alternative phasing schemes. Results showed that with the traditional ITE equation, the clearance interval requires approximately 2 seconds, while the conflict zone method results in almost 0 seconds for the lagging left-turn case and approximately 1 second for leading lefts (varying slightly with the conflicting movement pairs). The conflict zone method may cause considerably lower red times, thus increasing intersection capacity. However, implementation may be difficult in the United States given that existing controllers provide clearance intervals on the sole basis of the currently terminating phase. For example, for a standard eight-phase operation with protected and leading left turns, the phase that follows a mainline through phase would serve the side street left turn, but if the controller skips that phase, then the red calculation must be based on the through phase for the mainline street. The difference in the distance to the nearest conflicting lane would be different, so the clearance interval would be different. Existing controllers do not currently support this functionality.

Yellow Change Intervals Based on Driver Behavior and Risk of Being in a Dilemma Zone

Rakha et al. (2011) developed an approach to compute clearance interval for through vehicles based on drivers' response at the onset of yellow and the probability that drivers are not in the dilemma zone. Rakha et al. (2011) collected data for two approach speeds: 45 and 55 mph. The study recruited 24 drivers in three equal age-groups. The study design held that 50 percent of the trials would indicate yellow/red signal, while the remaining 50 percent would display a green signal. To examine driver behavior, the onset of yellow was based on the time-to-stop line (varied between 2.0 and 4.6 seconds) at the instructed speed. The yellow interval used for the test case was 4 seconds for the 45-mph test and 5 seconds for the 55-mph test. Results indicated that the kinematic equation fails to account for variations in perception-reaction time and deceleration between different drivers approaching the same intersection at the onset of yellow.

Methods Focusing on Driver Behavior and Probability of Stopping

Over the past 2 decades, researchers have conducted substantive study into driver behavior and probability of stopping at the onset of a yellow signal. Much of this research has focused on behavior within dilemma zones and has explored driver decisions to stop or go with respect to vehicle speed, distance (or travel time) to stop line, driver characteristics (e.g., age and gender), and vehicle type. The following is a summary of key findings.

Travel Time to Stop Line

Elmitiny et al. (2009) collected field data at a high-speed intersection (posted speed of 45 mph where most vehicles traveled at 50 mph) in central Florida. When travel time to the stop line was 4 seconds, both stop-and-go decision probabilities were close to 0.5. Most research showed that red light running (RLR) occurred when travel time to the stop line was 4–5 seconds. If the travel time is shorter than this value, most vehicles proceed through the intersection during yellow. If the travel time is longer than this value, most vehicles stop. Yang et al. (2014) proposed driver behavior models in yellow intervals using only through vehicles. The research showed that travel time to the stop line is one of the most important factors affecting driver behavior in the yellow interval. Additionally, Yang et al. (2014), when comparing similar conditions with and without a timer, examined the effect of countdown timers on drivers' decisions and found that the presence of a countdown timer appears to increase the number of vehicles that pass through the intersection.

Approach Vehicle Speed

Liu, Chang, and Yu (2012) classified driver response to yellow using the assumption that there exists a critical distance perceived by a normal driver based on the recommended deceleration, perception-reaction time, and approach speed. Using driver behavior data from six intersections in Maryland, Liu, Chang, and Yu (2012) showed that the speed of an approaching vehicle is the best indicator for driver aggressiveness (i.e., vehicles that passed the intersection during yellow despite being far upstream of the critical distance). Li, Jia, and Shao (2016) aimed to predict driver stop/go decisions and red light violations during yellow intervals. Using vehicle trajectory data from 1,086 vehicles from two intersections, the researchers found approach speed to be an explanatory variable that met the 0.05 significance levels to model stop/go decisions. Results showed that drivers with high approach speeds are more likely to make go decisions and that for every 1-mph increase in approach speed, drivers are approximately 15 percent more likely to go than to stop when the controller displays yellow at the critical distance.

Driver Characteristics

Papaioannou (2007) examined driver behavior at an urban intersection in Greece and observed 2,452 vehicles that faced a yellow indication. The data showed that female drivers made the correct decision at the onset of yellow more than male drivers, and the percentage of aggressive (yellow-signal-violating) female drivers was significantly lower than the percentage of aggressive male drivers. Liu, Chang, and Yu (2012) found similar results for drivers who use sport utility vehicles (SUVs), in which male SUV drivers tend to take more-aggressive actions when approaching a yellow phase than female SUV drivers. Savolainen (2016) investigated driver behavior at the onset of yellow in a traffic simulator environment and explored driving behavior with respect to speed, distance, age, gender, and cellular phone use. The results showed the probability of stopping was the highest among younger male drivers. Savolainen speculated that this could be due to familiarity and comfort in a simulated driving environment where drivers tended to stop more frequently as they become more familiar with the driving environment. Liu, Chang, and Yu (2012) conducted a field study and found that young male drivers tend to be more aggressive than older male drivers.

Other Factors Impacting Driver Behavior at the Onset of Yellow

In addition to travel time to the stop line, approach speed, and driver characteristics, researchers have also investigated other factors (e.g., level of traffic congestion and effects of platoons) related to drivers' responses to the yellow indication. Liu, Chang, and Yu (2012) found that drivers on minor streets with shorter green durations and those who are familiar with operational conditions are more likely to take an aggressive decision to proceed on yellow. Another finding was that drivers are more likely to proceed on yellow when following another vehicle (i.e., as part of a platoon) compared with when they are the leading drivers (Elmitiny et al. 2009). Another factor is the effect of cellular phone use on driver reaction to yellow. Despite limited research on this subject compared with other factors, Savolainen's traffic simulator research showed that drivers are more likely to stop when using handheld phones or hands-free devices compared with baseline conditions with no phone conversations (Savolainen 2016). This could indicate drivers' overreacting to a yellow signal when distracted, although driver reactions could differ in the real world compared with a simulated environment.

CCI PERFORMANCE ASSESSMENT

The intent of the CCI is to reduce the potential for crashes associated with signal phase termination. Traffic analysts generally believe that these interval durations have some influence on crash potential (McGee et al. 2012). The CCIs can also influence intersection operations (Tarnoff 2004). As a result, the performance assessment of these intervals must consider both safety and operations. The first half of this chapter described different methods for determining the duration of the CCIs. These methods attempt to achieve an acceptable balance between safety and efficient traffic operations. However, no one method has emerged as suitable for use in all U.S. jurisdictions. This lack of consensus may, in part, be due to differences in driver behavior, traffic laws, and enforcement levels that vary widely from jurisdiction to jurisdiction. These differences may translate into perceived (or observed) safety and operational benefits obtained by one method over another in the various jurisdictions.

The second half of this chapter synthesizes information provided in the literature describing the safety and operational effectiveness of the CCI. The findings may provide the foundation for establishing a formal process for assessing the performance of alternative CCIs. Researchers could implement this assessment process when developing a proposed new method for estimating CCIs. Additionally, practitioners could implement the process when determining the suitability of CCIs at a specified intersection.

Safety-Surrogate-Based Measures

This section documents findings from a review of the literature on safety surrogate measures that analysts have used to assess the performance of the change interval and clearance interval. In general, the most reliable safety performance assessment of these intervals involves the frequency or severity of related crashes. However, if crash-based measures are challenging to quantify, analysts can use safety surrogate measures to infer a relative level of safety, provided the measure has a credible relationship with crash frequency or severity.

The review of the literature revealed that a wide range of surrogate measures have helped to assess the CCIs. The typical document cites the use of a measure to quantify the change in performance associated with a change in the duration of one or both intervals. A few of the documents describe a regression model that predicts a performance measure as a function of site characteristics. Only a couple of documents describe the need to conduct a performance assessment of installed intervals and then identify appropriate measures for this purpose. This section summarizes the findings from a review of these documents.

The more commonly reported performance measures focus on red light violations and include some type of normalization using an exposure measure. Table 6 identifies the family of potential measures that could help to assess CCI-related safety performance (Bonneson, Zimmerman, and Brewer 2002). The second column of table 6 lists a range of frequency-based measures that can help quantify CCI-related safety performance. Analysts have converted these measures into a rate or percentage using one or more of the exposure measures listed in the third column of the table. For example, analysts have reported frequency-based measure 4 as a rate in terms of “vehicles entering during the clearance interval per hour,” “vehicles entering during the clearance interval per cycle,” or “vehicles entering during the red clearance interval per total vehicles." A frequency or rate can be quantified for a given signal phase, an intersection approach, or the overall intersection.

Table 6. Change-period-related surrogate safety performance measures.

Time Period	Frequency-Based Measure	Exposure[a,b]	Location
During the change interval (Y_c)	1. Rear-end conflicts 2. Vehicles entering during Y_c 3. Cycles with one or more entries during Y_c	…per hour …per cycle …per vehicle	…per phase …per approach …per intersection
During the clearance interval (R_c)	4. Vehicles entering during R_c 5. Cycles with one or more entries during R_c 6. Vehicles in intersection at end of R_c (late exit) 7. Vehicles entering in first *x* seconds of R_c 8. Conflicts with opposing left-turn vehicle		
After the clearance interval (R_c)	9. Vehicles entering after R_c 10. Vehicles exiting after R_c 11. Right-angle conflicts		

Source: Bonneson, Zimmerman, and Brewer.

[a]*Per vehicle* relates to the total number of vehicles counted for the subject location.
[b]If the frequency measure is divided by the exposure measure and they have common units (e.g., cycles with one or more entries per cycle), then the ratio is often multiplied by 100 and expressed as a percentage.

Some of the surrogate measures listed in table 6 are more appropriate for evaluating the change interval, and some are more appropriate for evaluating the clearance interval. Practitioners and researchers widely use some of these measures but rarely use others of these measures. The remainder of this section addresses the more commonly used surrogate measures within the literature.

Yellow Change Interval

Performance Measures

Assessments of the change interval reported in the literature typically focus on red-light-violation-related measures. The units of measurement include the ratio of violation frequency and some measure of exposure (e.g., hour, signal cycles, and total vehicles). Table 6 previously discussed a wide range of possible performance measures.

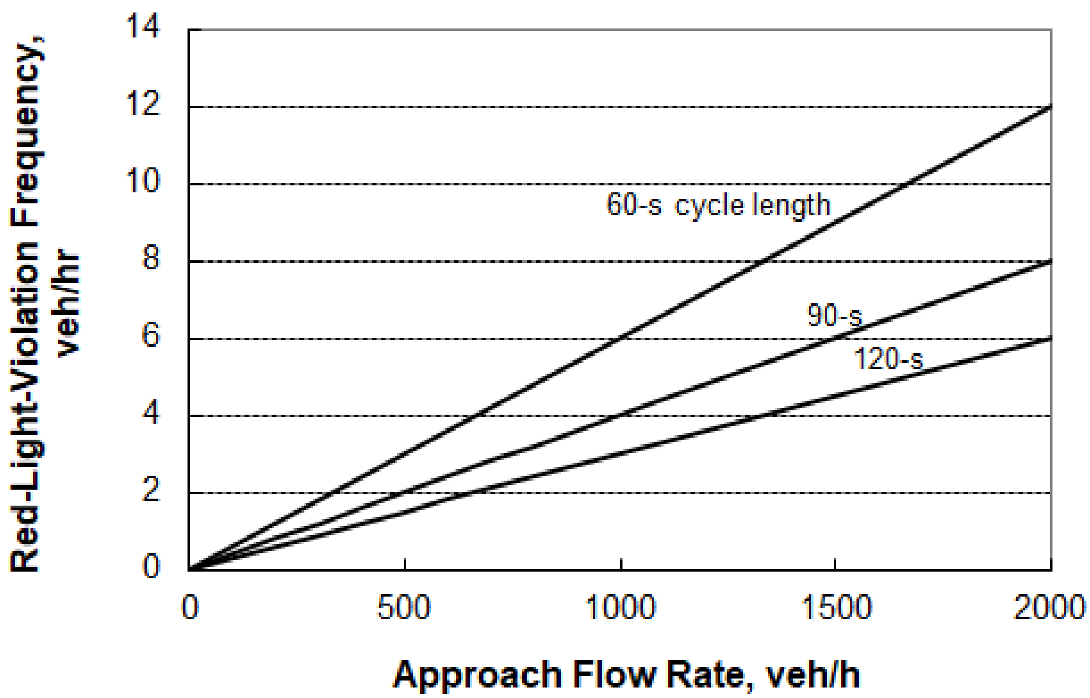
Guidelines for Determining Traffic Signal Change and Clearance Intervals (ITE 2020) identifies the following performance measures as useful for assessing the change interval duration:

- Percentage of vehicles entering the intersection after the termination of the change interval
- Percentage of cycles where one or more vehicles enter the intersection during the clearance interval

Of the two measures listed, *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020) advises that the first measure is the primary measure. It further advises that when this percentage exceeds a locally accepted value, engineers may lengthen the change interval to produce a percentage that conforms to the accepted value. It does not address the case where the percentage is less than a locally accepted value.

In Singapore, Lum and Wong (1998) observed 8.8 red light violations per 1,000 vehicles at intersections without camera enforcement. In the same city, Chin (1989) found the average red light violation rate was 0.33 violation per signal cycle. In the United Kingdom, Baguley (1988) measured red light violation frequency at seven intersections. The Baguley report found that drivers in the United Kingdom study violated the red at an average rate of 5.3 violations per 1,000 vehicles.

Bonneson, Zimmerman, and Brewer (2002) found that the frequency of RLR is highly correlated with traffic volume and the number of presented yellow indications per hour (i.e., the number of signal cycles per hour). The study recommended the use of red light violations per 10,000 vehicle-cycles. Based on a study of 10 intersections in Texas, Bonneson, Zimmerman, and Brewer (2002) reported an average red light violation rate of 1.0 violation per 10,000 vehicle-cycles. Figure 14 shows the frequency of red light violation that coincides with this rate. The trends in this figure indicate that red light violation frequency increases with increasing approach flow rate and with decreasing cycle length.



Source: Bonneson, Zimmerman, and Brewer.

s = seconds; veh/hr = vehicles per hour.

Figure 14. Graph. Predicted effect of flow rate and cycle length on red light violation frequency.

In recent years, many public agencies have installed automated traffic signal performance measures (ATSPMs) to monitor the service provided to travelers by their traffic control signals. Agencies traditionally use ATSPMs for signal operations and maintenance, but the measures can also quantify a variety of safety performance measures. To quantify CCI-related measures, these systems require the placement of a detector in each traffic lane, just downstream of the stop line. The system software excludes vehicles traveling slowly (e.g., less than 15 mph) to ensure that the vehicle count excludes vehicles turning (e.g., right-turn-on-red vehicles) or stopping on the detector. Measures that can be used to evaluate the safety performance of the yellow change interval include the count of yellow actuations (i.e., vehicles entering during yellow indication), red actuations (i.e., vehicles entering during red indication), and red light violation occurrences (i.e., vehicles entering after the end of the yellow indication) (Nevers et al. 2020).

Typically, the counts noted in the previous paragraph combine with other controller data to provide higher-order measures for assessing the relative crash potential among intersections. Higher-order measures that can help to assess the safety performance of the yellow change interval include average duration of yellow interval used, percent of vehicles entering during the yellow indication, and percent of vehicles entering during the red indication (i.e., percent red light violations) (Atkins North America 2016). The literature review did not identify any research reports describing an evaluation of the accuracy of these measures when obtained from an automated measurement system.

The examination of red light violation rates reported in the literature revealed significant differences in the definitions of a red light violation. Those studies that used an enforcement camera to measure violation frequency typically defined the violation as being any entry to the intersection after the grace period elapses. The issue in this instance is that the grace period typically varies among cities and camera vendors. Moreover, studies using manual observation typically define a violation as any entry after the onset of red (i.e., the studies use no grace period). These differences pose challenges to the comparison and interpretation of red light violation rates among studies.

A primary role of enforcement is to deter motorists from committing violations. Hence, citation data are likely to show an initial increase at the start of a heightened enforcement program and then a reduction as the program matures. Moreover, many enforcement agencies use citation rate as a measure of officer productivity. This usage introduces possible bias because it encourages officers to choose enforcement methods and locations that maximize the number of citations they write. For these reasons, traffic analysts should avoid using the frequency of citations as a measure for assessing CCI-related performance (Bonneson, Zimmerman, and Quiroga 2003).

Models for Predicting a Performance Measure

Bonneson and Son (2003) developed a model for predicting the frequency of red light violations. The researchers intended for analysts to use the model to determine if an intersection approach has potential for safety improvement and to evaluate various countermeasures (e.g., increase the change interval). The model is based on a probability-of-stopping model. The researchers estimated the model’s coefficients using data collected at 20 intersection approaches representing 10,018 observed signal cycles. The equation in figure 15 describes a model for pretimed signal phases.

$$N_{RV} = \frac{Q}{0.927\ C} ln[1 + exp(2.30 - 0.927\ Y_c - 0.334\ B_p + 0.0435\ V - 0.0180 L_p + 0.220\ R_p)]$$

Source: Bonneson and Son.

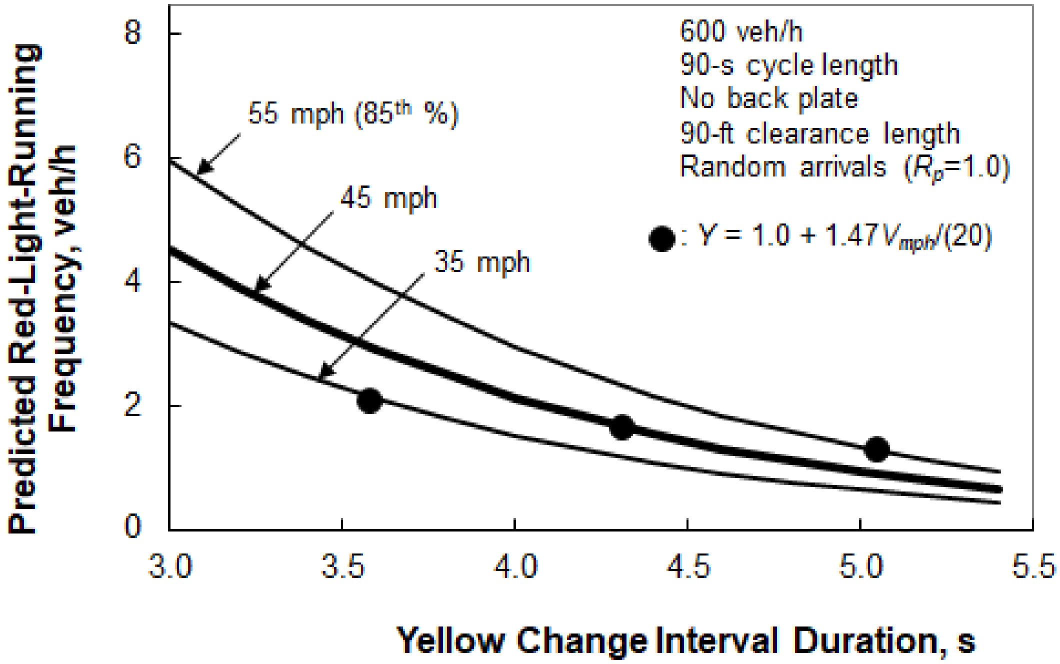
Figure 15. Equation. Predicted red light violation frequency.

Where:

N_{RV} = predicted average red light violation frequency (vehicles/hour)
Q = approach flow rate (vehicles/hour)
C = cycle length (seconds)
Y_c = yellow change interval duration (seconds)
B_p = indicator variable for back plate presence (= 1 if back plate present, 0 otherwise)
V = average running speed (mph)
L_p = clearance path length (ft)
R_p = platoon ratio (= phase end flow rate Q_e divided by Q)

Figure 15 indicates that red light violation frequency decreases with an increase in change interval duration, addition of signal back plates, reduction in running speed, increase in clearance path length, and decrease in platoon ratio (i.e., a reduction in quality of signal coordination).

Figure 16 illustrates the predicted effect of change interval duration and 85th-percentile speed on the frequency of red light violations (Bonneson and Son 2003). The researchers estimated 85th-percentile speed as being 12 percent higher than the average running speed. The trends in this figure indicate that, for the same change interval duration, the frequency of red light violations is higher on higher-speed approaches.



Source: Bonneson and Son.

ft = foot; mph = miles per hour; R_p = platoon ratio; s = seconds; veh/h = vehicles per hour; V_{mph} = average running speed; Y = yellow change interval duration.

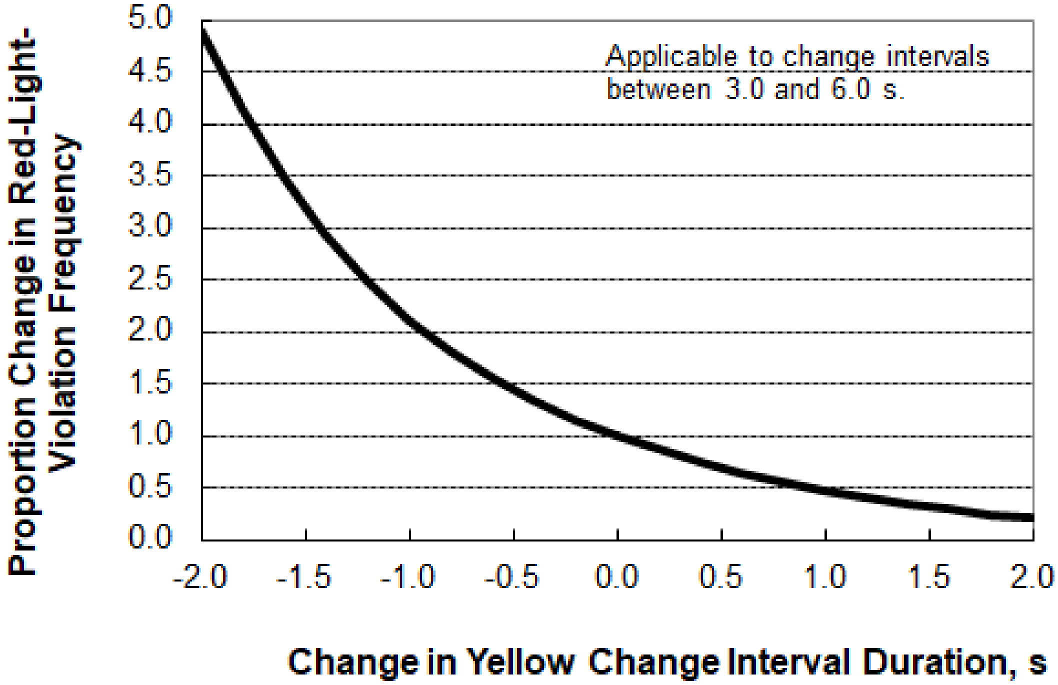
Figure 16. Graph. Predicted effect of yellow change interval duration and speed on red light violation frequency.

The dots in figure 16 indicate the change interval duration computed using the equation provided in the figure. The location of the dots suggests that use of this equation yields about 2.0 red light violations per hour (or 0.8 red light violation per 10,000 vehicle-cycles) for the conditions represented in the figure.

Performance Change due to a Change in Interval Duration

The frequency of vehicles entering the intersection after the termination of the change interval (i.e., red light violation frequency) has been the subject of study by several researchers. These researchers examined the change in red light violation frequency associated with an increase in the change interval duration.

Bonneson and Son (2003) used the equation in figure 15 to predict the effect of a change in change interval duration on the frequency of red light violations. Figure 17 shows this trend. The trend in this figure indicates that an increase in change interval duration decreases red light violations. For example, an increase in change interval duration of 1.0 second is associated with a proportion change of 0.47, which corresponds to a 53-percent reduction.



Source: Bonneson and Son.

s = seconds.

Figure 17. Graph. Predicted change in violation frequency associated with change in change interval duration.

Bonneson and Zimmerman (2004a) conducted a before-and-after study at 10 intersections in Texas. The research found that an increase of 1.0 second in the change interval duration (provided that the duration did not exceed 5.5 seconds) decreased the frequency of red light violations by at least 50 percent. This finding is consistent with the trend line in figure 17. Van der Horst (1988) reported a similar finding.

Retting, Ferguson, and Farmer (2008) conducted a before-and-after study at two intersections in Pennsylvania. The research found that an increase of 1.0 second in the change interval duration decreased the frequency of red light violations by 36 percent.

Red Clearance Interval

This section summarizes findings from a review of the literature on surrogate measures used to assess the safety performance of the red clearance interval.

Performance Measures

The literature has reported a few measures for assessing the performance of the clearance interval, and this section identifies these measures. Table 6 previously discussed a wide range of possible performance measures.

Guidelines for Determining Traffic Signal Change and Clearance Intervals identifies the "percent of cycles where one or more vehicles fail to clear the intersection during the clearance interval" (ITE 2020, page 69) as being useful for assessing the clearance interval duration. It acknowledges that if the change interval is too short, then vehicles will be in the intersection during the clearance interval even if the clearance interval duration is adequate. For this reason, it advises that analysts assess the change interval performance before assessing the clearance interval.

Retting and Greene (1997) quantified late exit cycles as a measure for assessing the performance of the clearance interval. The report defined a late exit cycle as a cycle where at least one vehicle from the subject approach was still in the intersection at the end of the clearance interval.

In recent years, many public agencies have installed ATSPMs at signalized intersections. To quantify CCI-related measures using ATSPMs and thereby evaluate the safety performance of the red clearance interval, agencies can use the count of red actuations. (i.e., vehicles entering during red clearance) (Nevers et al. 2020).

Typically, the count of red actuations combines with other controller data to provide higher-order measures for assessing relative crash potential among intersections. A higher-order measure that can help to assess the safety performance of the red clearance interval is the average duration of red clearance used (Atkins North America 2016). The literature review did not identify any research reports describing an evaluation of the accuracy of this measure when obtained from an automated measurement system.

Models for Predicting a Performance Measure

The literature review did not identify any models for predicting a surrogate-based clearance-interval-related performance measure. However, researchers could modify the equation in figure 15 to predict the frequency of vehicles entering after the end of the clearance interval. Researchers would achieve this modification by redefining the variable Y_c in the equation to Y_c = yellow change interval duration + red clearance interval duration, seconds. Further research is needed to confirm the reliability of this model extrapolation.

Performance Change due to a Change in Interval Duration

Retting and Greene (1997) evaluated the association between the percentage of late exit cycles and clearance interval duration. The authors conducted a before-and-after study with control groups at 20 intersection approaches in New York. The study found that the percentage of late exit cycles decreased at those approaches where the clearance interval increased.

Crash-Based Measures

This section documents findings from a review of the literature on crash-based measures that analysts have used to assess the performance of the change interval and clearance interval. The review revealed that analysts have used several crash-based measures to assess the CCIs. As with the review of safety surrogate measures, the typical document cites the use of a measure to quantify the change in performance associated with a change in the duration of one or both intervals. A few of the documents describe a model that predicts a performance measure as a function of site characteristics. Only one of the documents describes a process for conducting a crash-based performance assessment of installed intervals (Bonneson and Zimmerman 2004b). This section summarizes the findings from a review of these documents.

The more commonly reported performance measures focus on crash types often associated with the CCI. Table 7 identifies the family of potential crash-based measures that analysts could use to assess CCI-related safety performance.

Table 7. Change-period-related crash-based performance measures.

Time Period	Frequency-Based Measure	Severity	Exposure[a]	Location
During the change interval	1. Rear-end crashes	…fatal and injury …all severity levels	…per year …per vehicle	…per phase …per approach …per intersection
During the clearance interval	2. Opposing left-turn-related crashes			
After the clearance interval	3. Right-angle crashes			

[a]*Per vehicle* relates to the total number of vehicles counted for the subject location.

The second column of table 7 lists a range of frequency-based measures that analysts can use to quantify CCI-related safety performance. Analysts can convert each of these measures into a rate for a specific severity level using one or more of the exposure measures in the fourth column of the table. Analysts can quantify a frequency or rate for a given signal phase, an intersection approach, or the overall intersection. Some of the crash-based measures listed in table 7 are more appropriate for evaluating the change interval, and some are more appropriate for evaluating the clearance interval. Practitioners and researchers widely use some of these measures but rarely use others of these measures. The remainder of this section addresses the more commonly used crash-based measures within the literature, first discussing measures used to evaluate the yellow change interval and then measures to evaluate the red clearance interval.

Yellow Change Interval

Performance Measures

Bonneson and Zimmerman (2004b) developed guidelines for identifying intersection approaches with the potential for reducing fatal and injury red-light-related crash frequency on the subject approach and rear-end crash frequency on the subject approach. These procedures identify intersection approaches with significantly above-average numbers of red light violation crashes. The authors provided additional procedures to quantify the road-user benefit associated with a range of countermeasures (e.g., increase the change interval duration).

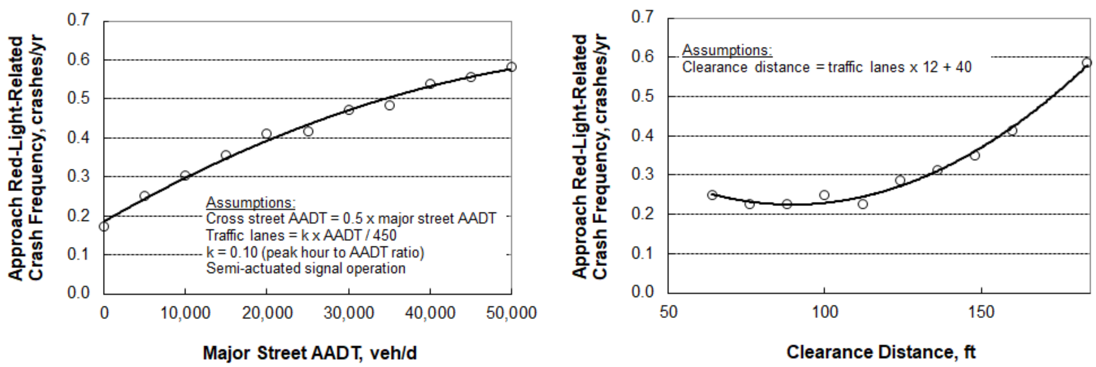
Persaud, Gross, and Srinivasan (2012) used the following measures to evaluate the safety effect of changes in the change interval duration:

- Total crash frequency (all crash types and severities) at the subject intersection
- Fatal and injury crash frequency (all crash types) at the subject intersection
- Rear-end crash frequency (all severities) at the subject intersection
- Right-angle crash frequency (all severities) at the subject intersection

Models for Predicting a Performance Measure

Mohamedshah, Chen, and Council (2000) used crash data from California to develop a regression model for predicting the frequency of crashes related to red light violations on an intersection approach. The database included 4,709 red-light-related crashes that occurred during a 4-year period at 1,756 four-legged, urban intersections. The researchers considered a variety of factors in the calibration of the model. The factors retained in the model included annual average daily traffic (AADT) on both intersecting streets, number of lanes crossed, presence of left-turn bays, and type of traffic control (i.e., pretimed, actuated, or semiactuated).

The data reported by Mohamedshah, Chen, and Council (2000) helped the authors of this report to examine the effect of AADT volume and lanes crossed on red-light-related crashes. Figure 18 shows the results of this examination. The study converted the number of lanes crossed to an equivalent distance required by the RLR driver to clear the intersection. The trends in this figure indicate that crashes related to red light violations increase with major street traffic volume and with an increase in clearance distance (provided that the clearance distance exceeds 100 feet).



Source: Federal Highway Administration. Source: Federal Highway Administration.

AADT = annual average daily traffic; ft = feet; k = peak hour volume/AADT ratio; veh/d = vehicles per day; yr = year.

A. Effect of major street traffic volume. B. Effect of clearance distance.

Figure 18. Graphs. Predicted effect of traffic volume and clearance distance on crash frequency.

Bonneson and Zimmerman (2006) developed a regression model for predicting the frequency of crashes related to red light violations on an intersection approach. The database included 296 red-light-related crashes that occurred during a 3-year period at 47 intersections in Texas. The researchers intended analysts to use the model to determine if an intersection approach has potential for safety improvement and to evaluate various countermeasures (e.g., increase the change interval). The equations in figure 19 describe this model.

$$N_{RC} = \left(\frac{Q_d}{1000}\right)^{0.509} exp[-4.70 + 0.186d_i + 0.533T_c]$$

with

$$d_i = \frac{1.47V_{sl}}{2(Y_c - 1)}$$

and

$$T_c = \left|\frac{L_p}{1.47V_{sl}} - 2.5\right|$$

Source: Bonneson and Zimmerman.

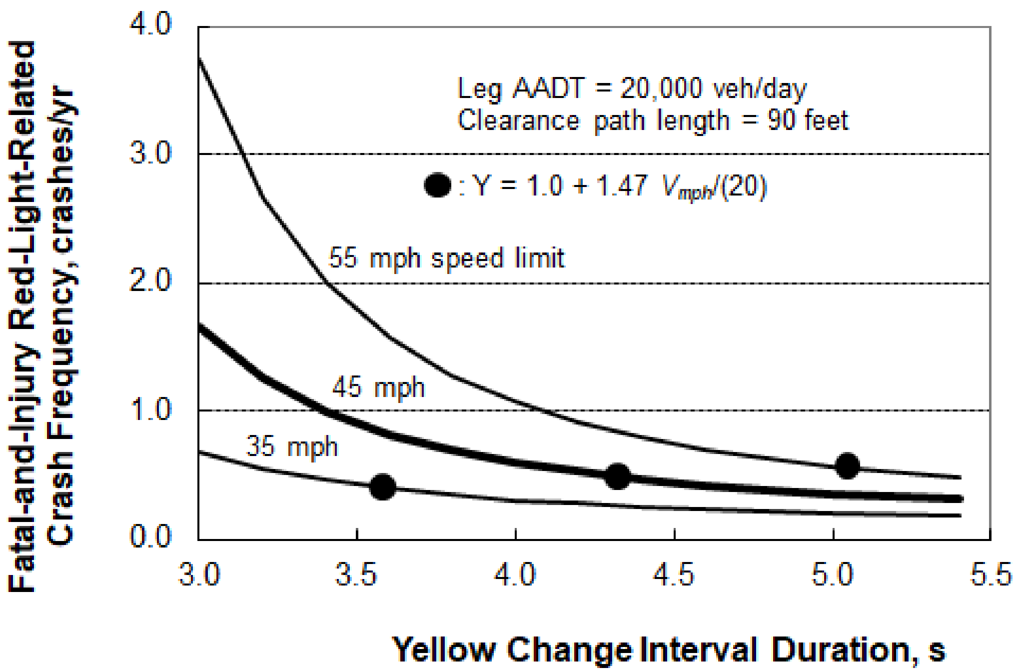
Figure 19. Equations. Predicted red-light-violation-related crash frequency.

Where:

NRC = predicted fatal and injury red-light-violation-related crash frequency for the subject approach (crash/year)
Qd = intersection leg AADT (two-way total) (vehicles/day)
di = deceleration implied by speed limit and change interval duration (ft/s2)
Tc = clearance time deviation (relative to 2.5) (seconds)
Vsl = approach speed limit (mph)
Yc = yellow change interval duration (seconds)
Lp = clearance path length (ft)

The equations in figure 19 indicate that red-light-violation-related crash frequency decreases with an increase in the change interval duration, a decrease in the approach speed limit, and a change in clearance time toward 2.5 seconds.

Figure 20 illustrates the predicted effect of change interval duration and speed limit on the frequency of fatal and injury red-light-violation-related crashes. The trends in this figure indicate that, for the same change interval duration, the frequency of red-light-violation-related crashes is higher on higher-speed approaches. This trend is similar to that for red light violation frequency shown in figure 16. The dots in figure 20 indicate the change interval duration computed using the equation provided in the figure. The location of the dots suggests that use of this equation yields about 0.5 fatal and injury red-light-violation-related crash per year for the conditions represented in the figure.



Source: Bonneson and Zimmerman.

AADT = annual average daily traffic; mph = miles per hour; s = seconds; veh/day = vehicles per day; V_{mph} = average running speed; *Y* = yellow change interval duration; yr = year.

Figure 20. Graph. Predicted effect of yellow change interval duration and speed on red-light-violation-related crash frequency.

Performance Change Due to a Change in Interval Duration

Several researchers have studied the frequency of CCI-related crashes. These researchers focused on the change in red-light-violation-related crash frequency associated with an increase in the change interval duration.

Persaud, Gross, and Srinivasan (2012) obtained data for 31 intersections at which the change interval or clearance interval duration had changed during an 11-year study and 135 intersections at which there had been no change in interval duration. The authors did not indicate how many phases or approaches had changed at each intersection. The study used a cross-sectional analysis of the data to determine the crash reduction associated with the modifications. Table 8 summarizes the findings related to the change interval. None of the computed changes in crash frequency are statistically significant, and they collectively do not demonstrate a consistent trend.

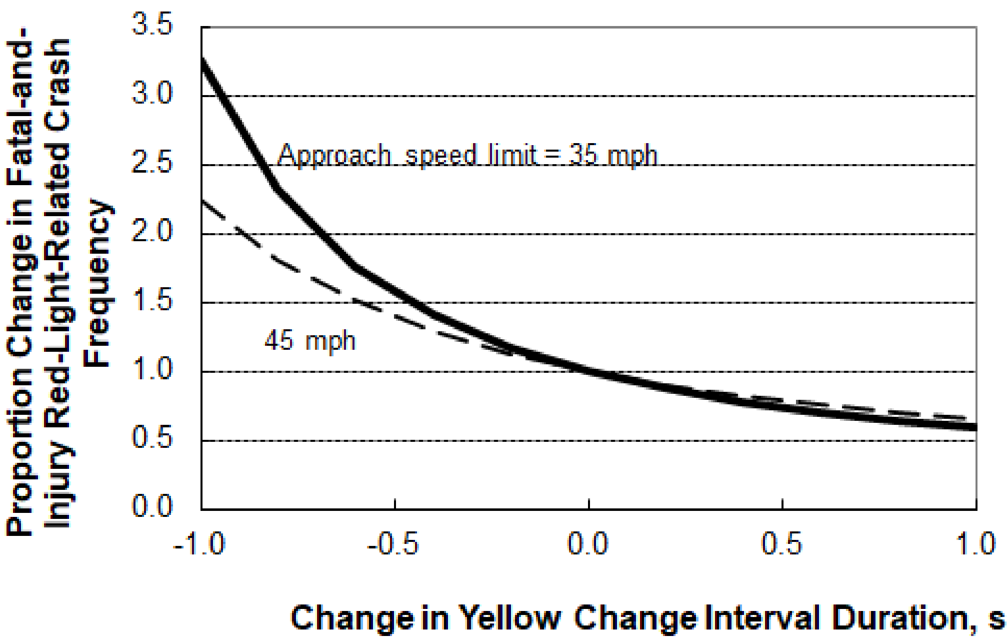
Table 8. Change in crash frequency associated with a modified change interval.

Modification	Number of Intersections Modified	Crash Type	Crash Severity Level	Change[a]
Increase change interval by 1.0 second	5	Rear end	All	6.6% decrease
		Right angle	All	7.6% increase
Increase change and clearance intervals (CCIs) by an average of 0.8 second and 1.2 seconds, respectively	11	Rear end	All	11.7% increase
		Right angle	All	3.9% decrease

Source: Persaud, Gross, and Srinivasan.

[a]None of the changes are statistically significant at the 0.05 level.

Bonneson and Zimmerman (2006) used the equations in figure 16 to predict the effect of a change in change interval duration on the frequency of fatal and injury red-light-violation-related crashes. Figure 21 shows this trend. The trend lines in this figure are consistent with those related to the change in red light violation frequency shown in figure 17. They indicate that an increase in change interval duration decreases red-light-violation-related crashes. For example, an increase in change interval duration of 1.0 second is associated with a proportion change of 0.60, which corresponds to a 40-percent reduction in crash frequency.



Source: Bonneson and Zimmerman.

mph = miles per hour; s = seconds.

Figure 21. Graph. Predicted change in fatal and injury red-light-related crashes associated with change in change interval duration.

Red Clearance Interval

Performance Measures

Souleyrette, McDonald, and O'Brien (2007) examined the relationship between the clearance interval duration and the frequency of target crashes. The authors defined target crashes as crash types that likely relate to red light violations or the presence of a red clearance interval. The crash types included in the target crash group were head-on, rear end, right angle, left turn, sideswipe, and right turn. The examination focused on target crash frequency for the overall intersection.

Persaud, Gross, and Srinivasan (2012) used the following measures to evaluate the safety effect of changes in the clearance interval duration:

- Total crash frequency (all crash types and severities) at the subject intersection
- Fatal and injury crash frequency (all crash types) at the subject intersection
- Rear-end crash frequency (all severities) at the subject intersection
- Right-angle crash frequency (all severities) at the subject intersection

Zimmerman and Bonneson (2005) examined photographs of crashes caused by a red light violation (as captured by automated enforcement cameras permanently installed at the intersection). The objective of the examination was to quantify the distribution of time-into-red that the red-light-violation-related crash occurred. This measure is informative about clearance interval performance but difficult to acquire given the limited number of automated enforcement cameras deployed in most cities.

Models for Predicting a Performance Measure

The literature review did not identify any models for predicting a crash-based clearance interval-related performance measure. However, Li and Abbas (2010) developed a stochastic simulation tool that incorporates models based on kinematics and driver behavior. The tool uses these models to compute the CCI durations that minimize a hazard index. This index represents a weighted-average probability of rear-end crash or right-angle crash as a result of a phase termination. The authors suggest using the tool to assess a specified intersection phase and its associated CCIs.

Performance Change due to a Change in Interval Duration

Souleyrette, McDonald, and O'Brien (2007) examined the relationship between the clearance interval duration and the frequency of several crash types that are likely related to red light violations or the presence of a red clearance interval (i.e., target crashes). The research identified four-legged signalized intersections in Minneapolis, with each intersection leg having a 30-mph speed limit. The researchers conducted a before-and-after study with 22 intersections having red clearance intervals and 47 intersections having no red clearance intervals. The study did not indicate how many phases or approaches at each of the 22 intersections had red clearance intervals. The study compared crash data from a 5-year before period with crash data from a

5-year after period. The study found that target crashes increased by about 30 percent at intersections where agencies added red clearance intervals.

Persaud, Gross, and Srinivasan (2012) obtained data for 31 intersections at which the change interval or clearance interval duration had changed during an 11-year study and 135 intersections at which there had been no change in interval duration. The study did not indicate how many phases or approaches had changed at each intersection. The study used a cross-sectional analysis of the data to determine the crash reduction associated with the modifications. Table 9 summarizes the findings related to the clearance interval. The first three rows of the table suggest that an isolated increase in the clearance interval can reduce crash frequency. However, the final three rows suggest that an increase in CCIs tends to be offsetting such that the net change in safety is negligible.

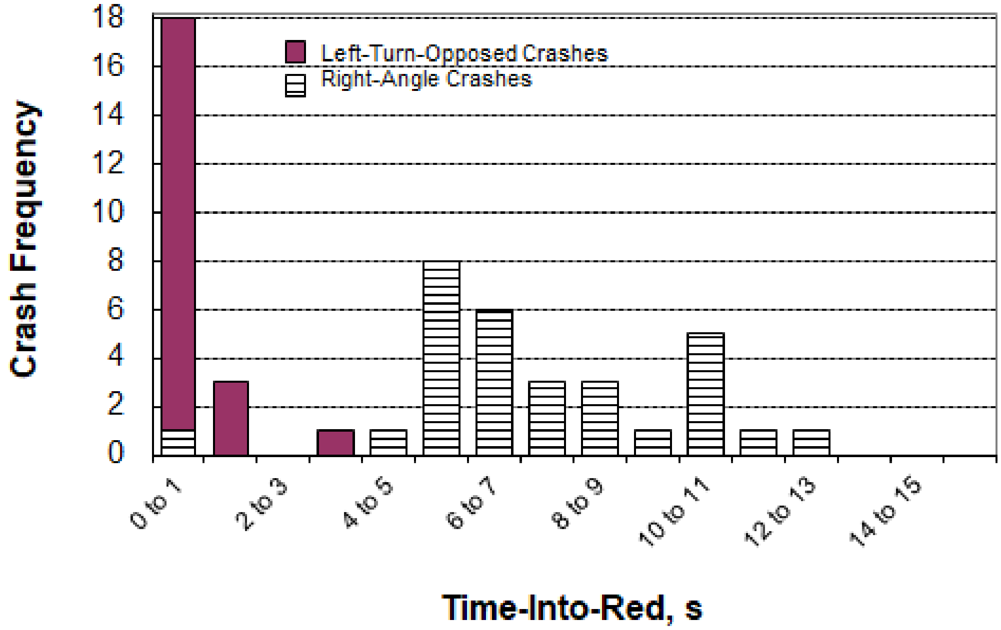
Table 9. Change in crash frequency associated with a modified clearance interval.

Modification	Number of Intersections Modified	Crash Type	Crash Severity Level	Change
Increase clearance interval by an average of 1.1 seconds	14	Rear end	All	19.6% decrease
		Right angle	All	3.4% decrease
		All	All	20.2% decrease[a]
Increase CCIs by an average of 0.8 second and 1.2 seconds, respectively	11	Rear end	All	11.7% increase
		Right angle	All	3.9% decrease
		All	All	0.9% decrease

Source: Persaud, Gross, and Srinivasan.

[a]Statistically significant at the 0.05 level.

Zimmerman and Bonneson (2005) examined photographs of 63 crashes caused by a red light violation (as captured by automated enforcement cameras permanently installed at the intersection). The researchers obtained photographs from intersections located in several States. Each photograph included a time stamp that indicated the time-into-red that the crash had occurred. The researchers separated distributions for the observed 22 opposing left-turn-related crashes and 41 right-angle crashes. Figure 22 shows the frequency of crashes as a function of time-into-red, as reported by Zimmerman and Bonneson (2005). The trends in this figure indicate that opposing left-turn-related crashes typically occur in the first few seconds of red. With one exception, the right-angle crashes occurred after 5.0 seconds of red. Based on these trends, Bonneson and Zimmerman (2004c) observed that increasing the red clearance interval is likely to reduce the portion of right-angle crashes that occur in the first few seconds of red. However, the researchers stated that these crashes are relatively infrequent, so increasing the red clearance interval may not significantly reduce the total number of right-angle crashes.



Source: Zimmerman and Bonneson.

s = seconds.

Figure 22. Bar chart. Crash frequency in the first few seconds of red.

Operations-Based Measures

This section describes findings from a review of operations-based measures used to assess the performance of the change interval and clearance interval. In contrast to the safety-based measures, the authors of this report found very few documents to describe operations-based measures.

The delay to vehicles served by a specific phase at a signalized intersection is a function of the effective green time available for their service. The effective green time is equal to the phase duration minus the phase lost time l_t. Figure 23 illustrates the *Highway Capacity Manual* (HCM) (Transportation Research Board (TRB) 2016) equation for computing the phase lost time.

$$l_t = l_1 + Y_c + R_c - e$$

Source: Transportation Research Board.

Figure 23. Equation. Phase lost time.

Where:

- l_t = phase lost time (seconds)
- l_1 = start-up lost time (≈ 2.0) (seconds)
- Y_c = yellow change interval duration (seconds)
- R_c = red clearance interval duration (seconds)
- e = extension of effective green (≈ 2.0) (seconds)

The variable definitions in figure 23 provide default values for start-up lost time and extension of effective green. When these default values are appropriate for a given location, the phase lost time computation is $l_t = Y_c + R_c$. In general, vehicle delay will increase with an increase in phase lost time (TRB 2016). Based on the relationships described in the previous paragraph, it follows that vehicle delay will increase with an increase in either the change interval, the clearance interval, or both.

Tarnoff (2004) examined the effect of clearance interval duration on phase capacity and vehicle delay for a typical signalized intersection. The author used an equation for computing vehicle delay as a function of cycle length, phase lost time, saturation flow rate, and phase traffic volume. Table 10 lists the computed delay values. The table values illustrate the effect on delay of increasing the clearance interval from 0.5 to 5.0 seconds. The values in the second and third columns of table 10 make this comparison when the phases have a volume-to-capacity ratio of 0.50. The fourth and fifth columns make this comparison when the volume-to-capacity ratio is 0.90. The values in the second and third columns indicate that the increase in the clearance interval duration increases vehicle delay by 0.6 to 1.9 seconds per vehicle when the volume-to-capacity ratio is low to moderate. However, if this ratio is high, then vehicle delay can increase by up to 15 seconds per vehicle for an eight-phase intersection.

Table 10. Predicted effect of red clearance interval duration and vehicle delay.

Number of Signal Phases	Vehicle Delay (seconds per vehicle) by Volume-to-Capacity Ratio (*v/c*)			
	***v/c* = 0.50**		***v/c* = 0.90**	
	R_c = 0.5 seconds	**R_c = 5.0 seconds**	**R_c = 0.5 seconds**	**R_c = 5.0 seconds**
2	0.4	1.0	1.8	5.3
4	1.3	2.4	6.8	13.1
6	2.8	4.3	15.8	25.8
8	4.8	6.7	30.0	45.6

R_c = red clearance interval duration.

BENCHMARKING

In addition to the literature review, the research team conducted a benchmarking survey to document the state of the practice for the CCIs. Due to the time required for approval of the benchmarking survey for distribution to a large number of State DOTs and local agencies, the research team distributed the benchmarking survey to only a small number of agencies. The next phase of the research will expand this survey to include additional State DOTs and local agencies.

The objectives of the survey are to (1) document the current state of the practice for future comparison, (2) identify barriers to the development and implementation of a nationally accepted standard for traffic signal CCIs within States and local agencies, and (3) help identify gaps and research actions to facilitate this development and implementation. Table 11 presents the research team’s list of data elements to collect from agencies during benchmarking.

Table 11. Proposed data elements to collect from agencies for benchmarking purposes.

Topic Area	Description
General information	• Name of agency • Agency type • Survey respondent name
Agency characteristics	• Number of signals managed by agency • Controller precision of CCI durations • Number of traffic engineers in agency • Number of technicians in agency
General policies	• Method used to determine duration of CCI • Allocation of time between CCIs • Practices, laws, and procedures that dictate CCI methods • Minimum and maximum durations for CCIs • Frequency of review of CCIs
Variables	• Use of variables (e.g., vehicle speeds of different movement types, vehicle length, and deceleration rate) • Variation of variables due to site condition (e.g., curvature, sight distance, and driveway density) • Value used for vehicle speeds (e.g., 85th-percentile speed and design speed) for different movement types • Procedure for field data collection of speed • Frequency of field data collection of speed • Procedure for measuring intersection width and grade
Special conditions	• Procedure for calculating CCIs for site characteristics (e.g., turn phases, large heavy-vehicle proportion, and bicycle phase)
Automated enforcement	• Use and count of automated enforcement devices • Duration of grace period • Case studies relevant to automated enforcement
Bicycle clearance	• Procedure for determining CCI for bicycle phases
Practice adjustments	• Recent changes to CCI timing practices • Data sources used to refine or evaluate CCI • Case studies related to impact of CCI

Benchmarking Survey Format

The research team developed a web-based user interface to collect data directly from respondents or to input data consistently. The web-based user interface used modern practices for accessible HyperText Markup Language Version 5, which allows dynamically adapting to respondents' answers as data collection occurs. This enables future data collection in an automated manner if the research team distributes the benchmarking survey to other agencies.

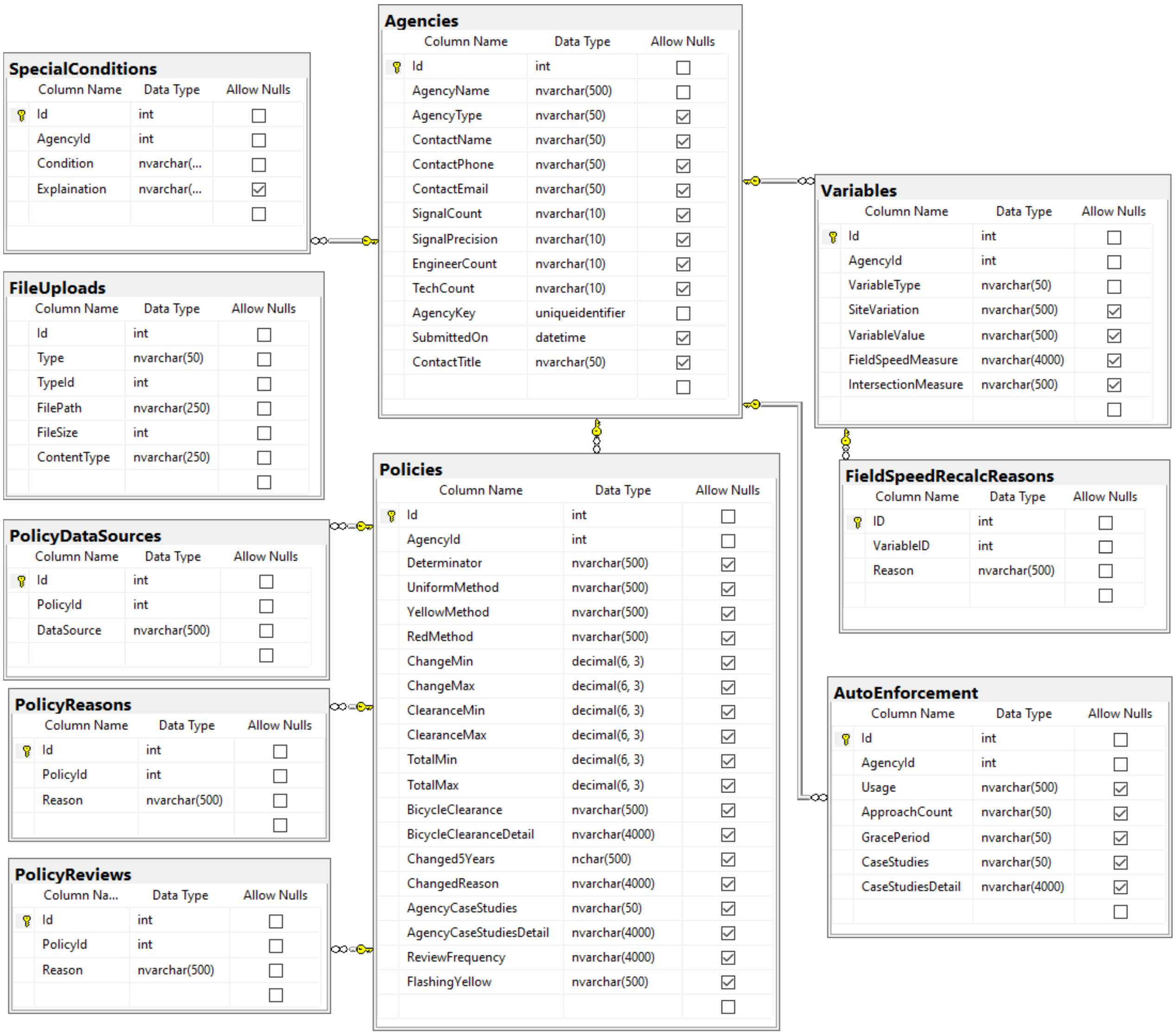
Data Storage

To store benchmarking data and information, the research team used a relational database and Structured Query Language (SQL). The database schema design modeled the relationships between data entities (survey questions and answers) and allowed for performant querying and analysis of the data. The team documented the data with a data dictionary. In the benchmarking plan, the team identified the key pieces of information and data and studied their common attributes and relationships to inform the database structure. Database documentation included a table schema and a data dictionary describing the columns and expected ranges of values. The goal of this documentation was to inform future researchers who may analyze the data but who may not have firsthand knowledge of the development or underlying structure of the database.

Database Structure

Figure 24 shows the structure of the relational database. Each box represents a table. The rows in the boxes are the column names. Each column lists the SQL data type as well as the nullability of the column. Most columns allow nulls so that respondents can answer questions sequentially. This is necessary because the null columns in existing rows will update after responses to each question. Also, because of the adaptive survey flowchart, the system will not pose all questions every time.

To accommodate multiselect questions, a separate and related table is necessary for each question that can have multiple answers. These tables relate to their base table. A line connecting the tables in the diagram represents this one-to-many relationship. The infinity symbol (∞) represents the many sides of this relationship. The key side of the line points to the table that holds the foreign key. Some questions ask the user to upload a file or several files. When a user uploads a file through the website, the database will track the file name and related question, file size, and content type. The process stores raw files on the web server’s file system. The database stores the relative local path of these files as they migrate to the web server.



Source: Federal Highway Administration.

Figure 24. Diagram. Relational database schema.

Database Access

Respondents can access the database through a web interface. Each respondent can access a unique link to their own instance of the survey. The team can choose to fill out the agency's name (question 1) on the survey, at which point the system creates a unique link that the research team can give to the agency contact and provide access to the additional questions. Researchers have direct access to the raw database with SQL queries, or through visualization software.

Benchmarking Survey Distribution List

The team distributed the benchmarking survey to 17 agencies. These agencies included State department of transportations (DOTs) and local agencies in the United States along with international agencies, as shown in table 12.

Table 12. Agencies in the benchmarking survey.

Agency Type	Name of Agency
State DOTs	Connecticut DOT
	Georgia DOT
	Illinois DOT
	Indiana DOT
	Maryland DOT
	Pennsylvania DOT
	Utah DOT
	Virginia DOT
City	City of Austin, TX
	City of Portland, OR
County	Washington County, OR
	Oakland County, MI
International	Australia
	Denmark
	Germany
	Japan
	Netherlands

Benchmarking Survey Results

Survey results showed that local agencies use 3 seconds as the minimum and 6 seconds as the maximum for the yellow change interval, consistent with the MUTCD. Some of the international agencies, however, use 2 seconds as the minimum yellow change interval. This can be, in part, due to the extensive presence of bicycle and tram signals in those countries, as their needs for the yellow change intervals may be different. Another finding is that while some agencies use a maximum for the red clearance intervals, others do not have an upper limit where intersection characteristics dictate the required red clearance interval.

Regarding the calculation methods used by agencies, approximately 70 percent of the respondents indicated they use ITE's traditional kinematic equation to calculate yellow change interval. One respondent indicated using the uniform method, and one respondent stated using a constant duration for the yellow change interval. For calculating the red clearance interval, responses varied by agency because some used the ITE equation and others used their own methods. Agencies that use some sort of equation (e.g., ITE traditional and ITE extended kinematic) to calculate yellow change interval indicated using the variables provided in the ITE equations (i.e., deceleration, grade, perception-reaction time, and approach speed). For approach speed calculations, most agencies use posted speed, while a few agencies use either design speed or 85th-percentile speed.

In terms of data sources agencies use to evaluate CCIs, most agencies indicated using field data and ATSPMs. A few other agencies stated they use basic safety messages (BSMs) from connected vehicles (CVs) and video trajectory data to evaluate CCIs.

Finally, agencies mentioned they use a few special conditions for CCI calculations, summarized as follows:

- For approaches with considerable heavy-vehicle activity, in calculation of the yellow change interval, some agencies use a deceleration value that is lower than 10 feet per second.

- Some international agencies estimate red clearance interval using the conflict-zone method previously discussed.

- For high-speed approaches where the calculation of the yellow change interval results in a value that is longer than 6.0 seconds, agencies add the additional amount (i.e., over 6.0 seconds) to the red clearance interval.

- For left-turning movements, for the calculation of yellow change interval, some agencies assume an approach speed of 25 mph, which typically results in a yellow change interval of 3.0 seconds. For protected only left turns, agencies assume a vehicle speed of 20 mph for the red clearance interval calculation.

SUMMARY OF WORK PUBLISHED OUTSIDE OF PEER REVIEWED AND PUBLIC SECTOR SOURCES

The review of work published outside of peer reviewed and public sector sources indicated that many of these documents focus on two topics with respect to CCIs: (1) articles that highlighted the limitations of the traditional kinematic equation for turning vehicles and introduced the extended kinematic equation to overcome these limitations and (2) articles that critiqued the mathematical basis and the assumptions made for the extended kinematic equation as well as recommended updates to the extended kinematic equation for turning maneuvers. Because the papers studied herein have not gone through peer review, the research team conducted a critical review of these papers by first summarizing papers and then concluding with observations regarding the merit of the paper's results. Additionally, it is important to note that for some of the work published outside of peer reviewed and public sector sources produced multiple versions of those documents on the same topic. As a result, this review presents only the original work rather than discussing different versions of the same work. Finally, the summary of this work also includes a summary of key discussions and comments from the ITE's e-Community forum regarding CCIs.

Articles Related to the Extended Kinematic Equation

Järlström self published articles (i.e., not peer-reviewed) to overcome the limitations of the kinematic equation for turning vehicles. In a 2020 article, Järlström provided a detailed overview of the kinematic equation developed by Gazis, Herman, and Maradudin (GHM) (1960). The article introduced an extended version of the kinematic equation to include deceleration required for turning vehicles and to overcome some of the limitations of the GHM solution[3]. This work influenced the *ITE Recommended Practice* (ITE 2020), introducing a new equation to determine yellow change intervals based on Järlström's extended kinematic equation. On the other hand, Järlström's work has resulted in new concerns among practitioners and researchers.

A fundamental premise of Järlström's extended equation is that the yellow duration should provide drivers at the critical distance either (1) sufficient time to go if they maintain speed or decelerate at the maximum deceleration rate to the entry speed or (2) sufficient distance to stop if they accept a deceleration greater than the maximum deceleration rate. To validate the extended kinematic equation (inclusive of the assumed driving behavior and associated turning vehicle trajectories), Järlström recorded vehicle motion data traversing GHM's critical distance (calculated using the original kinematic equation) for a right-turning vehicle by using a commercial data collection system that could interface with the controller area network (CAN) global positioning system (GPS) data logger. Video cameras mounted in the vehicle provided a view from the driver's perspective.

These data for a right-turning vehicle suggest that a vehicle decelerating within the critical distance before making a turn loosely follows the extended kinematic equation. The extended kinematic equation developed by Järlström is an advancement of the previous GHM equation. However, the proposed model has also generated the following concerns among practitioners and researchers:

- The extended kinematic equation assumes that turning drivers maintain their approach speed during the perception-reaction time. This assumption is questionable and would benefit from further research because, anecdotally, turning drivers start decelerating to the intersection entry speed (i.e., turning speed) well before the onset of the yellow indication.

- While the data recorded by Järlström indicate that a right-turning vehicle primarily followed the extended kinematic equation, the data were collected from only a single intersection and only for right-turning vehicles.

- In the data collection effort by Järlström, the driver was aware of the data collection, which might have resulted in an adjustment in driver behavior. As a result, further field data collection and research could help to better understand turning drivers' behavior before and at the onset of yellow.

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[3]Järlström, M. 2020. June 28. *An Extended Kinematic Equation*. Beaverton, OR:

- The extended kinematic equation sometimes results in yellow intervals for left turns (and protected right turns) that exceed the accepted limits used by some agencies.

- The calculated intervals sometimes conflict with the MUTCD guidance (FHWA 2009), which constrains the yellow duration to 3.0–6.0 seconds.

In a recent article, Beeber (2020) reviewed the required minimum yellow change interval for drivers approaching an intersection in both through and turning lanes. The article attempted to answer the question of where a turning driver must begin to decelerate to achieve the driver's target intersection entry speed. Beeber addressed this question because the extended kinematic equation assumes drivers preparing to turn decelerate at the same rate as when deciding to stop in response to yellow onset. This assumption is questionable because anecdotally, practitioners believe that drivers decelerate more gently when preparing for a turn than they do for coming to a complete stop following the onset of yellow. These practitioners believe that slowing down for a turn typically begins during the green indication, and if the signal display changes to yellow, the slowing is likely to continue during perception-reaction time. Practitioners also hold a belief that turning drivers require a smaller perception-reaction time than through drivers because turning drivers' impending turn maneuver encourages a heightened awareness of the intersection's proximity and signal status (e.g., they typically anticipate stopping).

To address this argument, Beeber showed that a driver need not begin decelerating to the target entry speed until closer to the intersection than the minimum stopping distance. Therefore, Beeber concluded that the assumptions for the extended kinematic equation are reasonable because they address the worst-case scenario or boundary condition.

While in theory it is correct that turning drivers need not decelerate gently before yellow onset, researchers should still consider (1) whether practitioners should design yellow change intervals based on this boundary condition, which leads to lengthy yellow durations for turning vehicles, and (2) how most turning drivers behave when approaching the intersection during the green indication. Based on this review of the Beeber article, agencies could not confidently apply the extended kinematic equation to turning movements until researchers can answer some additional questions. As a minimum, these additional questions should include:

- Where or when on the approach do turning drivers begin to decelerate to their turn speed?

- What are the decelerations and entry speeds of those turning drivers who decide to go in response to yellow onset?

- What is the deceleration of those turning drivers who decide to stop in response to yellow onset?

- What is the perception-reaction time of turning drivers in response to yellow onset?

Non-Peer Reviewed Work That Critiqued the Extended Kinematic Equation

To address the previously described concerns related to the extended kinematic equation for turning vehicles, several researchers and practitioners critiqued the extended kinematic equation and developed recommended updates to the extended kinematic equation for turning maneuvers. Okitsu suggested a modification to the extended kinematic equation[4]. In this modification, Okitsu assumed left-turning drivers start decelerating to the intersection entry speed (i.e., turn speed) before the critical point and that this deceleration is lower than the deceleration drivers use to safely stop when encountering a yellow signal. In his calculation, Okitsu assumed that drivers slow down from approach speed to intersection entry speed using an average (and constant) deceleration of 5 feet per second squared (ft/sec^2). This, in turn, results in shorter yellow change intervals compared with the kinematic equation.

Bonneson and Kittelson[5] (2020) conducted a detailed review of the extended kinematic equation, with a particular focus on the mathematical basis and the inherent assumptions. The article stated that the process of slowing down on the intersection approach during green is inherent to the turn maneuver and should affect the computation of yellow change interval for a turn movement. Following this notion, the researchers derived equations to determine the yellow change interval based on the worst-case situation, where the turning driver has decided to start slowing down for the turn a fraction of a second before the controller displays a yellow indication. A turning driver that starts to slow down for the turn well before the onset of the yellow indication would have sufficient distance to stop in response to a yellow signal, and therefore the analysis did not consider those vehicles.

Furth (2021) also developed a model for turning vehicles by using the kinematic relationship to address the same concern that the extended model results in excessively long yellow intervals for turning vehicles.[6] In his model, Furth assumed drivers who prepare for a turn decelerate more gently than they do for stopping at the onset of a yellow signal and that deceleration starts before reaching the critical point with respect to onset of a yellow signal. Similar to Okitsu's model, he also assumed 5 ft/sec^2 for the turn deceleration and 10 ft/sec^2 to decelerate at the onset of a yellow signal. Additionally, Furth assumed a perception reaction time of 1.0 second if a turning driver has not started decelerating and a perception-reaction time of 0.6 second if a driver has already started to slow down while preparing for a turn.

Table 13 provides a comparison of left-turn yellow interval durations by using the models reviewed and discussed in this document. Table 13 displays this comparison under varying approach speeds while assuming 20 mph for intersection entry speed and 10 ft/sec^2 for braking deceleration at the onset of a yellow signal (i.e., not when decelerating from intersection approach speed to intersection entry speed).

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[4]Okitsu, W. 2022. "Implementing Yellow Change Intervals for Turning Movements from the ITE Recommended Practice." Presented at ITE 2022 Annual Meeting. New Orleans, LA: ITE.
[5]Bonneson, J., and W. Kittelson, 2020. "Change Interval for Turning Movements."
[6]Furth, P.G., 2021. "Turn Lane Kinematics.".

Table 13. Comparison of left-turn yellow interval durations by different methods.

Approach Speed (mph)	Original Kinematic Equation (sec)	Extended Kinematic Equation (sec)	Okitsu's Model (sec)	Bonneson and Kittelson's Model (sec)	Furth's model (sec)
25	2.8	3.2	2.8	2.8	2.8
30	3.2	3.9	3.2	3.3	3.2
35	3.6	4.7	3.4	3.8	3.8
40	3.9	5.4	3.4	4.3	3.8
45	4.3	6.1	3.4	4.9	3.8
50	4.7	6.9	3.4	5.5	3.8
55	5.0	7.6	3.4	6.1	3.8

Results show that the proposed models result in yellow change intervals that are considerably lower than the extended kinematic equation for turning vehicles. However, researchers did not validate the recommended models using field data. Rather, the assumptions made (e.g., deceleration from approach speed to intersection entry speed) were based on judgment rather than field data. Therefore, as described in the review of the paper by Beeber, additional research will help to understand the trajectories and behavior of turning drivers under varying intersection and turn lane characteristics. Additionally, Okitsu's and Furth's models could benefit from additional sensitivity analysis.

Summary of Key Discussions from ITE's E-Community Forum

The topic of the CCI has also been a hot topic in the ITE's e-community forum and practitioners have discussed the topic extensively over the past several years. Since 2015, there were 20 distinctive topics from over 110 individuals related to the CCI. When reviewing the comments from ITE's e-community, researchers focused mostly on the comments that are beneficial for the future directions of the CCI Pooled Fund Study. The following provides a summary of key comments from the ITE's e-community forum.

Speed Studies

Several comments addressed the need for better understanding of the deceleration characteristics through speed measurements, which seems to be one of the cornerstones of potential future practices where more-observational methods help to determine CCIs. It seems that an effective and affordable speed measurement system is not yet available or in use for both through vehicles and turning vehicles for this purpose.

Driver Expectations and Adaptation

Many comments addressed the question of whether drivers adapt to traffic signal timing changes and how long such adaptations last. Also, several comments addressed drivers' learned habits and expectations regarding traffic signal timings and overall intersection settings. Given the lack of available data in this regard, future research should validate or reject the hypothesis regarding adaptability.

Variety of Users and Conditions

These comments discussed mainly the need for suggested practices to consider not only motorized traffic but also users of other transportation modes. Additionally, many comments in this category discussed the fact that no one formula can account for all traffic behaviors or vehicle types.

Automated Enforcement

Several individuals noted that the way certain agencies apply speed enforcement may make it challenging to set a national practice related to the CCIs. Specifically, most individuals questioned the precision used with automated enforcement (particularly with zero tolerance grace periods) when the guidance to determine CCIs relies on several assumptions.

Missing Studies

Multiple professionals pointed out that no research or studies address several of the questions related to CCIs. While some of these claims are likely because these professionals are not aware of such studies, future research may help to answer these questions. One of the most common comments in the ITE's e-community forum was about the lack of studies to back up the claim that lengthy yellow change intervals promote driver disrespect for the traffic control signal (the adaptation hypothesis noted above). Another missing study was the lack of substantial vehicle speed data (trajectories) for various posted speed limits and lane configurations related to CCIs. The *ITE Journal* provided a list of 11 research areas that would be useful in further refining the concepts and procedures in the ITE-recommended practice (Lindley 2020):

- Safety benefits of yellow change and red clearance intervals
- Impact on driver behavior and safety of yellow change intervals greater than 5 seconds
- Perception-reaction time and deceleration for alerted drivers for turning movements
- Approach and passage speed variations associated with different left-turn-lane characteristics
- Approach and passage speed variations for different right-turn-lane characteristics
- Passage speed variation on the path through an intersection from left or right turns
- Data collection methods for approach speeds of through movements compared with posted speed limits
- Approach speeds on nonposted roadways and on roadways with speed limits of 35 mph or less
- Easy-to-implement method to determine the length of travel path through intersections for turning movement and complex intersection geometries

- Effect of weather conditions
- Detector configuration

CHAPTER 4. PHASE II RESEARCH PLAN

Through review of national and international literature and agency practices and with feedback from the technical advisory panel (TAP) and FHWA, the research team identified two categories of research needs: (1) methods for determining traffic signal CCIs and (2) performance assessment (i.e., the outcomes of decision making) of traffic signal CCIs.

RESEARCH NEEDS FOR CALCULATION METHODS

Practitioners have not achieved a national consensus on how to determine the CCIs under a variety of operational conditions. To help overcome limitations of the existing methods and to help researchers determine appropriate methods, the following list suggests research needs related to methods for determining CCIs:

- **The effects of long yellow change intervals for through vehicles on driver behavior:** Some methods suggest caution in the use of a long yellow change interval and recommend using a maximum value (e.g., 5 seconds), since practitioners have a general perception that longer yellow change intervals encourage driver disrespect (researchers also need to specify the definition of *longer*). The literature has limited research on performance of longer yellow change intervals, specifically within its context and use on higher-speed roadways. Additional research can help better understand the effects of longer durations of yellow change intervals on driving behavior.

- **Speed, deceleration, and perception-reaction time assumptions for the kinematic equation:** The traditional kinematic equation (Gazis et al. 1960) many agencies adopt assumes a certain driver behavior model with assumptions on approach speed, deceleration, and perception-reaction time. A few researchers analyzed driver behavior for varying intersection conditions and found that most drivers do not conform to the kinematic model and assumptions. With recent advancements in data collection possibilities (particularly vehicle speed trajectories), additional research can now further investigate these assumptions.

- **Various speed assumptions of the extended kinematic equation:** The extended kinematic equation (Beeber 2020) uses approach speed and entry speeds to determine CCIs[1]. For turning movements, the extended equation suggests using the 85th-percentile approach speed based on the assumption that turning drivers maintain their approach speeds prior to the onset of yellow and during the perception-reaction time. (This assumption is based on figure 2.3 in *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020, page 15), where the initial speed, V_0, is shown to be constant in advance of and during the perception-reaction time period, t_{pr}.) This assumption needs to be further researched using field data because traffic engineers anecdotally believe that turning drivers are aware of the approaching turn location and

[1]Järlström, M. 2020. June 28. *An Extended Kinematic Equation*. Beaverton, OR:

start decelerating to the applicable intersection entry speed (i.e., turning speed) when they are in advance of the critical point (i.e., the point at which a through driver presented with the onset of a yellow indication and traveling at speed V_0 would have just enough distance to stop and just enough time to clear the stop line). Researchers need to further analyze perception-reaction time and deceleration for turning vehicles (both for right- and left-turning vehicles) for different left-turn configurations, age-groups, vehicle types, and approach speeds. It will be critical to developing relationships between properly posted speed limits and the speeds used in calculations (specifically for small agencies with limited resources), which will lead to greater uniformity of application.

- **CCIs for left- and right-turning vehicles:** Researchers should examine approach and passage speed variations for different left- and right-turn-lane characteristics (e.g., speed limits, turning geometry, age-groups, vehicle types, turn lane length, effects of conflicting pedestrians, weather, and protected versus permitted phasing) for the determination of CCIs for left- and right-turn phases.

RESEARCH NEEDS FOR PERFORMANCE ASSESSMENT

Over the past few decades, researchers have assessed the performance of CCIs (Wortman and Matthias 1983; Bonneson and Zimmerman 2004a; McGee et al. 2012). The findings in many areas have not been conclusive, which is partly because of the lack of formally recognized performance measures. Developing a clear and consistent way to assess how changes to yellow change and red clearance intervals impact the safety and efficiency of signalized intersections is of key importance for agencies managing traffic signals. This is especially the case in situations when newly recommended practices are unlikely to bring the benefits estimated by various engineering equations and models. In such cases, in addition to safety and efficiency's possibly not improving, these agencies may incur notable (and unnecessary) costs to modify the existing signal timings.

Based on the literature review, the research team recognizes research needs related to the performance measures. The team also recognizes the need for a process for assessing the performance of alternative CCIs. Researchers could use such a process for proposing new methods for estimating CCIs. Practitioners could use the process for determining suitability of the CCIs at a specified intersection. The following list provides suggested research related to the assessment of the CCIs:

- **Crash-based measures for assessing CCIs:** The literature has limited information about the effects of the duration of yellow change intervals on crash frequency. No studies have examined the safety effect of decreasing the duration of yellow change intervals or adding or modifying a red clearance interval. The literature review did not identify any studies that examine crashes associated with left-turn or right-turn movements (and their conflicting movements). The literature has no research on the variation of these CCI crash-based measures related to various speed limits (low speed, 20-25-30 miles per hour [mph]; medium speed, 35-40-45 mph; and high speed, 50-55-60 mph). Thus, new research can develop crash-based measures for assessing CCIs.

- **Safety surrogate measures for assessing CCIs:** Most of the research identified in the literature review focuses on the use of measures related to red light violations. The literature review did not identify any studies that examine the safety effects of a decrease in duration of the yellow change interval. No identified studies used safety surrogates to assess adding a red clearance interval or decreasing the duration of a red clearance interval. Finally, no identified studies examine conflicts associated with the left-turn or right-turn movements (and their conflicting movements). Thus, new research could develop safety surrogate measures for assessing CCIs.

- **Safety assessment procedure and measures:** The findings from the literature review did not reveal any formal procedure for assessing the performance of CCIs. Thus, new research could establish such a procedure for assessing the level of safety associated with alternative CCIs for a specified signal phase at an intersection. The research could identify appropriate performance measures and methods for quantifying these measures. Such a procedure could also be suitable for practitioners and researchers to test newly proposed methods for estimating CCIs.

- **Impact on driver behavior and safety of relatively long yellow change intervals:** Yellow change intervals that are shorter than needed by most drivers are likely to increase crash frequency. The literature has less information about the effects of yellow change intervals that are longer than needed. Anecdotal information suggests that longer yellow change intervals will increase crash frequency and promote driver disrespect for the traffic control signal; the literature is not definitive on this issue. New research could assess the impact of relatively long yellow change intervals on driver behavior and safety.

RESEARCH PLAN

Chapter 3 summarized key research needs in two categories: gaps related to methods for determining CCIs and gaps related to performance assessment of CCIs.

These two gaps correspond to two objectives of the research plan:

- Improve existing methods or develop new methods for determining CCIs that agencies can implement under varying operating conditions and intersection characteristics
- Develop a procedure to assess performance of the existing CCIs and identify attainable, measurable performance metrics for a quantitative assessment of interval changes

The purpose of the first objective is to propose improved methods to determine CCIs, especially for new traffic signal installations or when operational conditions of the traffic signals significantly change. The purpose of the second objective is to provide agencies a tool to assess how modifications to CCIs impact safety, efficiency, and other performance measures of the current signals. The second objective can help agencies quantify the effects of CCIs from a safety and mobility perspective.

The recent literature review identified several research studies that can fulfill both objectives. Table 14 shows experimental factors identified by stakeholders and the literature review (chapter 3). The research team considered these factors when developing the research studies presented in table 14. For each factor, the research team proposed a range of levels to test in the experiments. Some studies capture multiple factors, but no single study can cover all factors and levels. As such, the researchers prioritized factors they deemed to be of biggest interest in impact in the research studies presented in table 14 based on the research gaps identified. The research team developed eight studies and grouped them into three categories: (1) methods for determining CCIs, (2) performance metrics and evaluation process, and (3) related research questions that arose during the plan development.

Table 14. Factors to be considered for the relevant research studies.

Factor	Levels
Posted speed	Low, <30 mph; mid, 35-40-45 mph; high, >50 mph
Area	Urban/suburban/rural (with additional variety based on the land use; presence of multimodal operations and similar)
Street size	Small, 2 or 3 lanes; mid, 4 or 5 lanes; large, ≥6 lanes
Turn lanes	Existence (yes/no) Direction (left/right) Number (1, 2, 3) U-turn allowed (yes/no) Length (ft)
Cross-street size	Small, ≤50 ft; mid, 51–99 ft; large, ≥100 ft
Angle of cross street	90°, shallower, sharper (combined with approach versus entry speed?)
Traversed turning path through intersection	Length (*x* ft) Curvature (*y*-ft radius)
Grade	–6 percent to +6 percent by 1 percent
Access	Driveway influence in intersection approach (yes/no) Number (*x* driveways) Volume (*y* movements per driveway)
Parking	On-street parking (yes/no)
Vehicle movement	Left, through, right
Adjacent signal	<0.5 mile, ≥0.5 mile (corridor context coordinated or isolated)
Signal cycle length	≥90 seconds, 91–120 seconds, 121–180 seconds, ≥181 seconds (alternatively combine these with duration of waiting time or level of congestion)
Change interval	<4 seconds, 4.1–4.5 seconds, 4.6–5.0 seconds, 5.1–5.5 seconds, 5.6–6.0 seconds, ≥6.1 seconds
Clearance interval	0 seconds, ≤0.5 seconds, 0.6–1.0 seconds, 1.1–1.5 seconds, 1.6–2.0 seconds, 2.1–3.0 seconds, ≥3.0 seconds
Signal phasing	Permitted, protected, permitted/protected (P/P) lead, P/P lag
Automated enforcement	Yes (at intersection), in community, none
Vehicles	Passenger car, motorcycle, bus, recreational vehicle (RV), single unit (SU) truck, tractor/trailer truck, multiunit truck
Driver demographics	Socioeconomic characteristics
Driver familiarity	Commute versus recreational/event
Weather	Dry, wet, ice/storm
Detectors	Impact of detector configurations, locations, size, type of use

Research Studies on the Calculation Methods

Study 1: Driver Behavior Effects of Long Yellow Change Intervals for Through Vehicles

Objectives

The objectives of this study are to investigate whether long yellow change intervals for through vehicles (e.g., >4.5–5 seconds) impact driver behavior and red light running (RLR) differently from intersections with more-typical durations of yellow change intervals (<4.5–5 seconds). The definition of long yellow change intervals will be based either on the outcomes from a survey of relevant stakeholders or by defining a threshold or difference in relation to the default values obtained from the traditional kinematic equation (Gazis et al. 1960) versus those applied in the field. As an example, the traditional kinematic equation may yield 4.0 seconds of yellow change duration for a location, but the operator uses a value of 5.5 seconds for some reason (e.g., a different calculation method, a rule of thumb, need to implement the minimum value from another signal group, and rounding up to the next nearest half-second interval).

Example Hypotheses

Below are examples of hypotheses this research study should address.[2] To use statistically correct notation, the formulation of each null hypothesis states an opposite outcome of what a desirable expectation should be, such that the subsequent research outcomes can ideally reject the hypothesis.

- **$H1_0$:** The through vehicles at intersections with long (>4.5–5-second) yellow change intervals are less likely to engage in RLR than the same type of vehicles at intersections with more-typical yellow change intervals (<4.5–5 seconds).

- **$H2_0$:** The through vehicles at intersections with long (>4.5–5-second) yellow change intervals are less likely to enter the intersection on a late yellow than the same type of vehicles at the intersections with more-typical yellow change intervals (<4.5–5 seconds).

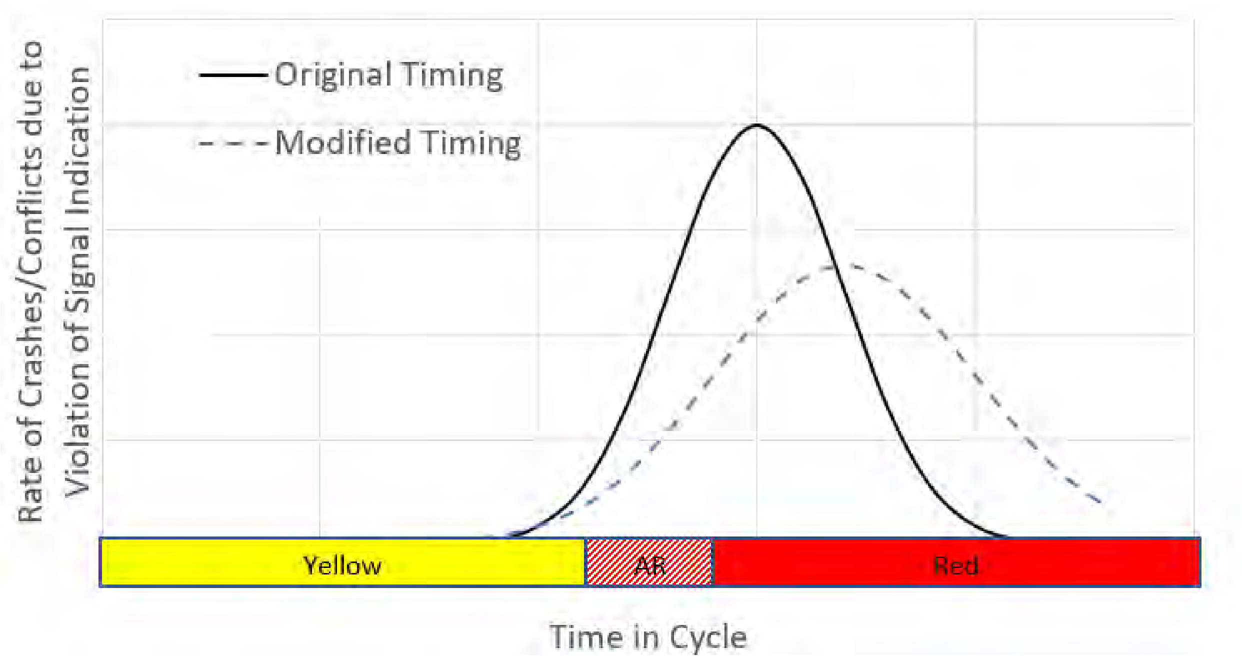
- **$H3_0$:** The through vehicles at intersections with long (>4.5–5-second) yellow change intervals are more likely to stop (probability of stopping, as a surrogate measure of driver's behavior) than the same type of vehicles at the intersections with more typical yellow change intervals (<4.5–5 seconds).

Expected Outcomes:

It is likely that the study will reject all relevant null hypotheses. The findings from this study should show that extensively long yellow times (e.g., >4.5–5 seconds) encourage through drivers to not stop, to enter the intersections late relative to the onset of yellow and red, and to run through the red light more often than when change intervals are shorter (<4.5–5 seconds). It is expected that the data used in this study can show that cumulative probability distributions (representing through vehicles' entrances) move to the right along the time axis (farther in

[2]The list of hypotheses is not inclusive, and it will depend on the extent of the study and type of data that are available.

yellow and red time) for longer yellow change intervals (figure 25). The results of this study should help to define the specific break point durations of a long versus typical change interval relative to intersection characteristics.



Source: Federal Highway Administration.

AR = all red.

Figure 25. Graph. Hypothetical impact of extended change interval on safety measures.

Methods

The researchers will work with a few agencies (e.g., a select number of pooled fund participant agencies) that have data before and after the agencies increased their yellow intervals for through vehicles. Considering that it may be difficult to find cases when an agency has increased the yellow change interval for through movements, the researchers will compare long yellow change interval intersections with control intersections having similar characteristics (e.g., approach speed and volume-to-capacity ratio). The analysis will focus on the proportions of vehicles arriving during the yellow change interval and during the red clearance interval. The researchers will study the probability of RLR, late-yellow arrivals, or similar performance measures to test the null hypotheses. This study could be either a before-and-after study or a comparison site study. The study could be a driving simulation study with a single driver going through intersections with different CCIs. The research team will assess feasibility and outcomes of various options.

As a subset of this study, researchers will try to investigate how drivers react when faced with inconsistently derived CCIs. This investigation will require identifying boundary conditions and agencies where such inconsistencies appear. This research question focuses on the need for and benefits of nationally uniform policies (more than what a single jurisdiction can accomplish alone). It may be valuable to know if it is difficult for drivers to acclimate to different CCIs (where such differences are significant). This study could occur at a signal test track or with a driving simulator.

Factors

The following factors could support the selection of data collection locations:

- Area type: urban/suburban/rural

- Change interval: <4.0 seconds, 4.1–4.5 seconds, 4.6–5.0 seconds, 5.1–5.5 seconds, 5.6–6.0 seconds, ≥6.1 seconds

- Clearance interval: 0 seconds, 0.1–0.5 seconds, 1.0–1.4 seconds, 1.5–1.9 seconds, 2.0–2.9 seconds, ≥3.0 seconds

- Driver familiarity (commute versus recreational/event)

- Grade: –6 percent to +6 percent by 1 percent

- Posted speed: low, <30 mph; mid, 35-–40-45 mph; high, >50 mph (approach versus posted)

- Street size: small, 2 or 3 lanes; mid, 4 or 5 lanes; large, ≥6 lanes

Several of these factors will be interdependent. For example, larger streets (with more lanes) that are often located in suburban areas will probably have higher speeds. For this reason, it may be infeasible to investigate all possible combinations of the factors given above. However, after applying some groups of factors (e.g., area type, posted speed, and street size), the other factors should help in selecting an appropriate distribution of locations across a national scale. For example, after selecting a group of jurisdictions with appropriate shorter and longer CCIs (which is the first priority), researchers should ensure that some of these locations fall within specific geometric conditions (posted speed, area type, and street size), have various entering grades, belong to different climate and geographic regions, and possibly feature heterogenous familiarity of the drivers. The following factors are not related to location and do not affect selection of data collection locations.

Researchers should continually record (to the extent possible) these varying factors during data collection and later analyze them for each selected location:

- Automated or enhanced enforcement: yes (at intersection), in community, none
- Driver demographics
- Signal cycle length: <90 seconds, 90–120 seconds, 121–180 seconds, ≥181 seconds
- Signal phasing: permitted, protected, P/P lead, P/P lag
- Vehicles: passenger car, motorcycle, bus, RV, SU, truck (tractor/trailer), etc.
- Weather: dry, wet, ice/storm

It is unlikely these factors will play an important role in the selection of specific locations for the research study. However, after selecting those locations, the researchers should thoroughly document conditions representing such factors during data collection. For example, while collecting the data, researchers should try to monitor conditions such as classification of the vehicles, weather, and signal phase state and timing. Importantly, these factors tend to be time variant.

The following factors are of relatively low importance for this research study, but researchers should nevertheless collect their data to enable any subsequent analyses or studies:

- Access (driveway influence in intersection approach):
    - Driveway influence in intersection approach (yes/no)
    - Number (*x* driveways)
    - Volume (*y* movements per driveway)

- Adjacent signal: <0.5 mile, ≥0.5 mile (corridor context coordinated or isolated)

- On-street parking (yes/no)

- Angle of cross street: 90°, shallower, sharper (combined with approach versus entry speed?)

- Cross-street size: small, ≤50 ft; mid, 51–99 ft; large, ≥100 ft

- Impact of detector configurations, locations, size, and type of use

- Traversed turning path through intersection:
    - Length (*x* ft)
    - Curvature (*y*-ft radius)

- Turn lanes:
    - Existence (yes/no)
    - Direction (left/right)
    - Number (1, 2, 3)
    - (U-turn allowed = yes/no)
    - Length (ft)

- Vehicle movement: left, through, right

These factors are time-invariant factors whose statuses are stable. These factors will usually be constant for each studied intersection approach. Nevertheless, researchers should collect information about these factors to ensure the data can support subsequent analyses.

Data Collection

For this analysis, video data associated with appropriate feature extraction software can help extract relevant data. Other possible data sources for this study may include ATSPM data, where these data are not to replace but to complement the video data. The resulting data would help in developing cumulative probability distributions of drivers entering the intersection relative to the onset of yellow and red. Another alternative would be to collect such data from a driver simulator environment, in which case it would be necessary to train drivers to become familiar with the long yellow duration and observe how drivers' responses change over time (e.g., whether they are more likely or less likely to run red lights over time). To address all proposed hypotheses, this study will require collecting video data that can help to derive relevant performance metrics (e.g., probability of stopping), which will most likely require that multiple vehicular events (e.g., crossing stop and exit lines) be extracted from the videos. On the signal side, this study will require high-resolution (e.g., 10-hertz (Hz) (10-times-per-second frequency)) signal status data for CCIs.

Study 2: Understanding Driving Behavior When Reacting to Yellow Change Intervals for Through Movements

Objectives

The objectives of this study are to understand driver behavior under various traffic conditions for through movements. This study will primarily observe and analyze how drivers react prior to and at the onset of yellow (e.g., by analyzing how many drivers stop or clear the intersection). The study will also analyze approach speed, perception-reaction time, and deceleration rates associated with specific external factors that may impact driving behavior. Thus, this study will investigate how different these characteristics are for various factors that impact driving behavior and compare these factors (i.e., approach speed, perception-reaction time, deceleration) with the assumptions used by the traditional kinematic equation (Gazis et al. 1960).

Example Hypotheses

Below are examples of hypotheses this research study should address:

- **$H1_0$:** The traditional kinematic equation assumes an approach speed that is greater than shown from the field data, for 95 percent of the vehicles and standardized intersection conditions.

- **$H2_0$:** The traditional kinematic equation assumes a perception-reaction time that is longer than shown from the field data, for 95 percent of the vehicles and standardized intersection conditions.

- **$H3_0$:** The traditional kinematic equation assumes a deceleration that is smaller than shown from the field data, for 95 percent of the vehicles and standardized intersection conditions.

Expected Outcomes

It is likely the experiments will result in a rejection of all null hypotheses. The findings from this study are likely to show that widely accepted values for approach speed, perception-reaction time, and deceleration are different from those observed in the field and that they are results of multiple factors, including age of the driver, geometry of the intersection, urban context, existence of the warning devices, etc. It is likely that field data can help in developing (e.g., by model-fitting techniques) a family of relationships that will show how these driving characteristics vary in different operational conditions.

Methods

This study will investigate driver behavior measured through approach speed, perception-reaction time, and deceleration of vehicles when drivers approach a signalized intersection and may face a change interval. The study will focus on different geometric and operational conditions, including various approach speeds (e.g., 35, 40, and 45 mph), amount of multimodal activity, ages of drivers, and presence of warning devices. The probability of stopping, percentages of vehicles entering after termination of the change interval and during the clearance interval, and other, similar performance measures will help assess the impact of wrong assumptions about driving behavior characteristics.

Factors

The following factors could support the selection of data collection locations:

- Area: urban/suburban/rural
- On-street parking (yes/no)
- Driver familiarity (commute versus recreational/event)
- Grade: –6 percent to +6 percent by 1 percent
- Posted speed: low, <30 mph; mid, 35-–40-45 mph; high, >50 mph (approach versus posted)
- Street size: small, 2 or 3 lanes; mid, 4 or 5 lanes; large, ≥6 lanes

Researchers do not have to consider the following factors when selecting where to collect relevant data. However, researchers should continually record these factors (to the extent possible) during data collection (as they vary) and later analyzed for each selected location:

- Automated or enhanced enforcement: yes (at intersection), in community, none
- Driver demographics
- Signal cycle length: <90 seconds, 90–120 seconds, 121–180 seconds, ≥181 seconds
- Signal phasing: permitted, protected, P/P lead, P/P lag
- Vehicles: passenger car, motorcycle, bus, RV, SU, truck (tractor/trailer), etc.
- Weather: dry, wet, ice/storm

The following factors are of relatively low importance for this research study, but researchers should collect their data to enable any subsequent analyses/studies:

- Access (driveway influence in intersection approach):
    - Driveway influence in intersection approach (yes/no)

    - Number (*x* driveways)
    - Volume (*y* movements per driveway)

Adjacent signal: <0.5 mile, ≥0.5 mile (corridor context coordinated or isolated)

- Angle of cross street: 90°, shallower, sharper (combined with approach versus entry speed?)

- Change interval: <4.0 seconds, 4.1–4.5 seconds, 4.6–5.0 seconds, 5.1–5.5 seconds, 5.6–6.0 seconds, ≥6.1 seconds

- Clearance interval: 0 seconds, 0.1–0.5 seconds, 1.0–1.4 seconds, 1.5–1.9 seconds, 2.0–2.9 seconds, ≥3.0 seconds

- Cross-street size: small, ≤50 ft; mid, 51–99 ft; large, ≥100 ft

- Impact of detector configurations, locations, size, and type of use

- Turn lanes:
    - Existence (yes/no)
    - Direction (left/right)
    - Number (1, 2, 3)
    - U-turn allowed (yes/no)
    - Length (ft)

- Traversed turning path through intersection:
    - Length (*x* ft)
    - Curvature (*y*-ft radius)

- Vehicle movement: left, through, right

Data Collection

Possible data sources may include individual vehicle trajectories from either connected-vehicle data (e.g., one-10th-of-a-second resolution), extracted movements from video footage, or a similar data source (e.g., a custom in-vehicle video setup) overlaid with the signal status data. From traffic signal data, this study will likely require status of the relevant traffic signal phases or groups recorded at 10-Hz frequency.

Study 3: Understanding Driving Behavior When Reacting to Yellow Change Intervals for Turning Movements

Objectives

The objective of this study is to understand driver behavior under various traffic conditions for left- and right-turn movements. This study will primarily observe and analyze how turning drivers react prior to and at the onset of yellow (e.g., by analyzing how many drivers stop or clear the intersection). The study will also analyze approach and entry speeds, perception-reaction time, and deceleration associated with specific external factors that may impact the driving behavior for turning vehicles. Thus, this study will investigate the way these driving characteristics vary for different factors that impact driving behavior for left and right turns and compare these driving characteristics with the assumptions used by the extended kinematic equation (Beeber 2020)[3].

Example Hypotheses

Below are examples of hypotheses this research study should address:

- **$H1_0$:** The approach speed at an intersection as used by the extended kinematic equation exhibits a uniform trend (constant value) during the initial phase of the approach (before and during the perception-reaction time).
- **$H2_0$:** The deceleration, after applying brake, as used by the extended kinematic equation, has a uniform trend and applies at the maximum (safe and comfortable) rate between the start of braking and entrance at the intersection.
- **$H3_0$:** The entry speed at an intersection as used by the extended kinematic equation exhibits a uniform trend (constant value) between the entry and exit points on the path crossing the intersection.
- **$H4_0$:** The extended kinematic equation requires a shorter change interval for left-turn vehicles than shown from the field data (e.g., for 95 percent of the vehicles and standardized intersection conditions).
- **$H5_0$:** The extended kinematic equation requires a shorter change interval for right-turn vehicles than shown from the field data (e.g., for 95 percent of the vehicles and standardized intersection conditions).
- **$H6_0$:** The extended kinematic equation requires a shorter clearance interval for left-turn vehicles than shown from the field data (e.g., for 95 percent of the vehicles and standardized intersection conditions).
- **$H7_0$:** The extended kinematic equation requires a shorter clearance interval for right-turn vehicles than shown from the field data (e.g., for 95 percent of the vehicles and standardized intersection conditions).

Expected Outcomes

It is likely the experiments will result in a rejection of all null hypotheses. Field data will likely show that the kinematic characteristics are not constant for turning vehicles but vary based on several external factors and vary with driver behavior. The findings from this study are also likely to show a family of relationships that defines CCIs based on a variety of independent variables (approach speed, entry speed, length of turn bay, type of phasing, etc.). It is also likely

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[3]Järlström, M. 2020. June 28. *An Extended Kinematic Equation*. Beaverton, OR:.

that findings from this study may shift attention, at least for some operations, from change time to the clearance time and vice versa.

Methods

The researchers will work with a select number of pooled fund participant agencies that have relevant before-and-after data to measure the approach and entry speeds and compare those values with the values suggested by the extended kinematic equation (Beeber 2020)[4]. The analysis should account for various types of approach speeds (e.g., 20–60 mph in 5-mph increments), turn bay characteristics (short length, long length, double lane), different phasing designs (protected only, protected/permitted, flashing yellow arrow), levels of multimodal users, age-groups, and vehicle types. The trends assumed in the hypotheses above will be either confirmed or rejected.

Factors

The following factors could support the selection of data collection locations:

- Area: urban/suburban/rural

- Traversed turning path through intersection:
    - Length (*x* ft)
    - Curvature (*y*-ft radius)

- Driver familiarity (commute versus recreational/event)

- Grade: –6 percent to +6 percent by 1 percent

- Posted speed: low, <30 mph; mid, 35-–40-45 mph; high, >50 mph (approach versus posted)

- Signal phasing: permitted, protected, P/P lead, P/P lag

- Street size: small, 2 or 3 lanes; mid, 4 or 5 lanes; large, ≥6 lanes

- Turn lanes:
    - Existence (yes/no)
    - Direction (left/right)
    - Number (1, 2, 3)
    - U-turn allowed (yes/no)
    - Length (ft)

- Vehicle movement: left, through, right

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[4]Järlström, M. 2020. June 28. *An Extended Kinematic Equation*. Beaverton, OR:.

The following factors do not affect the appropriate data collection locations. However, researchers should continually record (to the extent possible) the following factors during data collection as they vary, and later analyze them for each selected location:

- Automated or enhanced enforcement: yes (at intersection), in community, none
- Driver demographics
- Signal cycle length: <90 seconds, 90–120 seconds, 121–180 seconds, ≥181 seconds
- Vehicles: passenger car, motorcycle, bus, RV, SU, truck (tractor/trailer), etc.
- Weather: dry, wet, ice/storm

The following factors are of relatively low importance for this research study, but their data should be collected to enable any subsequent analyses/studies:

- Access (driveway influence in intersection approach)
    - Driveway influence in intersection approach (yes/no)
    - Number (*x* driveways)
    - Volume (*y* movements per driveway)

Adjacent signal: <0.5 mile, ≥0.5 mile (corridor context coordinated or isolated)

- On-street parking (yes/no)

- Angle of cross street: 90°, shallower, sharper (combined with approach versus entry speed?)

- Change interval: <4.0 seconds, 4.1–4.5 seconds, 4.6–5.0 seconds, 5.1–5.5 seconds, 5.6–6.0 seconds, ≥6.1 seconds

- Clearance interval: 0 seconds, 0.1–0.5 seconds, 1.0–1.4 seconds, 1.5–1.9 seconds, 2.0–2.9 seconds, ≥3.0 seconds

- Cross-street size: small, ≤50 ft; mid, 51–99 ft; large, ≥100 ft

- Impact of detector configurations, locations, size, and type of use

Data Collection

For this analysis, high-resolution trajectory (every one-10th of a second) data will be key to extracting required speeds and accelerations at the highest level of accuracy. The data will need to cover a wide range of operational and geometrical conditions, age-groups, vehicle types, and approach speeds. Potential data sources could include connected-vehicle data, extracted vehicular movements from video footage, custom in-vehicle video data collection, or similar data in combination with the signal status data. Researchers could consider driving simulation data if they could validate and train that data against a relevant field data sample. From the perspective of traffic signal data, this study should require status of the relevant traffic signal phases or groups recorded at 10-Hz frequency.

Research Studies on Performance Assessment

The following three research studies focus on performance assessments for CCIs. The findings from these studies will fill the existing research gaps and help practitioners and researchers understand how modifications to the CCIs impact safety and operations at signalized intersections.

Study 4: Crash Safety Assessment of Yellow Change and Red Clearance Intervals

Objectives

The objectives of this study are to (1) determine crash-based measures (i.e., target crashes) suitable for evaluating the CCI associated with a given signal phase and (2) quantify the change in the frequency and severity of target and total crashes associated with a modification to the CCIs.

Previous similar research studies either have not investigated or did not produce conclusive findings on:

- Impact of decrease in yellow change interval duration on safety metrics (e.g., crash frequency)
- Impact of either increase or decrease of red clearance interval duration on safety metrics
- Crashes associated with the CCIs of left-turn or right-turn movements

Example Hypotheses

Below are examples of hypotheses this research study should address[5]:

- **$H1_0$:** Fatal and injury RLR-related crash frequencies increase with an increase in yellow interval.
- **$H2_0$:** Total RLR-related crash frequencies increase with an increase in yellow change interval.
- **$H3_0$:** Fatal and injury RLR-related crash frequencies increase with an increase in clearance interval.
- **$H4_0$:** Total RLR-related crash frequencies increase with an increase in clearance interval.

Expected Outcomes

The analytic tools developed to achieve the second objective should help in predicting the average crash frequency (by severity) for a specific signal phase and movement combination as a

[5]Hypothesis can expand to several similar hypotheses with various types of crashes (e.g., rear end, opposing left turn, and right angle).

function of the change interval, the clearance interval, and other site characteristics. These tools should support the identification of locations with the potential for safety improvement through changes to the CCIs. They should also support the safety evaluation of alternative CCIs at specified locations (including alternatives where a reduction in interval duration is under consideration). Figure 20 previously showed an example of a relationship that predicts crash frequency as a function of a yellow interval duration.

Methods

The research team will address the objectives uniquely for each of the following movements: left turn, through, and right turn. The researchers will consider analyses incorporating nonmotorized modes of traffic. The research team will also consider CCI performance for alternative types of left-turn operation, such as protected only, permitted only, and protected permitted.

Factors

The following primary factors could support the selection of data collection locations:

- Area: urban/suburban/rural
- On-street parking (yes/no)
- Change interval: <4.0 seconds, 4.1–4.5 seconds, 4.6–5.0 seconds, 5.1–5.5 seconds, 5.6–6.0 seconds, ≥6.1 seconds
- Clearance interval: 0 seconds, 0.1–0.5 seconds, 1.0–1.4 seconds, 1.5–1.9 seconds, 2.0–2.9 seconds, ≥3.0 seconds
- Driver familiarity (commute versus recreational/event)
- Grade: –6 percent to +6 percent by 1 percent
- Posted speed: low <30 mph; mid 35–40–45 mph; high >50 mph; (approach versus posted)
- Signal phasing: permitted, protected, P/P lead, P/P lag
- Street size: small, 2 or 3 lanes; mid, 4 or 5 lanes; large, ≥6 lanes
- Turn lanes:
    - Existence (yes/no)
    - Direction (left/right)
    - Number (1, 2, 3)
    - U-turn allowed (yes/no)
    - Length (ft)
- Vehicle movement: left, through, right

The following factors are of relatively low importance for this research study, but researchers should collect their data to enable subsequent analyses/studies:

- Access (driveway influence in intersection approach):
  - Driveway influence in intersection approach (yes/no)
  - Number (*x* driveways)
  - Volume (*y* movements per driveway)

- Traversed turning path through intersection:
  - Length (*x* ft)
  - Curvature (*y*-ft radius)

- Adjacent signal: <0.5 mile, ≥0.5 mile (corridor context coordinated or isolated)

- Angle of cross street: 90°, shallower, sharper (combined with approach versus entry speed?)

- Automated enforcement: yes (at intersection), in community, none

- Cross-street size: small, ≤50 ft; mid, 51–99 ft; large, ≥100 ft

- Driver demographics

- Impact of detector configurations, locations, size, and type of use

- Signal cycle length: <90 seconds, 90–120 seconds, 121–180 seconds, ≥181 seconds

- Vehicles fleet (expected percentages): passenger car, motorcycle, bus, RV, SU, truck (tractor/trailer), etc.

- Weather: dry, wet, ice/storm

Data Collection:

This study will use crash data from a representative number of sites with operational conditions that correspond to the intended purposes of this study (e.g., various types of movements, various phasing designs, and multimodal users). The researchers will work with stakeholders to identify representative locations that properly cover various geographic, operational, and automated enforcement options around the Nation. Collectively, to address all proposed hypotheses, this study will likely require relevant crash statistics (e.g., various severities and crash types). From the perspective of traffic signal data, it is likely this study will require historical records of the relevant signal timings (e.g., CCIs).

Study 5: Surrogate Safety Assessment of Yellow Change and Red Clearance Intervals

Objectives

The objectives of this study are to (1) determine the surrogate-based measures suitable for evaluating the CCI associated with a given signal phase and (2) quantify the change in the performance associated with a modification to the CCI.

Previous similar research studies have not investigated:

- Impact of decrease in yellow change interval duration on the surrogate safety metrics
- Impact of either increase or decrease of red clearance interval duration on the surrogate safety metrics
- Conflicts associated with CCIs of left-turn or right-turn movements

Example Hypotheses

Below are examples of hypotheses this research study should address[6]:

- **$H1_0$:** Proportion change in red light violation frequency increases with a positive change of yellow change interval.
- **$H2_0$:** Proportion change in frequency of late exits increases with a positive change of red clearance interval.
- **$H3_0$:** Proportion change in frequency of late exits increases with a negative change of red clearance interval.
- **$H4_0$:** Proportion change in red light violation frequency increases with a positive change of yellow change interval for left-turn movements.
- **$H5_0$:** Proportion change in frequency of late exits increases with a positive change of red clearance interval for left-turn movements.
- **$H6_0$:** Proportion change in frequency of late exits increases with a negative change of red clearance interval for left-turn movements.
- **$H7_0$:** Proportion change in red light violation frequency increases with a positive change of yellow change interval for right-turn movements.
- **$H8_0$:** Proportion change in frequency of late exits increases with a positive change of red clearance interval for right-turn movements.

[6]Hypothesis can branch out into several similar hypotheses with various surrogate safety performance measures.

- **$H9_0$:** Proportion change in frequency of late exits increases with a negative change of red clearance interval for right-turn movements.

Expected Outcomes

The analytic tools developed to achieve the second objective should be able to predict a reliable surrogate measure for a specific signal phase and movement combination as a function of the yellow interval, the red interval, and other site characteristics. These tools should support identifying locations that have the potential for safety improvement through changes to the CCIs. The tools should also support the safety evaluation of alternative CCIs at specified locations (including alternatives where a reduction in interval duration is under consideration). Figure 17 previously showed an example of a relationship that predicts frequency of RLR as a function of a change interval duration.

Methods

The research should address these objectives uniquely for each of the following movements: left turn, through, and right turn. Researchers should consider analyses incorporating nonmotorized modes of traffic. One or more reliable measures should be available for practitioners and researchers to use. The research team will establish the connection between these measures and crash frequency (or severity) using sound statistical techniques. The researchers will consider CCI performance for alternative operational left-turn phasing modes, such as protected only, permitted only, and protected permitted.

Factors

This study should work with the data collected for research studies 1–3. Factors that direct the execution of those studies will also be relevant for this study.

Data Collection

The study may be able to use new technologies for video feature extraction to collect and retrieve safety surrogate performance measures (e.g., synthesized time-to-collision and postencroachment time) at signalized intersections. For example, custom-deployed high-resolution video cameras can record vehicular conflicts and near misses at signalized intersections. Processing those video recordings can extract relevant features representing vehicular conflicts. Researchers will record the videos so that the signal status is visible all the time and/or the signal timing clock will synchronize with the recorded video and high-resolution signal timing data. Video footage from some of the red light cameras can potentially provide relevant videos for this study.

Study 6: Safety Assessment Procedure and Measures

Objectives

The objective of this study is to develop a procedure for assessing the level of safety associated with alternative CCIs for a specified signal phase at an intersection. The researchers will identify appropriate performance measures and methods for quantifying these measures. The measures should collectively address operations and safety. The study should give special attention to using existing infrastructure and datasets (e.g., high-resolution ATSPM data) to assess the impact of various CCIs on the selected surrogate safety performance measures.

Methods

The list of safety-based measures should include safety surrogates and crash-based measures. The connection between each surrogate measure and crash frequency (or severity) will become clearer (either in previous research or during this research study) via the use of sound statistical techniques. The researchers will identify suitable threshold values for each measure to indicate when a location has the potential for improvement.

Factors

This study will develop procedures based on the outcomes and findings from research studies 4 and 5; therefore, factors used in studies 4 and 5 will also apply to this study.

Data Collection

To collectively address all proposed hypotheses, the researchers expect this study will require collecting video data that can be used to derive surrogate safety performance measures (e.g., probability of stopping). This will most likely require extracting multiple vehicular events (e.g., crossing stop and exit lines) from the videos. On the traffic signal side, the researchers expect this study will likely require historical records of the relevant signal timings (e.g., CCIs).

Expected Outcomes

The procedure will describe how analysts can evaluate CCIs at an intersection to ensure the intervals are neither too long nor too short to accommodate the needs of most drivers. The procedure will describe how practitioners can use the evaluation results to make informed decisions about the adequacy of CCIs at a specific location (regardless of the method used to compute interval durations). The procedure will be suitable for implementation by researchers when developing a proposed new method for estimating CCIs.

Research Studies on Other Relevant Questions

The literature review has not identified these research studies as major priorities but has instead revealed research gaps that the next phase of the research could explore. This section presents two additional research studies and provides details on those studies.

Study 7: Investigation of Pairwise Conflict-Zone Method for Red Clearance Intervals and the Method's Applicability to U.S. Controllers and Practices

Objectives

The objective of this study is to evaluate challenges and opportunities for applying the conflict-zone method in the United States for selecting red clearance intervals. The researchers will investigate applicability of this method to the common U.S. geometric conditions, phase designs, and ability to implement relevant timings in the U.S. controllers, as well as explore compatibility with MUTCD language.

Example Hypotheses

The following is an example of a hypothesis this research study should address: $H1_0$: U.S. controllers cannot support the conflict-zone method that many international (e.g., European) locations use.

Expected Outcomes

The study will likely reject the preliminary hypothesis. This research will be able to identify alternate or preferable methods and parameters for calculating and implementing CCIs and will use that information to propose changes for inclusion in a future edition of the MUTCD.

Methods

This study will initially focus on reviewing relevant international methods (e.g., the Dutch method that agencies use in the Netherlands). A subsequent set of structured interviews with signal controller manufacturers and relevant signal agencies could then explore the feasibility and potential benefits of using a similar approach in the United States. The study would then follow up with hardware-in-the-loop simulation experiments to configure and test controller settings.

Factors

The following factors could support the selection of data collection locations:

- Angle of cross street: 90°, shallower, sharper (combined with approach versus entry speed?)
- Clearance interval: 0 seconds, 0.1–0.5 seconds, 1.0–1.4 seconds, 1.5–1.9 seconds, 2.0–2.9 seconds, ≥3.0 seconds
- Cross-street size: small, ≤50 ft; mid, 51–99 ft; large, ≥100 ft
- Driver familiarity (commute versus recreational/event)
- Grade: –6 percent to +6 percent by 1 percent
- Intersection type: conventional intersection, single-point urban interchanges (SPUI), diverging diamond interchanges, restricted-crossing U-turn intersection (RCUT), etc.
- Multimodal operations: tramways, pedestrians, bicyclists, etc.
- Posted speed: low, <30 mph; mid, 35-–40-45 mph; high, >50 mph (approach versus posted)

- Signal phasing: permitted, protected, P/P lead, P/P lag
- Street size: small, 2 or 3 lanes; mid, 4 or 5 lanes; large, ≥6 lanes
- Traversed turning path through intersection:
  - Length (*x* ft)
  - Curvature (*y*-ft radius)
- Turn lanes:
  - Existence (yes/no)
  - Direction (left/right)
  - Number (1, 2, 3)
  - U-turn allowed (yes/no)
  - Length (ft)
- Vehicle movement: left, through, right

Not all the values for all the factors should be considered. The researchers will give more importance to the combination of conditions where road geometry or other circumstances may create conditions where commonly applied methods to calculate clearance times may not always give proper values. For example, wider roads and roads with more-complex intersection geometry (e.g., SPUIs and DDIs) may warrant clearance times that may be difficult to properly calculate by using conventional methods.

The following factors are of relatively low importance for this research study, but the study could continually collect this data (where possible) to enable subsequent analyses/studies:

- Access (driveway influence in intersection approach):
  - Driveway influence in intersection approach (yes/no)Number (*x* driveways)
  - Volume (*y* movements per driveway)
- Adjacent signal: <0.5 mile, ≥0.5 mile (corridor context coordinated or isolated)
- Area: urban/suburban/rural
- Automated enforcement: yes (at intersection), in community, none
- Change interval: 4.0 seconds, 4.1–4.5 seconds, 4.6–5.0 seconds, 5.1–5.5 seconds, 5.6–6.0 seconds, ≥6.1 seconds
- Driver demographics
- On-street parking (yes/no)
- Impact of detector configurations, locations, size, and type of use
- Signal cycle length: <90 seconds, 90–120 seconds, 121–180 seconds, ≥181 seconds

- Vehicles: passenger car, motorcycle, bus, RV, SU, truck (tractor/trailer), etc.
- Weather: dry, wet, ice/storm

Data Collection

If the initial findings lead to promising outcomes, the research team will design testing scenarios to apply the original method—developed and used in the Netherlands—at different types of intersections (and for different conflicting movements) to validate its applicability at U.S. intersections. It is likely that some type of trajectory data, possibly from the other proposed studies, will be a prerequisite to collecting clearance times for vehicles making various traffic movements. Prior studies have used similar concepts in the United States for SPUIs and DDIs. Thus, researchers can explore potential inclusion of such alternative intersections in this study.

Study 8: Mobility and Capacity Assessment of Yellow Change and Red Clearance Intervals

Objectives

The objective of this study is to investigate the impact of modifying CCIs on mobility and capacity metrics at signalized intersections.

Example Hypotheses

Below are examples of hypotheses this research study should address:

- **$H1_0$:** Longer CCIs increase capacity metrics of signalized intersections.
- **$H2_0$:** Longer CCIs increase mobility metrics of signalized intersections.
- **$H3_0$:** Intersection approaches with longer delay times experience lower numbers of driver disrespects (e.g., RLR).
- **$H4_0$:** Intersection capacity cannot significantly increase without adverse safety impacts during times of day (TODs) with higher traffic congestion.

Expected Outcomes

The experimental outcomes will likely result in a rejection of all null hypotheses. This means that increases in CCIs will result in reduced intersection capacity and increased vehicular delay. It is likely that developed relationships will show how sensitive intersection capacity and delay are to modifications in CCIs. Such findings will help traffic signal engineers understand how increases and decreases in change and/or clearance interval impacts overall intersection operations.

Methods

The researchers will develop a family of relationships, based on either well-established HCM (TRB 2016) analysis, field measurements, or similar sources that show how CCIs impact capacity metrics at a signalized intersection. A similar approach would help in estimating mobility metrics, such as lost time, delay, or stops. The method will be comprehensive enough so that traffic signal engineers can understand how a modification of a change and/or clearance interval impacts capacity and mobility. When comparing capacity and efficiency impacts with potential safety impacts, such findings will help signal engineers decide whether considered modifications would be helpful. This method can help in estimating the impact of applying various CCIs for different TOD patterns. Anecdotal knowledge indicates that congested traffic (e.g., during peak traffic hours) does not arrive at the intersection at the free-flow speed and may be able to operate with shorter CCIs. In such cases, if these intervals vary with the TOD signal patterns, there could be improvements in efficiency without sacrificing anything on the safety side.

Another use of this method is to compare driver behavior (aggressiveness) at intersections that have long waiting times (e.g., long cycle length and split failure) with driver behavior at intersections where such conditions do not exist to pressure drivers to maximize use of an intersection’s capacity. This approach would likely require the researchers to compare operations at two intersections where, all other conditions being comparable, only the waiting times are significantly different. Possibly, this can be a single intersection evaluated for various TOD periods. It may be noteworthy to hypothesize that the two above-mentioned factors could work against each other to create a deceptive outcome of no impact on the safety or surrogate safety at an intersection. For example, while decreased speed of movement during the congested hour could have a positive impact on reducing RLR, the pressure to maximally use existing capacity could create a negative impact, thus yielding a net zero outcome.

Factors

Researchers can consider various factors in this study. Unlike the previous studies, where such factors may affect the selection of proper data collection sites, the impact of such factors in this study may be significantly different. In this study, those factors will mainly impact saturation flow rates, which can help in estimating the impact of CCI modifications on intersection delay and capacity. Depending on how many various conditions the researchers select for investigation, the researchers should identify which factors could be helpful when estimating the impact of interval changes on intersection mobility and capacity. Not all possible cases may use mature analytical models to estimate impacts on mobility and safety. For example, analytical solutions for estimating delays and capacity for some alternative-geometry intersections may not be at the same level of maturity as those used for conventional four-legged intersections.

Data Collection

In the most simplistic case, the study would not need any data, as the well-established analytical formulas could help in developing relevant relationships. However, it may be valuable to validate such estimates with (at least some) field measurements or simulated data (from properly calibrated and validated models). The field data could be based on video recordings accompanied by relevant signal timing data to estimate overall intersection capacity and delay based on video feature extraction (especially for capacity and throughput). If researchers cannot reliably estimate mobility measures from the field data, the researchers could use microsimulation data instead. To collectively address all proposed hypotheses, the researchers expect this study will require traffic data as (1) measured or estimated saturation flows (or similar capacity measures) and (2) video data that can help to derive surrogate safety performance measures (e.g., probability of stopping), which will most likely require extracting multiple vehicular events (e.g., crossing stop and exit lines) from the videos. On the signal side, this study will likely require historical records of signal timings and TOD plans.

Prioritization and Similarity of the Research Studies

Table 15 summarizes the priority of studies from highest (1) to lowest (8). The research team derived these priorities based on consensus from project stakeholder meetings and based on the (lack of) availability of previous research on certain topics.

Table 15 also proposes potential grouping of studies into data collection campaigns (e.g., when researchers can collect the data for a certain study along with the data for another study, and similarities between the studies). A data collection campaign represents a single effort taken to collect specific data (usually of various types) that can support multiple studies. For example, one data collection campaign could consist of collecting video footage from various intersection approaches. Later, this video footage could help to separately extract relevant information for through movements versus right or left turns from separate studies. Similarly, such footage could help in extracting vehicular trajectories, snapshots of vehicular positions (e.g., passing on late yellow), or traffic congestion, which could support various purposes in different studies.
Table 15 also summarizes preliminary hypotheses associated with each research study, and the data collection methods that would likely support each study (the research team's data collection and analysis plan provide more discussion of this part).

Table 15. Summary of the research studies, data collection campaigns and methods, and preliminary hypotheses.

#	Research Study Name	Priority	Collection Campaigns	Hypotheses (Paraphrased) (Tests Will Try to Reject)	Data Collection Methods (Alternatives)
1	Driver Behavior Effects of Long Yellow Change Intervals for Through Vehicles	3	I	1. Longer yellow = more RLR 2. Longer yellow = more late yellow entries 3. Longer yellow = through vehicles likely to stop	Video data with feature extraction; complement with ATSPM; driving simulator
2	Understanding Driving Behavior When Reacting to Yellow Change Intervals for Through Movements	4	II	1. KE approach speed > field data 2. KE PRT > field data 3. KE deceleration < field data	Vehicle trajectories and signal state
3	Understanding Driving Behavior When Reacting to Yellow Change for Turning Movements	1	II	1. EKE approach speed is constant 2. EKE deceleration applies uniformly 3. EKE entry speed is uniform 4. EKE requires shorter change for left turn 5. EKE requires shorter change for right turn 6. EKE requires shorter clearance for left turn 7. EKE requires shorter clearance for right turn	Vehicle trajectories and signal state
4	Crash Safety Assessment of Change and Clearance Intervals	6	III	1. Longer yellow = more FI RLR crashes 2. Longer yellow = more total RLR crashes 3. Longer clearance = more FI RLR crashes 4. Longer clearance = more total RLR crashes	Crash data and history of signal timing

ATSPM = automated traffic signal performance measure; EKE = extended kinematic equation; FI = fatal injury; KE = kinematic equation; N/A = not applicable; PRT = perception-reaction time; RLR = red light running.

Table 15. Summary of the research studies, data collection campaigns and methods, and preliminary hypotheses. (continuation)

#	Research Study Name	Priority	Collection Campaigns	Hypotheses (Paraphrased) (Tests Will Try to Reject)	Data Collection Methods (Alternatives)
5	Surrogate Safety Assessment of Change and Clearance Intervals	5	IV (and I)	1. Longer yellow = more RLR (through) 2. Longer yellow = more late exits (through) 3. Shorter clearance = more late exits (through) 4. Longer yellow = more RLR (left) 5. Longer yellow = more late exits (left) 6. Shorter clearance = more late exits (left) 7. Longer yellow = more RLR (right) 8. Longer yellow = more late exits (right) 9. Shorter clearance = more late exits (right)	Relevant surrogate safety measures (violations and late exits) and history of signal timing
6	Safety Assessment Procedure and Measures	2	N/A	N/A	N/A
7	Investigation of Pairwise Conflict-Zone Method for Red Clearance Intervals and Its Applicability to the U.S. Controllers	7	V (and II)	1. U.S. controllers cannot support the conflict-zone method	Test of concept in simulation, etc.; some field measurements
8	Mobility and Capacity Assessment of Change and Clearance Intervals	8	I, II, IV	1. Longer yellow and red increase capacity 2. Longer yellow and red increase mobility 3. Longer delays = less RLR 4. Capacity cannot increase?	Vehicle counts and delays at intersection and signal timing data

ATSPM = automated traffic signal performance measure; EKE = extended kinematic equation; FI = fatal injury; KE = kinematic equation; N/A = not applicable; PRT = perception-reaction time; RLR = red light running.

CHAPTER 5. PHASE II DATA COLLECTION AND ANALYSIS

This chapter presents a data collection plan for a future phase of the pooled fund study. The data collection plan follows on from the research plan, presented in chapter 4, to suggest datasets the research team believes can answer questions related to the eight research studies.

This data collection plan contains two sections. The first section presents a survey of relevant data types, which originate (1) from a survey of the literature, (2) from interactions with project stakeholders, and (3) from experiences of the research team in collecting data to analyze traffic signal operations. The section discusses research environments and details information about several potential datasets. The second section relates the data collection methods to the research studies and includes both a summary of each research study and a list of key research questions for each study. The section discusses the relevant data collection environments and datasets, which lead to identifying a preferred dataset and in some cases, an alternative dataset. After discussing considerations that would influence the selection of datasets, the section summarizes the preferred data collection methods for the eight studies.

SURVEY OF DATA

This section examines types of data that researchers may consider when addressing research studies to help develop suggestions for traffic signal CCIs. The section presents a synopsis of each data collection alternative, including examples where available, and assesses the readiness and availability of the data.

Overview

Over the years, researchers have used different data collection methods to evaluate different aspects of traffic signal operations. These methods have ranged from microscopic details of driver and vehicle behavior to macroscopic observations of safety performance over multiple years. Data from both ends of this spectrum are relevant to understanding how drivers react to CCIs and to evaluating the performance of these intervals. At the publication time of *NCHRP Report 731* (McGee et al. 2012), fewer cost-effective datasets were available compared with datasets that are presently available. *NCHRP Report 731* incorporated data from 83 locations using video cameras mounted onto modular 20-foot poles. Researchers manually analyzed the video data to extract the relevant data. Several alternative datasets exist today. These include CV datasets, trajectories from sensors, high-resolution data from ATSPM systems, and a potential for automated analysis of video, which may permit researchers to obtain a much larger dataset for a greater variety of conditions.

A variety of different types of data are available. Data that record vehicle movement (speeds and positions) and the signal state with high resolution represent a key data type for documenting and assessing driver behavior at signalized intersections during CCIs. Using data on vehicle position and speed, an analyst may be able to derive other metrics, such as the acceleration or deceleration, or information about potential conflicts (e.g., time to collision [TTC] and postencroachment time [PET]). Other types of data can cover the operational and safety performance of these intersections over periods of time. Such datasets provide a record of the state of a location over time or the history of performance. In addition to this observational data, the sites involved in the data collection also have contextual data (such as the posted speed limit, geometry of the street, and distance from neighboring signals). Documentation of those data is key for giving context to and interpreting results of the more detailed performance data. Table 16 presents an overview of the data types discussed in this plan, according to the category of data and the test environment where researchers would collect the data. Some data sources are relevant to more than one category. The following sections of the chapter present information on each potential data source, but the test environment also plays a role that brings advantages and limitations to the data collection strategy.

Table 16. Organization of observational data types by test environment and data category.

Data Category	Test Environment			
	Driving Public	**Naturalistic Test Driver**	**Real Test Track**	**Simulated Test Track**
Vehicle: internal	Global positioning system (GPS) data	In-vehicle video; controller area network (CAN) bus and similar; GPS data	In-vehicle video; CAN bus and similar	In-vehicle video; virtual vehicle instrumentation
Vehicle: broadcast	Basic safety message (BSM); commercial connected vehicle	BSM	BSM	Not applicable (N/A)
Observer: vehicle motion	Manual analysis; automated analysis; sensor-based trajectory	Not needed	Not needed	N/A
Observer: outcome oriented	Signal state data[1]; red light camera; safety data	N/A	N/A	Microsimulation

[1]More commonly known as high-resolution data.

Two basic data sources exist among the five data categories in table 16. The first source is data that researchers can obtain only in the vehicle itself. The second source consists of data that researchers collect through external observation. Some types of vehicle data are not feasible to communicate to external devices and therefore necessitate onboard equipment. Table 16 identifies these types as internal data. Other vehicle data, labeled as *broadcast*, are much more feasible to transmit wirelessly. The literature has no requirement for onboard equipment to obtain such data. Researchers may also obtain data by observing traffic behavior without any vehicle-side information. Table 16 divides these into two categories: vehicle motion, which focuses on the position and speed of vehicles, and outcome oriented, which focuses on the operational and safety performance of the site.

Table 16 also lists four test environments in which data collection may occur. Both of the first two environments are naturalistic environments, in that they capture the behavior of actual drivers in ordinary traffic scenarios. Observations of the driving public have shown that drivers are unaware of data collection and therefore have no reason to adjust their behavior. Using instrumented vehicles would involve drivers whom the researchers would need to inform of data collection. Although these drivers would operate the vehicles in real-world environments, they would know that researchers have been making logs of their driving behavior. It may be reasonable to assume that any tendency of drivers to adjust their behavior would diminish over longer periods of data collection, such as in the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) (Antin et al. 2019), where participants drove vehicles with onboard instrumentation for weeks or longer.

Test tracks, which may be real or simulated, are alternatives to naturalistic environments. Selected test drivers pilot vehicles in real or virtual test tracks. Researchers can control test conditions, including vehicle speed, time of the start of yellow relative to vehicle position and speed, driver characteristics, vehicle type, and desired movement at the intersection. The tradeoff for this greater degree of control is some degree of dissimilarity to real-world driving conditions. In virtual environments, researchers can exert yet more control over the test conditions. The impacts of these differences, however, are likely more important to some research questions than to others. For instance, in a carefully designed experiment, reaction time would be much easier to measure if the experimenter could control the timing of the stimulus (e.g., the start of yellow) than if the experimenter had no such control.

Table 17 compares the time scales of observational and contextual data elements. Many of the data in table 17 pertain to vehicle position and speed and belong to the shortest time scale. Relevant contextual data are evident at this time scale, such as the vehicle classification and identification of the movement made by each vehicle. Next, other data may vary on an hourly or daily basis. Although not common, CCIs may be variable by time of day. Operational performance is quantifiable on an hourly or daily basis using tools such as ATSPMs. Contextual data, such as weather and lighting conditions or overall volumes, may vary within a day. Crash data and AADT often occur on an annual time scale, while researchers can consider many items as static or unlikely to change during the study period. Much of the contextual data belong to this category.

Table 17. Comparison of time scales for observational and contextual data.

Time Scale	Observational Data	Contextual Data
Second or subsecond	• Vehicle position and speed (and derivatives thereof) • Signal state • Vehicle systems data	• Movement of vehicle • Classification of observed vehicles • Presence of bicycles or pedestrians
Hourly or daily	• Duration of change and clearance intervals • Operational performance measures (e.g., ATSPM)	• Weather conditions • Lighting conditions • Cycle length • Hourly/daily traffic volume
Annual	• Number of crashes	• Average annual daily traffic

Table 17. Comparison of time scales for observational and contextual data. (continuation)

Time Scale	Observational Data	Contextual Data
Static	Not applicable	• Intersection angle • Approach grade • Area type • Lane configuration and lane widths • Crossing distance • Distance from other intersections • Driver demographics and familiarity • Detector layout • Presence of automated enforcement. • Signal phasing

ATSPM = automated traffic signal performance measure.

Preferred Data Characteristics

This section describes desirable attributes of data sources and includes two use cases for data collection on CCIs that may inform these desirable attributes. The first use case is the need to characterize and measure the reaction of drivers to CCIs. The second use case is the need to understand outcomes of policies.

The first use case—observing driver reaction to CCIs—includes events that take place on the order of fractions of a second. Drivers approaching a signal have a desired route that necessitates selecting a destination lane and an exit approach. As drivers approach the signal, they may interact with other road users, including other drivers, bicyclists, and pedestrians. Drivers may interact with, or at least need to observe, other road features. Amid this process, drivers will likely be aware of the signal state. If the state changes from green to yellow, drivers may face a decision about whether to go or to stop shortly after having observed this change. Then, according to that decision, drivers either decelerate to a stop or proceed through the intersection. The perception-reaction time is the principal factor influencing the latency in the decision. Researchers can potentially measure perception-reaction time as the time elapsed between the start of yellow and a measurable reaction, such as applying vehicle brakes, assuming that a stop decision requires drivers to apply brakes right away. A go decision—or a stop decision from a longer distance— may not yield a similarly observable event.

In addition to measuring the perception-reaction time, researchers can determine the driver's decision to stop or go by observing the vehicle trajectory. Researchers can then examine the data to link driver stop/go decisions to the distance from the intersection and travel speed at the start of yellow. Directly measuring these phenomena requires a way to observe or infer the vehicle movement and to cross-reference the record of movement against the start of yellow time. The relationship of each observed vehicle to other traffic is important to consider. Determination of the probability of stopping necessitates separation of the drivers who can choose whether to stop from the drivers who must stop because of other drivers' decisions. Other relevant observations, such as the time when vehicles enter or exit the intersection, may infer the number of violations at a site. Every vehicle on the approach to an intersection will have a particular speed at the time a green-to-yellow state change occurs. For each vehicle in motion, a type II dilemma zone may exist in ranges where drivers may choose between stopping or going. The actual position of the vehicle relative to this zone at the state change time and during the perception-reaction time may be relevant to understanding driver decisions.

Another use case for data collection is evaluation of outcomes before and after a policy change. One relevant study is the effect of longer yellow change intervals on intersection performance. Although observational data can capture the impact on driver behavior, the consequences of these changes are visible in the operational or safety performance, which a variety of data sources may capture as described in the next section.

Survey of Data Collection Alternatives

Video Recording with Manual Analysis

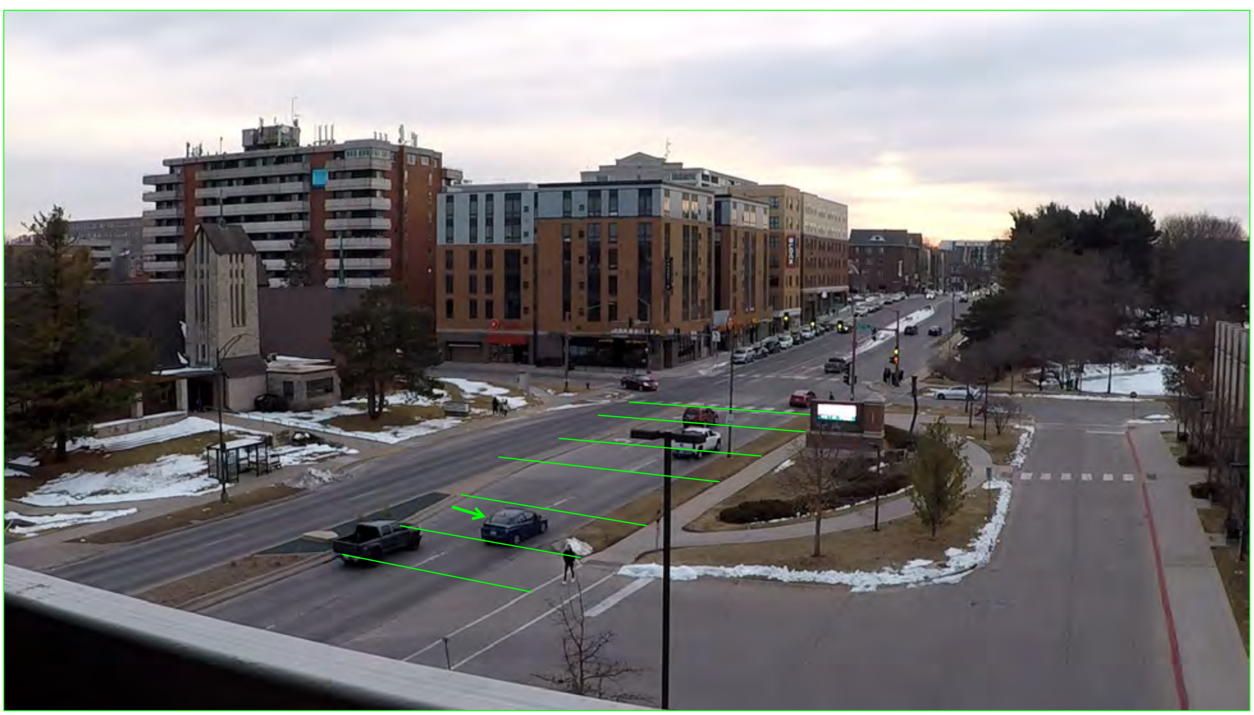
The most common type of data used in previous studies on CCIs is manual observations, supported mostly by video. The kinematic equation for CCI timing originated from a study by Gazis, Herman, and Maradudin (1960), which used 87 field measurements from manual observations. A follow-up study by Olson and Rothery (1961) used images from a 35-millimeter camera set up so that the start of yellow would trigger the shutter. The researchers also made manual observations to note which vehicles stopped. Since these studies, researchers have widely applied video recordings to the specific problem of analyzing CCIs or closely related aspects of signal operation (Stimpson, Zador, and Tarnoff 1980; Wortman and Matthias 1983; Chang, Messer, and Santiago 1985; Gates et al. 2007; Liu et al. 2007; Wei 2008; McGee et al. 2012; Baratian-Ghorghi, Zhou, and Franco-Watkins 2017; Simpson, Harrison, and Troy 2017; Tan et al. 2018; Fitzpatrick, Pratt, and Avelar 2021).

Most studies supported by video recordings include at least several hours of video footage from a few selected sites, up to hundreds of hours across numerous sites. Researchers assembled one of the largest sets of video recordings reported in these studies for *NCHRP Report 731* (McGee et al. 2012), which included 328 hours of video collected across 83 locations. This dataset captured 4,820 vehicles at the boundary of a dilemma zone during phase transitions. Hurwitz et al. (2011) processed 75 hours of video that captured about 1,900 vehicles affected by the onset of yellow. From the amounts of data extracted from hours of footage in these studies and others, one can estimate that video recordings of a signal approach under typical traffic loading may capture about 10–20 relevant events per hour.

Camera orientations vary among studies (typically varying based on research objectives), but most studies appear to include a single camera at a location where the camera captures the signal state and approaching traffic. Some studies have collected video from multiple vantage points (Elmitiny et al. 2009; Zhang et al. 2010; Kang, Rahman, and Lee 2020). Additional studies have supplemented video recordings with additional data, such as radar speed detection (Papaioannou 2007) and pneumatic tubes for recording vehicle speeds (Hurwitz, Knodler, and Nyquist 2011).

Figure 26 shows an image from a video recording of an approach to an intersection. The image contains lines that demarcate the positions of pavement markings. Recent aerial photographs from the site show the same pavement markings, which permit an analyst to measure the distance from the stop bar. The image displays the video frame at the exact moment when the yellow indication becomes visible. The highlighted vehicle in the frame is the first to apply brakes and come to a stop. Figure 27 shows the data that result from recording the vehicle position as the vehicle crosses each of the lines shown in figure 26. Figure 27-A shows distance over time, and figure 27-B shows speed versus distance for the same data. In figure 27-A, the horizontal axis shows time starting from when the example vehicle crosses the first line on the approach. From these data, an analyst can determine the vehicle was located approximately 140 ft from the intersection and traveling approximately 36 feet per second when the signal turned yellow. The video also confirms that the vehicle comes to a stop. One goal of analysis would be to extract a sufficient number of such observations to estimate the probability of stopping for a given distance and speed and perhaps other characteristics such as the desired turning movement or vehicle type.

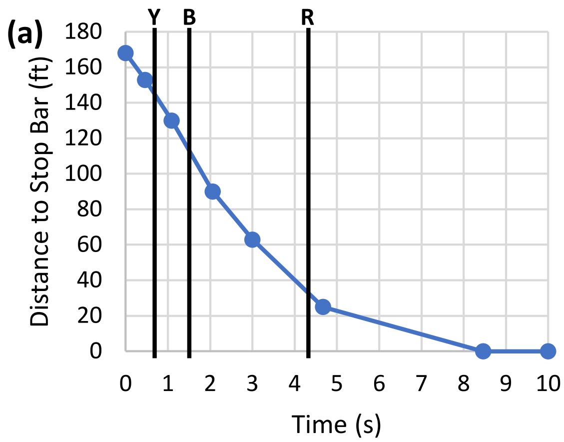
At present, video data are relatively inexpensive to capture. Researchers can discreetly install numerous types of small cameras at temporary locations onsite to record video for periods of time. At some locations, existing cameras may be available that could capture relevant video, and researchers may also equip cameras on drones (Hainen et al. 2015). Many of these cameras are capable of recording at high resolutions and frame rates. It is necessary to identify appropriate locations onsite for the cameras to achieve a point of view that collects the relevant observable elements (signal state and approaching vehicles). Previous studies have used a variety of strategies, including temporary mounting of cameras behind road signs and using portable trailers. Coordination with agencies to mount cameras or park trailers may be necessary. Setup and removal of the video collection equipment require some effort, and manual analysis of the video may require more effort.



Source: Federal Highway Administration.

Note: Lines show positions of pavement markings with known distances to the stop bar.

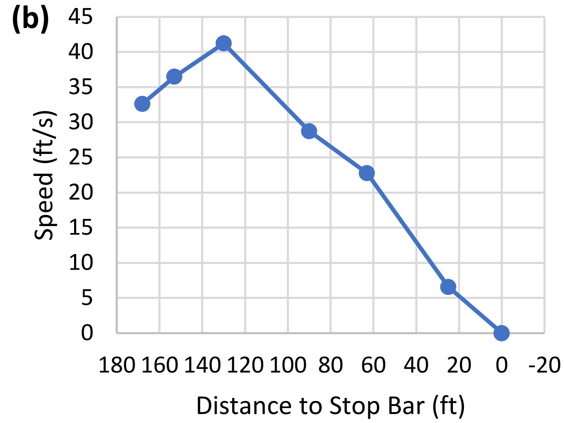
Figure 26. Photograph. Onset of yellow captured in a 1920-by-1080-pixel resolution video.



Source: Federal Highway Administration.

B = brake light on; R = start of red; s = seconds; Y = start of yellow.

A. Vehicle distance over time.



Source: Federal Highway Administration.

ft/s = ft per second.

B. Vehicle speed versus distance to stop bar.

Figure 27. Charts. (a) Movement of the first passenger car to stop in the right lane indicated by the arrow in figure 26; (b) speed-versus-distance plot of the same data.

Video Recording With Automated Analysis

One way to potentially reduce the amount of time needed to analyze video is to perform automated analysis of the video. At present, several machine-learning methods can track objects in videos (Buch, Velastin, and Orwell 2011; Shirazi and Morris 2015; Tageldin, Sayed, and Ismail 2018; Zhang, Yang, and Sun 2019). Emerging commercial solutions are also available. Considerable research in this area examines a wide variety of applications. Figure 28 shows an example where an algorithm tracked the passenger car described in figure 26 and figure 27 from the moment the car entered the field of view up to where it came to a stop at the intersection. The dots in the image show individual locations of the data in video frames at a time resolution of 30 frames per second, or 0.033 second per frame. To produce this image, an analyst applied the YOLO algorithm (Redmon and Farhadi 2018) for vehicle detection and ByteTrack (Zhang et al. 2021) for vehicle tracking. The tracker created bounding boxes around the vehicle in each frame. The figure shows the center points of the bounding boxes to represent the trajectory.

Although there has recently been an increasing amount of research on automated analysis of video, relatively few applications of automated analysis methods exist to passively collected video data to address CCIs. One study used proprietary software for semiautomated analysis (Polders et al. 2015). Another study mentioned the development of a system for processing video data (Li, Jia, and Shao 2016) but focused more on the modeling aspects of the study and included less information about the reduction of the video data. Private companies have also explored uses of automated video analysis for a variety of data analytics products.

Source: Federal Highway Administration.

Note: Green line shows the trajectory of passenger car shown in figure 26.

Figure 28. Photograph. Trajectory of passenger car shown in figure 26 obtained from analysis of video data by machine-learning techniques.

In addition to tracking vehicle motion, the same data can also facilitate development of surrogate safety metrics by relating vehicle trajectories to each other and measuring the time between vehicle presence in a conflicting area of the road. Two metrics used for this are PET and TTC. PET is the difference in time between one vehicle's leaving an area on the road and another vehicle's entering it. TTC is the hypothetical amount of time for a collision to occur when one vehicle follows another, the leading vehicle decelerates, and the following vehicle maintains its initial speed. The amount of red light running (RLR) may also serve as a useful surrogate safety metric.

Vehicle Trajectories From Detection Systems

Some vehicle detection systems offer data collection capabilities that may augment video analysis or serve as independent data sources. Agencies have widely deployed vehicle detection systems at signalized intersections for vehicle actuation and signal control purposes. However, most detection systems can report the presence of vehicles within a predefined zone or perhaps the count of vehicles passing by a section but are otherwise unable to offer more-enhanced data, such as vehicle position or speed. These detectors measure physical characteristics within these zones (such as response of a magnetometer or inductive loop) to determine vehicle presence. Some types of detectors sweep out a wide area rather than a particular zone. One example is radar detection. The basic principle of radar detection is that the sensor transmits electromagnetic energy and receives energy back from objects within a certain range. While some variations exist in types of radar detection, depending on the intended application some radar detectors can identify vehicle locations and speeds across several lanes. Many agencies use radar to measure speeds on freeway segments, although such systems typically aggregate speed into 1-minute intervals. For signal control, detection systems translate position information into the equivalent detector zone presence data required by signal controllers. To access the internal, disaggregate position and speed data, an interface is necessary to extract position data. This may be unavailable in every radar detection system or may require a special request to the vendor to access or enable it. Although many radar detectors are in place, not all of them are in locations to measure vehicle speeds and positions at the start of yellow. It will be important for researchers to verify the accuracy of the positions and speeds.

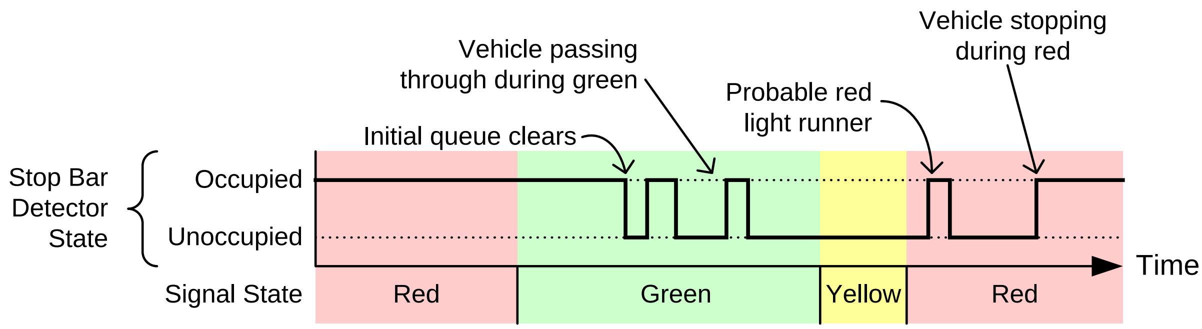
Some previous studies have employed radar detection to facilitate dilemma zone protection (Sharma, Bullock, and Peeta 2011; Day et al. 2019), evaluate red clearance intervals (Knodler et al. 2018), monitor RLR (Santiago-Chaparro et al. 2014), and evaluate the impact of advance warning flashers (Wang and Sharma 2016). The data may hold promise for potential application to research needs relative to CCIs. In recent years, newer detection systems have increased their performance by fusing radar data with video, while other systems based on real-time video analysis or light detection and ranging may emerge in the future. The resulting trajectory data could provide other information regarding left-turn behavior, such as vehicle speed at the critical distance, vehicle deceleration, and intersection entry speed.

Signal State Data (High-Resolution Data)

Traffic signal systems contain many different pieces of information stored as digital data and electrical impulses, such as the output states of signal heads or presence states of detectors. The type of cabinet determines how devices in the cabinet communicate the information. For example, in TS2 cabinets, communication occurs through the synchronous data link control bus. Other cabinet types may use direct wired connections. These data objects contain information about the state of the intersection.

In the past 15 years, data have become available to capture this information in the form of events occurring at intersections. The principal types of events are phase state changes and detector state changes. Most users of the data call it *high-resolution data*. Because this name is generic, this data collection plan refers to it as *signal state data* to avoid confusion with other data types that may also be high resolution. The term *high resolution* refers to the 0.1-second minimum resolution that a data logger writes as the state changes. Many modern signal controllers are currently able to record signal state data, and additional devices can collect the data for locations having incompatible controllers. Signal state data form the foundation for most performance measures that are part of ATSPMs. Some researchers employed signal state data to estimate the occurrence of RLR (Lu et al. 2015, Lavrenz et al. 2016) by cross-referencing detector activity with the onset of yellow times. Signal state data also support the visualization of yellow and red actuations in the open-source software for ATSPM developed by the Utah Department of Transportation. Other studies have employed similar concepts characterized as point detector data to estimate RLR (Lum and Halim 2005; Zhang et al. 2009).

Signal state data can provide a great deal of information about discrete events occurring at an intersection, potentially including the times when vehicles enter an intersection. However, the layout of detectors strongly influences the utility of the data. Many intersections have detectors located at the stop bar that provide presence data for actuation. These detection zones are typically about 50–60 ft or longer to capture a single vehicle, which may stop at various positions relative to the stop bar. If separate detection channels exist for individual lanes, then it may be possible to detect RLR when a vehicle passes over the detector at relatively high speeds (Lavrenz et al. 2016). Figure 29 illustrates this concept.



Source: Federal Highway Administration.

Figure 29. Diagram. On-off trace of vehicle presence during initial red phase corresponding to vehicle entering the intersection at high speed after start of red.

The brief occupied trace occurring shortly after the start of red likely represents a vehicle entering the intersection after the start of red (assuming the detector is located close to the stop bar). The placement of detectors on the exits of the intersection would provide this information, possibly with better fidelity than a stop bar detector (Lu et al. 2015), but exit detectors are not common. This technique will not work if long latency times exist in the transitions between occupied and unoccupied states or if the detection technology does not work well otherwise.

Using multiple setback detectors may permit developing information about vehicle behavior at the start of yellow. For example, arranging multiple setback detectors in a speed trap configuration would permit estimating speeds. The detection-control system for dilemma zone protection (Zimmerman and Bonneson 2005) uses such a configuration. However, the 0.1-second data resolution is too coarse to allow high-fidelity speed estimation directly from the signal state data. For example, if the zone consists of two 6-foot detectors spaced 10 feet apart (a distance of 16 feet between loop leading edges), the time difference between the detector-on event of the first and second loops would be 0.16 second for a vehicle traveling at 70 miles per hour (mph), but 0.24 second for a vehicle traveling at 45 mph. In other words, 0.08 second (smaller than the data resolution of 0.1 second) spans a speed range of more than 25 mph. More likely, the developer of data-logging software would have to establish a secondary process to extract the estimated speed and provide a new event to log it or otherwise introduce a secondary stream of data.

Signal state data also support development of other performance measures that may characterize conditions onsite, such as estimates of traffic volume, quality of progression, and capacity utilization (Day et al. 2014). Similar to estimating RLR, each of these applications requires an appropriate detector layout. Using detection types such as video, new detection zones for research purposes (i.e., not driving actuation) are relatively easy to add to the detector layout, as long as enough spare detector channels can send the data to the controller.

Many intersections can currently log signal state data. The cost of implementing data logging is relatively low (perhaps a few thousand dollars to buy a data-logging unit). In some cases, the cost may be zero—for example, if the only needed action is to turn on the data-logging feature.

However, the quality of the data heavily depends on the detector layout, and many intersections may not have ideal layouts for data collection needs. In addition, detection systems vary in the quality of the data they provide. After selection of a site that has a good detector layout, the cost of collecting data is very low, especially if it is easy to retrieve the data from the site; for example, if the cabinet has an external connection over the internet (more likely within an agency-owned network or over a virtual private network). If such a connection does not exist, local data storage and manual retrieval is another option. The analysis of such data is not necessarily more difficult than other datasets presented in this report, although a moderate amount of data can accumulate over time. An intersection with AADT of about 50,000 is likely to generate approximately 100,000–150,000 events each day.

Red Light Enforcement Camera Data

Red light enforcement cameras represent another potential data source (Bar-Gera et al. 2015). Because they are permanent installations in continuous operation, such cameras offer the potential to obtain large amounts of data, as well as to obtain observations over long periods of time. Bar-Gera et al. (2015) reported capturing 200 million vehicle entrances from 37 cameras over a 2-year period. The data collection included about 5 million entrances during yellow. With such a large number of observations, the researchers were able to produce a detailed distribution of vehicles entering the intersection as a function of the time after the start of yellow. Although this dataset included millions of records, it included only the time of entry into the intersection and does not seem to provide information about stopping vehicles or the positions and speeds of vehicles at the onset of yellow. One disadvantage of this type of data is that red light enforcement cameras influence driver behavior. Any data obtained from a site where red light enforcement cameras are in use will probably bias driver behavior toward stopping relative to locations without enforcement. Even the presence of red light enforcement cameras within the same region may have such an influence. Despite the potential for obtaining large numbers of observations, a comprehensive dataset incorporating data from multiple regions would be challenging to establish using red light enforcement camera data.

Naturalistic Driving Data

Second Strategic Highway Research Program Naturalistic Driving Study

SHRP 2 NDS (Antin et al. 2019) collected data from more than 3,000 drivers as they traversed about 32 million miles of road in six different geographic regions of the United States.

What one might term *NDS data* actually consist of the following several related datasets:

- GPS records of the vehicle position
- Video recordings of views from the front and rear windows
- Video recordings of the driver’s face and hands and a view over the driver’s shoulder toward the center console
- Information from vehicle diagnostics

- Radar data recorded by instruments in the vehicle
- Gyroscope data recorded by instruments in the vehicle
- Analysis of driver's head position
- Other data

Because of the variety of vehicles used in the study, the quality of the data may vary from one trip to another. The dataset contains an enormous number of traversals of signalized intersections by test vehicles, but it is unclear how many reactions to yellow the data contain or their geographic distribution across different sites. The authors of this report attempted to estimate the likely number of potentially relevant events by considering tentative assumptions about the number of miles driven on signalized facilities and the likelihood of the vehicle's encountering a yellow event; the authors found there may be about 40,000–60,000 such events in the dataset. The distribution of these events according to specific intersections and movements is more difficult to estimate.

Accompanying the NDS data is the Roadway Information Database (Smadi et al. 2015), which contains information about the roads traversed by vehicles in the NDS. Cross-referencing the GPS positions (i.e., trajectories) of the vehicles with this information would permit researchers to identify potential traversals of traffic signals along specific paths corresponding to movements at the intersections. Additional parts of the dataset may provide the speed with better accuracy than the GPS data. After identification of intersection traversals, it would then be necessary to determine whether the signal is visible in the video. A number of conditions are likely to influence the visibility of signal heads, including weather and lighting conditions, occlusion by other vehicles, distance to the signal head, road geometry, and visual clutter (e.g., streetlights and the headlights and taillights of other vehicles). For example, in figure 30A, the signal heads are visible even though they are relatively far away. In figure 30B, some signal heads are at a similar distance, but they are difficult to tell apart from other lights in the field of view. Finally, after identifying intersection traversals with visible signal heads, it would then be necessary to examine which of these fall under the influence of CCIs.

Source: Antin et al.

A. Visible green signal head.

Source: Antin et al.

B. Obscured visibility of signal head by other light sources.

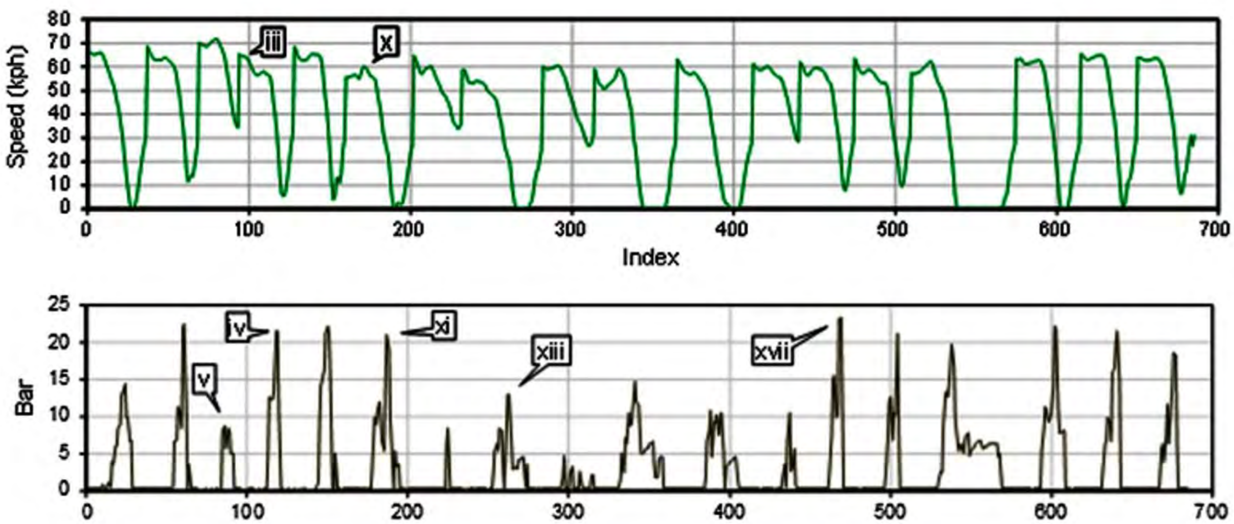
Figure 30. Photographs. Visibility of signal heads.

According to an entry in a list of studies in the NDS data repository, researchers have made preliminary investigations into the data to examine driver behavior in type II dilemma zones (Layman et al. 2019). Another entry in this list indicates that another group of researchers (Savio, Davoodi, and Sudweeks 2020) investigated the possibility of automated recognition of signal states in the data by using computer vision methods. Extracting relevant events will be key to using the dataset to analyze driver behavior at signals. The feasibility of automated extraction of the events at a large scale would be important to demonstrate. The distribution of the events by driver, location, and other conditions is also important. At the time of this writing, quantitative results from these studies are unavailable. SHRP 2 NDS (Antin et al. 2019) is unique in its massive scale and combination of multiple datasets. Mabuchi and Yamada (2015) in Japan developed a much smaller and more controlled, but similar, dataset, where 22 drivers followed the same route through 13 intersections. This study attempted to estimate the probability of stopping at the intersection relative to the time in yellow. This demonstrated the possibility of collecting new study-specific data.

Controller Area Network Data

The SHRP 2 NDS dataset includes data from vehicle diagnostic systems for some trips where the vehicles possessed the capability of providing such data. Monitoring of the controller area network (CAN) bus is the primary option for obtaining such data directly from vehicle systems (Farsi, Ratcliff, and Barbosa 1999). The CAN bus supports communication among devices inside a vehicle. The CAN bus transmits unencrypted messages between devices; it is therefore possible to interface with the CAN bus and monitor these messages. The CAN bus messages provide access to detailed information from vehicle systems, including wheel speeds, headlight use, turn signal use, and braking activity (Dingus et al. 2015; Li et al. 2020; Jha et al. 2021). Liu et al. (2007) evaluated the accuracy of speed measurements made from video by comparing the measurements against data obtained from the CAN bus in a test vehicle. The SHRP 2 NDS dataset also includes such information from some equipped vehicles.

Figure 31 shows an example of a few data elements the CAN bus permits access to. The upper chart shows a trace of the vehicle speed, while the lower chart shows the brake pressure during the same time interval. Data obtained from the CAN bus data can describe many different elements of driver and vehicle behavior in detail. However, the data are pertinent only to the observation vehicle, and they do not provide information about other vehicles or the surrounding environment. The CAN bus data may have value as a convenient way to capture observable items—such as vehicle speed or braking activity—for studies using a test vehicle augmented by other datasets, as in NDS data or driving on a test track.



Source: Li et al.

kph = kilometers per hour.

Figure 31. Charts. Vehicle speed and brake pressure obtained via controller area network bus monitoring.

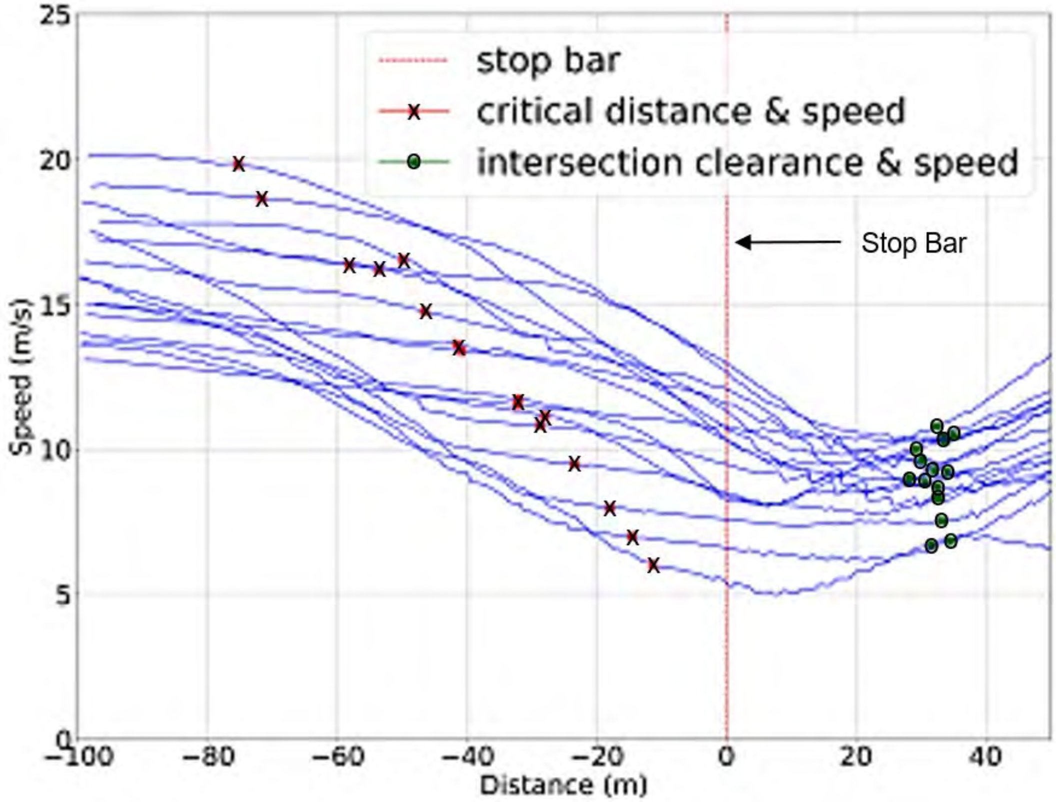
Similar Instrumentation for Studies on Test Tracks

Järlström (n.d.) employed similar data collection methods to collect data on vehicle motion in response to the onset of yellow. For this study, Järlström equipped a vehicle with a commercial data collection system that could interface with the CAN bus and record vehicle speed, acceleration, position, heading, and various other data elements. Video cameras mounted in the vehicle provided a view from the driver's perspective. For this study, the driver traveled on a closed course. A virtual signal indicated the start of yellow to the driver. The system produced a diagram of speed versus distance for stop/go decisions and a right-turn movement. Järlström used this setup to obtain data for developing the extended kinematic equation.

Vehicle-to-Infrastructure Communication

CVs may offer another option for obtaining similar types of data. CVs may exchange information with roadside infrastructure in the form of signal phase and timing (SPaT) messages communicated from infrastructure to the vehicle, and BSMs communicated from the vehicle to infrastructure and from vehicle to vehicle. Roadside units (RSUs) receive the communications on the infrastructure side. In part because of the SPaT Challenge initiative in recent years, several agencies across the United States have deployed RSUs, which would help facilitate collecting BSMs if additional equipment at the intersection is available to log the data. BSMs contain information, including the vehicle position, speed, and heading. Rather than collect data from within the vehicle as with the use of a CAN bus, RSUs collect the data. That would make it possible to capture naturalistic driving data from CVs on public roads. A reporting frequency of 10 times per second is common, which is lower than data collected in the vehicle but should still permit sufficiently detailed observations of driver response to yellow.

Figure 32 presents an example of data obtained from these data in a recent study (Jerome et al. 2022). RSUs installed at four intersections collected BSMs from CVs moving through left-turn movements. The researchers collected 24,460 trajectories over a study period of approximately 7 months. Of these, 262 trajectories from nine left-turn phases composed a dataset selected for the study. The charts in figure 32 present a speed-versus-distance view of some sample trajectories for left-turn vehicles, with symbols added to indicate the points where the vehicles reached the critical distance and where they cleared the intersection. Two challenges affect the use of this dataset: One is the need to locate RSUs at intersections; presumably, it would also be desirable to obtain video records at the same time to validate the data. It would probably also be desirable to record the time of the start of yellow. Another challenge is the relatively low penetration rate of CVs, which are still generally below 10 percent of the vehicle fleet at the time of writing. That relatively low penetration rate means that researchers would have to record data for a longer period of time to obtain a number of records comparable to that from other data collection methods.



Source: Jerome et al.

m = meter; m/s = meters per second.

Figure 32. Chart. Left-turn vehicle speed as a function of distance as recorded by connected-vehicle data.

Data from Test Tracks

Many of the data types mentioned previously are possible to collect in naturalistic (real-world) conditions or on test tracks. Test tracks offer additional options for experiment control. Test tracks are road facilities set aside for evaluating vehicle performance. These may include roadside instrumentation to assist with data collection, such as RSUs for obtaining BSMs, or installation of video cameras at vantage points more favorable than in real-world settings. Researchers may use instrumented vehicles equipped with data-recording devices to track speed, acceleration, and braking activity as the vehicles traverse the test track, similar to using instrumentation for naturalistic driving. When combined, these datasets can yield detailed information about travel characteristics of individual users. Whereas naturalistic driving data originate from tracking vehicle movement in public streets, the controlled environment of a test track can allow for high-precision control of certain study aspects, such as the time that a signal turns yellow relative to driver distance and speed. In naturalistic studies, researchers usually cannot control these events.

Webster in the United Kingdom was the first to use a test track for large-scale experiments examining the capacity of traffic signals[1]. This research yielded one of the first measurements of the probability of stopping as a function of speed and distance from the intersection. More recently, researchers have carried out several studies on closed test tracks with instrumented vehicles, including several studies on CCIs (El-Shawarby et al. 2007; Rakha, El-Shawarby, and Setti 2007; Rakha, El-Shawarby, and Amer 2011; Bryant, Rakha, and El-Shawarby 2015).

Various test tracks exist across the United States. Some focus more on vehicle performance, others on traffic safety and operations, and others on pavements. Few facilities include test roadways configured in intersection forms, and few have signal installations similar to real-world environments. However, temporary signals can serve the purpose of displaying signal output to a test track driver. In addition to permanently established test tracks, researchers could also potentially establish temporary test tracks elsewhere. Using a test track may require lead time to schedule and set up a facility for testing. Researchers would need to identify drivers and arrange to use test vehicles, which require approval by an institutional review board (IRB) in a process similar to that for naturalistic driving studies. Researchers can expect that organizations operating test tracks will recover their costs in usage fees based on the amount of time researchers use the track. A related issue is the number of samples a test track study would produce is considerably lower than a real-world study with passive data collection.

Commercial-Connected-Vehicle Data

Some vehicle manufacturers have included systems that can report similar data to the cloud. Different vendors have relationships with vehicle manufacturers to acquire and resell the data. Recent studies have demonstrated the utility of such data in measuring vehicle delays (Saldivar-Carranza et al. 2021). The time resolution of data available from vendors (typically one record every 3 seconds in current commercial offerings) may present a challenge for certain use cases, including addressing research questions related to the CCIs.

Figure 33A shows the trace of one vehicle from a commercial CV dataset showing distance over time. Figure 33B shows the instantaneous speed versus distance for the same data. Figure 33 presents the position as a distance from the stop bar on the vertical axis, while the horizontal axis represents the time to yellow. Zero represents the start of yellow, and negative numbers represent time after the start of yellow. In this case, the vehicle begins to slow even before the start of yellow, and it comes to a stop during yellow. The CCI durations came from the signal event data logged at the intersection, and the analyst made no correction to the time stamps. It is unknown whether the CV data clock times were properly in sync with the signal event data clock times. The possible lack of synchronization demonstrates a potential challenge in using this type of data. It is unknown why this vehicle came to a stop: Was it the first vehicle to stop, or did it come to a stop because of other traffic in front of it? The resting position of the vehicle is within 50 ft of the stop bar, but it is difficult to make inferences about its queue position from these data alone.

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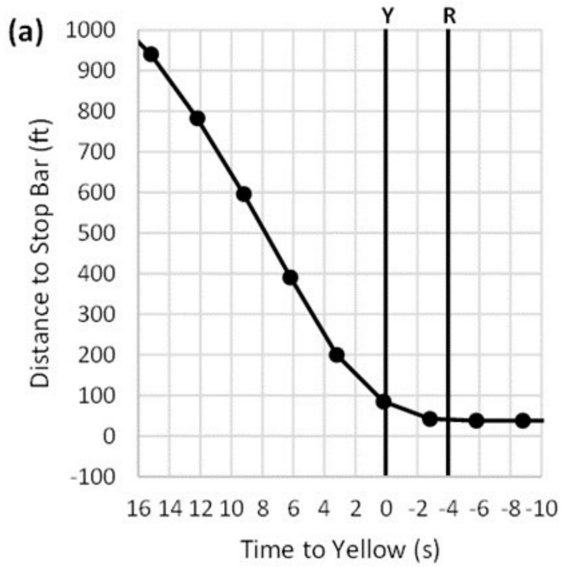
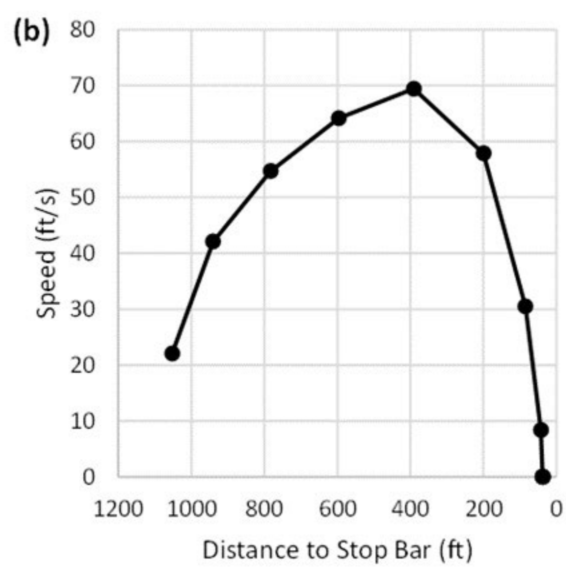
[1] Webster, F. 1959. *Progress of Work on a New Type of Controller for Traffic Signals on High-Speed Roads*. Research Note RH/3634. Crowthorne, U.K.: Road Research Laboratory.



Source: Federal Highway Administration.

Y = start of yellow, R = start of red

A. Distance over time for a single vehicle.



Source: Federal Highway Administration.

Y = start of yellow, R = start of red

B. Speed versus distance for the same data.

Figure 33. Charts. Commercial connected vehicle data showing a vehicle stopping at an intersection cross-referenced to the phase state times.

Driving Simulation

In a driving simulator, a test driver controls a vehicle in a simulated environment. Typically, displays are set up to mimic what the driver would see inside a vehicle in a real-world environment. Simulators may be elaborate. More-advanced simulators can replicate vehicle motion in three dimensions and supply a 360-degree view of the outside environment, which drivers can view from inside the vehicle body. Other driving simulators are simpler, including sufficient controls to pilot the vehicle and displays of the virtualized driving environment with computer monitors. Driving simulators afford the researcher an even greater degree of control over the test environment, including lighting and traffic conditions. A tradeoff is that the virtual environment is different from a real-world environment. The driver relies primarily on visual input, since most driving simulators do not provide tactile or other sensory feedback that may influence real-world driving behavior. The dataset also has a limitation in that a small number of drivers participate in data collection compared with real-world data collection, which captures a larger and more diverse group of drivers. Researchers have used driving simulators in several previous studies on driver reaction to yellow (Caird et al. 2007; Yan et al. 2009; Hurwitz et al. 2014; Haque et al. 2015; Machiani and Abbas 2016; Savolainen 2016; Hussain et al. 2020).

Microsimulation

Microsimulation studies use detailed models of traffic flow, typically based on mathematical, empirical, or hybrid models of car following, lane change, reaction to signal state, etc. Although microsimulation is unable to reproduce human behavior in reaction to yellow signals, a well-calibrated and -documented model may provide a reasonable approximation to permit researchers to evaluate the impact of control options and explore impacts on operation. Model calibration strongly influences the results and is a key challenge in the use of microsimulation data, especially if driver reaction to yellow signals changes over time (such as after the increase of yellow times). In general, microsimulation data would not be useful for research questions pertaining to driver behavior or real-world outcomes. Microsimulation data may have applications in exploring tangential research questions, such as testing whether control systems can support adjustments to clearance intervals depending on the preceding and next phases.

Crash Data

Analysts regularly use crash data to assess the safety performance of road facilities. Regardless of the methods researchers use to record driver reactions to yellow—or other elements related to the problem of setting CCIs—any changes in practice will ultimately necessitate evaluation of the methods through analysis of crash data. Some recent studies have examined impacts of introducing red clearance intervals at intersections (Souleyrette, McDonald, and O'Brien 2007), deployment of red light cameras (Miller, Khandelwal, and Garber 2006), use of advance warning signals (Schultz and Talbot 2009), and impact of increased yellow times (Guerin 2012). Two common types of crashes associated with CCIs are right-angle crashes because of RLR and rear-end crashes because of conflicts between drivers making different stop/go decisions.

Local and State jurisdictions typically maintain detailed crash data. The National Highway Traffic Safety Administration operates the Fatality Analysis Reporting System to store data on fatalities at a national level. Crash data analyses typically require several years of data collection before achieving conclusive results that can separate a trend against the background of random variation's occurring in crash data from year to year. Additional challenges include the difficulty in controlling a site's other changing characteristics (such as traffic volumes) over the before-and-after time periods. Frequently, researchers build multivariate models that can combine crash data with several independent variables to capture such varying characteristics. The change in the numbers of crashes caused by changes in control policies would need to be stronger than the unexplained variation in the models. Another challenge is managing signal control parameters over the longer time periods needed for crash studies, as discussed in the next section.

Changes in Signal Programming

Information about traffic signal controller programming will be important for studies on CCIs, especially studies that track performance over time. At minimum, the durations of the CCIs will be key information for all studies involving real-world data collection. Other data sources, such as signal event data, can produce the start and end times of the intervals when the study requires such detail. During longer studies, such as observations of crashes over time, it is possible that signal timing may change over time. Because most agencies do not keep records of past signal timing, the analyst would probably have to assume the signal timing did not change over certain periods of time. Coordination with the agency managing the signal will be important to ensure that this is a reasonable assumption.

Summary

This section provided information about several different types of data relevant to studies of CCIs. This section first presented an overview of data considering different categories based on the perspective of the data collection equipment and the test environment of the study. Next, this section discussed preferred data characteristics for the use cases of observational studies and outcome studies. Finally, this section presented a survey of various data types identified from a survey of past research and through interactions of the research team with different stakeholders. Example data from various studies, in addition to some new data obtained by the research team to facilitate this discussion, helped illustrate several datasets. In conclusion, vehicle trajectories (positions and speeds) are the most-relevant data for capturing driver behavior with respect to CCIs. Analysts could obtain these data through several different datasets presented in this chapter. The trajectory dataset must also contain signal state change times or use a supplementary, synchronized dataset containing the state change times. Contextual data about the data collection environment (such as lane configuration, speed limits, weather conditions, lighting conditions, and presence of pedestrians and bicycles) are also key. Analysts could potentially combine different datasets to develop a full picture of the operation. The next section discusses the studies identified in the research plan.

RESEARCH NEEDS AND DATA COLLECTION ALTERNATIVES

Data Needs for Identified Research Studies

This section describes the data needs for eight research studies identified in chapter 4 and examines the characteristics of data that would lead to development of that information. Each study discussion includes a list of potential data collection strategies that first considers the appropriate data environments and then the types of data that researchers can collect in that environment that would be most relevant to the principal study questions. Contextual data, such as the study location and conditions at the time of data collection, will be important to all studies discussed in this chapter. This discussion assumes the researchers would obtain such data regardless of the other data selected for specific observations needed for each study. Therefore, the following sections emphasize the importance of contextual data but do not include further details.

Study 1: Driver Behavior Effects of Long Yellow Change Intervals for Through Vehicles

The objective of this study is to investigate whether long yellow change intervals (e.g., >4.5–5 seconds) impact driver behavior and RLR for through vehicles differently from typical yellow change intervals (<4.5–5 seconds).

The principal study questions are:

- Are drivers of through vehicles less likely to engage in RLR at intersections with longer yellow change intervals?
- Are drivers of through vehicles less likely to enter the intersection in the later portions of yellow with longer yellow change intervals?

- Are drivers of through vehicles more likely to stop with longer yellow change intervals?

- Does speed play a role in driver behavior with longer change intervals?

Answering the principal questions would require capturing the time of entry at the intersection and the time of stopping. The most-relevant information will be for vehicles whose drivers can make decisions (i.e., they do not have to stop because they are following a vehicle that stops). Potential data collection methods for this study include the following:

- Naturalistic studies of the driving public would require implementation of longer yellow times in real-world locations. Studies of driver reaction to different yellow times are possible with selection of different sites with different yellow times but otherwise similar characteristics. Researchers will likely need to conduct multiple studies over time at sites with longer yellow times to investigate the possibility of driver adaptation:
  - Video recordings from the sites would likely capture most of the observable elements required to answer the research questions.
  - An alternative setup could consist of signal state data to obtain the start of yellow times in conjunction with BSMs or sensor trajectories to capture vehicle movement. Commercial CV data may have an insufficient time resolution to observe the actual time of entry with sufficient resolution.
  - Signal state data (with appropriate detector layout) and red light enforcement camera data may be able to capture the times of vehicle entry relative to start of yellow or start of red time. Such data may be unable to capture drivers who choose to stop rather than to go.

- Naturalistic studies with test drivers would be difficult to carry out because of the difficulty in establishing a driving course that includes through movements having different durations of yellow time. Data collected in the past are unlikely to include signals with longer yellow times in operation.

- Test track and driving simulation studies would permit testing the behavior of the same driver under different yellow times and other conditions.

Preferred Data Collection Method

The preferred data collection method is extraction of vehicle trajectory data from video recordings (by machine-learning-assisted feature extraction) or measurement of vehicle trajectory data by other means (BSMs or sensor-based trajectories) in the field. Researchers should collect vehicle trajectories sufficiently far back to capture vehicle behavior on the approach—at least 10 seconds upstream (e.g., 800 feet at 55 mph) could be effective. Video coverage would not necessarily need to record this if alternative data collection can capture trajectories at upstream locations. Researchers should record video of the intersection and the immediate area (e.g., up to maybe 100 feet upstream). Video recordings of the intersection would have value for extracting additional data such as surrogate safety metrics and for validation. Researchers should also record the signal state. This could involve the use of signal state data or feature extraction from video.

An alternate data collection method is naturalistic driving data, including video recordings (from a single vehicle's point of view) of signal status and the crossing/stop line event. As mentioned above, existing data may not include longer yellow change intervals. However, such data may be able to yield observations for such yellow times as do occur in the dataset. Another alternate method is CV data consisting of BSM messages, combined with signal state data or equivalent data recording the start of yellow times, when such data are available at meaningful sample sizes.

Study 2: Understanding Driving Behavior When Reacting to Yellow Change Intervals for Through Movements

The objectives are to understand driver behavior (measured through speed, deceleration, and perception-reaction time) involved in making a go/no-go decision for through movements and to investigate how different these (and other characteristics) are when compared with the assumptions used by the traditional kinematic equation.

The principal questions are:

- Do at least 95 percent of drivers approach intersections at speeds consistent with the assumptions of the traditional kinematic equation?
- Do at least 95 percent of drivers exhibit reaction times consistent with the assumptions of the traditional kinematic equation?
- Do at least 95 percent of drivers use decelerations consistent with the assumptions of the traditional kinematic equation?
- Do drivers adjust their speed on the approach (e.g., on approach to a stale green, within dilemma zone, and in reaction to start of yellow based on distance), and does this behavior vary with the posted speed limit?

Answering the above questions would require observations of driver speed, reaction time, and deceleration with sufficient sample sizes to characterize distributions and identify percentages of drivers with an acceptable level of confidence. Potential data collection methods for this study include the following:

- Naturalistic studies of the driving public would be the most useful test environments for characterizing distributions of driving behavior. Speed and deceleration are relatively straightforward to observe in the field, but it is more difficult to observe reaction time—except in the case of drivers who decide to stop. Even then, a stopping decision might not require immediate braking depending on the speed of the vehicle:
    - Video recordings from the sites would likely capture most of the observable elements required to answer the research questions. BSM data and sensor-based trajectories would also be able to capture the observable elements.
    - Commercial CV data have much lower time resolutions, would be unable to measure reaction time, and may not permit enough measurements to ascertain whether drivers maintain constant speed over the time period of interest.

- Reaction times would be easier to study in test environments. Naturalistic driving environments, test tracks, and driving simulators are all applicable environments for carrying out such a study. The principal challenge lies in obtaining a large sample rate for similar conditions. This would require the inclusion of many test subjects. Previously collected data on reaction time might also be applicable. Past researchers have made many observations of reaction time, so making additional observations might be unnecessary.

Preferred data collection method: Vehicle trajectory data coupled with the signal state, similar to that for study 1, which could be obtained using a variety of technologies: analysis of video (particularly machine-learning-assisted analysis), BSMs, or sensor-based trajectories are feasible. The 10-second distance mentioned for study 1 should suffice for study 2. Alternate method: CV data composed of BSM messages, combined with signal state data or equivalent data recording the start of yellow times, wherever such data are available at meaningful sample sizes.

Study 3: Understanding Driving Behavior When Reacting to Yellow Change for Turning Movements

The objectives are to understand driver behavior (measured through speed, deceleration, and perception-reaction time) involved in making a go/no-go decision for turning movements and to investigate how different these (and other characteristics) are when compared with the assumptions used by the extended kinematic equation. The kinematic equation assumes a constant approach speed, a constant (maximum) deceleration, and a constant entry speed with which a vehicle crosses the intersection. Researchers should verify these assumptions for both left- and right-turning movements and various operational conditions.

The principal questions are:

- Do drivers of vehicles approaching an intersection to make turning movements maintain a constant speed during the initial approach (before and during the perception-reaction time) consistent with the extended kinematic equation?

- Do drivers of vehicles approaching an intersection to make turning movements use a constant deceleration consistent with assumptions of the extended kinematic equation?

- Do drivers of vehicles maintain a constant entry speed when crossing the intersection consistent with assumptions of the extended kinematic equation?

- Is the intersection traversal behavior of at least 95 percent of drivers consistent with the clearance interval time calculated from the extended kinematic equation?

- How is driver behavior on turning movements influenced by intersection geometry, area type, and presence of conflicts with other road users near or within the intersection?

Similar to study 2, answering these questions would require observations of driver speed, reaction time, and deceleration. The spatial-temporal range of the observations may be slightly different for studying assumptions of the extended kinematic equation. However, it seems likely that in the setup of a site for data collection, a sufficient field of view for video recording or other types of data collection would seek to capture a range that is sufficient for study 2 and study 3. Ideally, these data would capture vehicle movement from a sufficient upstream distance on the approach and continuously track the vehicles as they traverse and exit the intersection. The same comments for study 2 regarding perception-reaction time would also apply to study 3.

Preferred data collection method: Vehicle trajectory data coupled with the signal state, similar to that for study 1, which could be obtained using a variety of technologies: analysis of video (particularly machine-learning-assisted analysis), BSMs, or sensor-based trajectories are likely feasible. The 10-second distance mentioned for study 1 should suffice for study 3. Alternate method: CV data composed of BSM messages, combined with signal state data or equivalent data recording the start of yellow times, when such data are available at meaningful sample sizes.

Study 4: Crash Safety Assessment of Change and Clearance Intervals

The objectives are to determine the crash-based measures (i.e., target crashes) suitable for evaluating the CCI associated with a given signal phase and to quantify the change in frequency and severity of target and total crashes associated with a modification to the change or clearance interval. The principal question is, Do fatal and/or injury RLR-related crashes increase in frequency with an increase in the yellow interval?

Because study 4 is concerned with safety outcomes, the principal dataset for evaluating these outcomes consists of crash data (other data sources are applicable to study 5). Careful site selection will ensure the study captures relevant operational conditions. Example considerations include different types of intersection geometries, traffic volumes, signal phase assignments, presence of multimodal traffic, and regional variation. As mentioned in the previous chapter, it will also be important to know the signal timing at these locations at the time of crash. The duration of yellow will be key, but researchers should know whether other changes to the signal timing occur, because they could also influence the safety performance. Accounting for such changes in an analysis of the crash data may help better identify the impact of the yellow change interval.

Preferred data collection method: Crash records for selected sites, with considerations as listed above. Signal timing data may also be of use, although it may be unnecessary to know all the different parameters (other than duration of CCIs).

Study 5: Surrogate Safety Assessment of Change and Clearance Intervals

The objectives are to determine the surrogate-based measures suitable for evaluating the change interval and the clearance interval associated with a given signal phase and to quantify the change in the performance associated with a modification to the change interval or the clearance interval. Surrogate safety metrics would include RLR, PET, and TTC. It is also important to understand how the surrogate safety metrics correlate with the actual safety performance.

The principal questions are:

- What is the variation in surrogate safety metrics with various CCI methods (e.g., kinematic, extended kinematic, rule of thumb, and stopping probability)?

- Is an increase in the yellow interval associated with a change in surrogate safety metrics?
- Is an increase in the red interval associated with a change in surrogate safety metrics?

Study 5 is concerned with the safety performance of intersections. Rather than using crash data, this study examines surrogate measures—primarily the frequency of RLR. Naturalistic studies of the driving public represent the only type of test environment that can characterize the frequency of RLR. Potential data collection methods for this study include the following:

- Site video recordings would capture observable elements required to answer the research questions (including RLR, PET, and TTC along with conflicting phase early entry (i.e., side street)). It will likely be possible to obtain such observations in other studies by using video data, but with RLR's being a subset of intersection traversals, video may not be the most effective way to capture red light violations.
- The purpose of red light enforcement cameras is to capture red light runners. The cameras obtain only RLR. As discussed in the previous chapter, some studies using such cameras were able to obtain very large numbers of vehicle entry times. However, the presence of enforcement cameras will introduce bias into driver behavior, so the results would not be generalizable to locations that lack enforcement cameras. Thus, this dataset may be of limited use other than perhaps to gather data at some limited locations:
    - Signal state data can yield estimates of RLR, and data collection is feasible over long periods of time. This dataset also captures the signal state. However, detectors must be appropriately located to estimate RLR. Moreover, they produce only RLR and cannot provide other metrics. It is not immediately clear how many intersections have good detector configurations that can also collect these data. Another related data source that may have potential is the use of sensor-based trajectory data, but relatively few existing locations have such sensors installed in a location to observe red light runners (stop bar detectors).
- BSMs from CVs have low sample rates, and RLR is a relatively rare event. Commercial CV data would be unable to definitively confirm RLR, which would require pairing CV datasets with traffic signal status.

Preferred data collection methods: Two options seem equally valid for this study. One option would be to use the same vehicle trajectory data proposed for studies 1, 2, and 3. The other option would be to use signal state data. In many locations across the United States, agencies have installed ATSPM systems, and thousands of intersections have controllers or other equipment that can record signal event data. Some, but not all, of these intersections have detector layouts that can yield these estimates. It is necessary to have separate detection channels in different lanes. The detection technology should also have low latency times when switching between occupied and unoccupied states.

Study 6: Safety Assessment Procedure and Measures

The objective is to develop a procedure for assessing the level of safety associated with alternative CCIs for a specified signal phase at an intersection. The research should identify appropriate performance measures and methods for quantifying these measures. The measures should collectively address operations and safety. Researchers should give special attention to using existing infrastructure and datasets (e.g., high-resolution ATSPM data) to assess impact of various CCIs on selected surrogate safety performance measures. If the existing infrastructure and datasets are not enough to achieve this objective, this study should identify minimum necessary infrastructure and data improvements to achieve such objective. The principal question is, How can researchers use existing datasets and infrastructure to assess safety impacts of alternative CCIs?

The goal of this study is to develop a methodology that might be able to yield an evaluation of outcomes rather than to answer a question based on observations of driving behavior or direct measurements of outcomes. This study may not necessarily require separate data collection activities from other studies. However, as a part of this study it will also be key to identify locations of interest where CCIs have changed. This would require a broad survey of agencies to identify these locations, which itself could represent a data collection effort. During these efforts it may also be possible to identify before-and-after data from agencies that have made changes to CCIs.

Study 7: Investigation of Pairwise Conflict Zone Method for Red Clearance Intervals and the Method's Applicability to U.S. Controllers and Practices

The objective is to evaluate challenges and opportunities for applying the conflict zone method in the United States for selecting red clearance intervals. The conflict zone method would introduce a new process for determining the duration of red clearance intervals whereby instead of technicians programming each interval per phase, technicians would instead program each interval by a combination of current phase and next phase (as well as what modes are present for that phase). This study would investigate applicability to common U.S. geometric conditions, phase designs, and ability to implement relevant timings in the U.S. controllers, as well as explore compatibility with MUTCD language. For example, the red clearance interval for a left-turn movement may be shorter if the next phase is the cross street through movement and may be longer if the next phase is the opposing through movement with a pedestrian call. This is an exploratory study.

Some preliminary study questions are:

- Can signal controllers developed for the U.S. market support (or will it be easy for manufacturers to modify them to support) red clearance intervals whose durations depend on the preceding phase and next phase? Researchers will need to assess the approximate share of traffic signals that fall into the easy, could-be-modified, can't-be-modified categories.

- How would this concept apply to overlaps and other signal timing objects specific to U.S. practice?

- How might signal timing practices change if analysts no longer assign the durations of red clearance intervals according only to the longest crossing time of the currently ending phase but are instead determined by the specific crossing time according to the combination of the current and next phase? And does this address the needs of pedestrians and bicycle clearance?

- How feasible is it to make such a change?

Some intersections in the United States use similar concepts, but they are not common. Examples include diverging diamond interchanges, where the clearance time needed for the crossover intersections is shorter than the clearance time needed for ramps. Depending on controller capabilities, overlaps with delayed start of green can introduce additional red time for the ramps, or dummy phases inserted into the phase sequence can serve the same purpose. Single-point urban interchanges sometimes use similar timing. Another situation occurs with trailing overlaps, which remain green longer than their parent phases and have applications for timing of offset intersections and similar locations. Although no U.S. signal controller currently supports these types of intervals, the user programmable logic available in some controllers might be able to introduce it for testing purposes. Microsimulation studies would be the first place where explorations of experimental signal timing methods could take place. Positive results from microsimulation studies may lead to bench testing with real control hardware, ultimately followed by field testing if the concepts prove to be effective and seem to be worth implementing. Researchers could evaluate studies of the operational or safety effects of such a method by means similar to those of other studies listed here.

Study 8: Mobility and Capacity Assessment of Change and Clearance Intervals

The objective is to investigate the impact of modifying CCIs on mobility and capacity metrics at signalized intersections.

The principal questions are:

- Do increases in CCIs change the capacity of signalized intersections?
- Do increases in CCIs change the mobility performance of signalized intersections?
- Do intersections experiencing longer delay times also experience a lower amount of RLR?
- Can intersection capacity increase without adverse safety impacts during times of day with higher amounts of traffic congestion?

Researchers frequently perform similar studies of capacity and mobility performance of traffic control systems, so datasets with applications to those studies should also be applicable here. Potential data collection methods for this study include the following:

- Naturalistic studies of the driving public are useful test environments for evaluation because they directly measure the performance of real-world traffic. The challenge in such real-world studies lies in managing a schedule for changes to traffic signal timing, the acceptability of the proposed changes to study, and the control of extraneous variables such as traffic demands and site conditions:

- Video recordings as described for study 1 and others would be applicable to this study, with extraction of delay or other performance measures. Video data collection may be more expensive or labor-intensive than other acceptable options.
  - Commercial CV data can provide samples of vehicle delays at intersections. Data vendors can supply data from long periods of time without the need for deploying equipment in the field to collect the data.
  - BSMs from CVs or sensor-based trajectories may also be applicable, but these bring a need to have equipment in the field to collect the data.
  - ATSPMs include a variety of performance measures that analysts can calculate with signal state data. The quality of the data is sensitive to detector layout, and a controller or other device must collect the data.

- Microsimulation studies represent another option for measuring operational performance under alternative control policies. They are much less expensive than field studies and permit greater control of test scenarios. In particular, studies of capacity can be facilitated by creating simulation scenarios with higher levels of demand than may exist at a particular real-world location to permit measurement of capacity. However, analysts need to calibrate the simulation model to replicate real-world activity, and the results would be very sensitive to the quality of calibration.

Preferred data collection method: Microsimulation studies would be the most convenient option for evaluating operational performance and are also the lowest risk in terms of testing various alternatives. Alternative method: Use of signal state data or commercial CV data offers means of obtaining real-world performance measures at relatively low cost.

Summary of Studies

The above discussion examined eight potential studies related to CCIs inspired by gaps found in literature review and agency practices. For each study, different types of data are more applicable than other types. The preceding section presented the most-favorable types of data that appear to be applicable in each study, along with potential alternatives for some studies. The next section discusses considerations for data selection.

Considerations for Data Selection

Researchers must account for practical considerations when selecting a dataset. These considerations are in addition to how well a particular dataset may help answer research questions that have emerged around CCIs.

Cost and Effort

Perhaps the most important consideration for use of any dataset is cost. Most data require some cost to obtain, whether a vendor directly sells the data or whether researchers procure equipment for data collection. In some cases, researchers may possess existing equipment, and researchers can recover the sunk costs of its procurement through use of the equipment. This ability to recover sunk costs can be especially true of testing facilities. In addition to procurement, other costs may come in the form of effort, such as worked person-hours of the research team members, lead time of processes, and overhead for use of the data.

Some of these efforts include:

- Calibration: Most data collection equipment needs some calibration to ensure that researchers can extract accurate information from the data.

- Validation: Some datasets are still emerging, and their accuracy and utility may not be well-known. Researchers may need to make additional effort to validate the data before committing to their use.

- Purchase of equipment: Some data collection options may require purchase of sensors or other data collection devices, supporting equipment, and supplies for installation and removal, connectivity, etc.

- Installation of equipment: The installation and removal of data collection devices will require some effort. For example, the mounting of video cameras from certain vantage points might require use of a bucket truck.

- Storage, processing, and /analysis: Large quantities of data may bring storage requirements that exceed the ability of local storage of flat files to effectively manage. It may be necessary to procure cloud services or a server to store the data and to potentially archive the data for longer periods of time. Data processing and analysis also bear some cost in either time, computing resources, or cost of a commercial solution.

- IRB approval: Studies involving human subjects where data collection potentially includes personally identifiable information are subject to approval by IRBs. This would be applicable to naturalistic-driving-study data. Although no direct cost is involved with IRB approval, the process can take time, especially if IRB requires changes to the research plan.

- Quantity of data required: Another consideration related to cost is the amount of data needed to perform an analysis and draw conclusions from it.

- Licensing of data: Researchers should be aware of their rights to use data purchased or licensed from a vendor, such as whether time limits exist on how long the data can be retained, or other restrictions.

Transferability

Regardless of the data types researchers select, transferability is an important consideration in site selection. *Transferability* refers to the concept that observations at one location and the inferences drawn from them can apply to other locations. To further explore the idea, it is helpful to think about the variety of configurations and environments of intersections that exist. A majority of intersections have similar geometries, most being the meeting point of two different two-way streets that have relatively little skew in the angle between the two intersections.

The variety of configurations and environments of intersections include the following:

- Phasing: use of protected-only, protected-permitted, permitted-only, or prohibited left turns; presence of right-turn overlaps; phase sequence
- Geometry: presence of turning lanes, approach speed, approach grade, approach curvature, lane width, density and spacing of signalized intersections
- Traffic modes and demands: presence of pedestrian crosswalks, presence of bus stops or other transit facilities, presence of bike lanes, presence of parking lanes near the intersection, traffic composition (e.g., percent heavy vehicles)
- Regional variations: use of permissive or restrictive yellow, driver behavior, urban or rural environment
- Signal operation: coordination; actuation and detector configuration; use of dilemma zone protection; signal timing
- Presence of traffic control devices: pedestrian countdown timers, advance warning flashers, red light enforcement cameras (at the site or other sites in the region)

Methodologies such as HCM (TRB 2016) and *Highway Safety Manual* (AASHTO 2010) handle the above varieties by considering a set of base conditions that reflect a certain set of default site characteristics for which each possible variant contributes to the outcome by means of an adjustment factor. For CCIs, such a factor already exists in the adjustment for approach grade in the kinematic equation and extended kinematic equation. It is not likely that all the above varieties have a substantial impact on the effects of CCI policies. It is also not feasible to test every possible variation. It is still desirable to select representative sites that capture the effects most likely to impact how drivers react to CCIs. At minimum, the selected sites should capture regional variations (especially between locations with restrictive or permissive yellow) and variations in phasing for through and turning movements within each region. If resources permit, the researchers might undertake additional tests to assess certain specific variations (e.g., impacts of the presence of pedestrian countdown timers), but it is probably unnecessary to capture each of these for different regions and phasing configurations.

Data Fusion

Another consideration for site selection and data collection methods is whether multiple data sources can provide a more complete view than a single source. Several literature studies combined video with other datasets or used limited amounts of data for validation or calibration.

Some examples of data fusion include:

- Researchers might collect a limited amount of data with BSMs or with a test vehicle with CAN bus data to record speed at high fidelity and compare these against data collected from other sources (video analysis, etc.) to verify the accuracy of the latter.

- Researchers might employ commercial CV data to conduct a high-level screening of locations for more detailed analysis with other data types.

- Some locations may be challenging with regard to identify a camera location that can capture the entire approach as well as the signal indications. A combination of video and signal state data might be able to provide a complete picture.

Chapter Summary

This chapter discussed types of data most applicable to each research study listed in chapter 4, along with a preferred data collection method. Table 18 summarizes the preferred data collection method for each study. This chapter provided a high-level discussion of these issues and tried not to be too prescriptive about the specifics of data collection methods and instead to permit flexibility and innovation in the next phase of this study. This discussion intended to capture key observables that would answer questions related to the research studies and identified datasets that seemed most promising to make these observations.

Table 18. Preferred data collection environment and method.

Study	Preferred Data Collection Method	Alternative Data Collection Method
Driver Behavior Effects of Long Yellow Change Intervals for Through Vehicles	Vehicle trajectories (speeds and positions) and signal state data	Naturalistic driving data; connected-vehicle (CV) data (basic safety messages, BSM) combined with signal state data or equivalent record of start of yellow times
Understanding Driving Behavior When Reacting to Yellow Change for Through Movements	Vehicle trajectories (speeds and positions) and signal state data	CV data (BSM) combined with signal state data or equivalent record of start of yellow times
Understanding Driving Behavior When Reacting to Yellow Change for Turning Movements	Vehicle trajectories (speeds and positions) and signal state data	CV data (BSM) combined with signal state data or equivalent record of start of yellow times
Crash Safety Assessment of Change and Clearance Intervals	Crash data	None
Surrogate Safety Assessment of Change and Clearance Intervals	Vehicle trajectories (speeds and positions) and signal state data	None
Safety Assessment Procedure and Measures	Potential agency survey to identify locations	None
Investigation of Pairwise Conflict Zone Method for Red Clearance Intervals and the Method's Applicability to U.S. Controllers and Practices	Microsimulation	None
Mobility and Capacity Assessment of Change and Clearance Intervals	Microsimulation	Signal state data or commercial-CV data

CHAPTER 6. SUMMARY OF FINDINGS

Agencies use CCIs at signalized intersections to safely transition the right-of-way between conflicting traffic movements. The appropriate determination of the CCI is key at signalized intersections to ensure safe transfer of the right-of-way while minimizing lost time (and therefore maximizing intersection capacity). Due to the importance of the subject, the CCI has been a topic of discussion in the industry for 70 years and many researchers have studied the topic. Even though many researchers and agencies have already explored this topic extensively, they have reached contradicting opinions. Practitioners have still not achieved a national consensus on how to determine the CCI durations under a variety of operational conditions.

This document presented a synthesis report of the pooled fund study led by FHWA. The study developed a synthesis of knowledge on traffic signal CCIs, identified research gaps, developed a research plan, and evaluated potential data collection alternatives. The outcomes of this study lay the foundation of the subsequent research to support documentation on CCIs. This study identified the following key findings.

CALCULATION METHODS

The review of the literature indicates two main methods for determining CCIs: (1) methods that follow some form of kinematic equation originally derived by Gazis, Herman, and Maradudin (1960) and (2) behavioral studies that analyze driving behavior and stopping probability at the onset of a yellow signal.

Kinematic Model

The kinematic model originally developed by Gazis, Herman, and Maradudin (1960) was based on a theoretical analysis and observations of the behaviors of drivers confronted by a yellow signal. The proposed model was a simple analytical model developed for through vehicles and assumed a constant approach speed, a constant deceleration, and a fixed value for perception-reaction time. The objective of the research was to provide insights into the problem of determining the proper duration of the yellow change interval rather than developing national guidance for agencies. Additionally, the research discussed some limitations of the developed analytical model and suggested additional factors for traffic engineers to consider (e.g., drivers' responses to short or long yellow intervals) when determining CCIs. However, since 1965, the recommended practice from ITE has leaned on the kinematic model originally developed by Gazis, Herman, and Maradudin (1960), with very few changes over the years (with the extended kinematic model as the biggest change).

The kinematic model has limitations because it follows a mostly deterministic approach (except for the approach speed). It assumes ideal or reasonable driving behavior characteristics, with specific values of perception-reaction time and acceptable deceleration when a driver faces a yellow signal. Another limitation is that it assumes a constant or uniform deceleration (particularly through applications of default values), which simplifies the calculation and makes it easier to adjust the equation for special cases. However, field data suggest that when drivers encounter a yellow signal, they do not necessarily follow the constant or uniform deceleration model, and only about 30 percent of the stopping vehicles had deceleration profiles that approximated the constant rate condition (Wortman and Matthias 1983; Wortman, Witkowski, and Fox 1985).

Stopping Probability Method

To overcome the limitations of the kinematic model, several researchers studied stopping probability functions at the onset of the yellow interval for a range of approach speeds (25–55 mph) to explore the potential use of a uniform duration for the yellow interval. Some of these studies found that the needs for the yellow change interval are independent of the approach speed and typically tend to be in the range of 4.0–5.0 seconds. While these study findings may support the use of a uniform yellow interval, such use may still pose risks without conducting additional research, because the suggested yellow change interval varied from one study intersection to another (e.g., some studies suggested using 4.5 seconds based on the 95 percent of going vehicles to reach the stop line, while others suggested 5.0 seconds).

Extended Kinematic Equation

ITE recently published *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (2020), which developed new guidelines for determining traffic signal CCIs and introduced the extended kinematic equation (Beeber 2020). The motivation for the extended kinematic equation was to address the oversimplification of the original kinematic equation for turning vehicles. As a result, the new guidance (ITE 2020) extended the original kinematic equation to consider turning movements. The revised equation recognizes that approach speed (used to calculate the yellow change interval) and entry speed (used to calculate the red clearance interval) for turning vehicles differ from through movements because turning drivers must decelerate within the critical distance.

While the new guidance (ITE 2020) that uses the extended kinematic equation incorporates turning movements, it resulted in the following concerns among practitioners and researchers:

- The guidelines in *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (ITE 2020) sometimes result in yellow change intervals for left-turn movements that are longer than the accepted limits used by some agencies. The calculated yellow intervals sometimes conflict with MUTCD guidance, which constrains the duration of the yellow interval to 3.0–6.0 seconds (FHWA 2009).

- The extended kinematic equation assumes turning drivers maintain their approach speed during perception-reaction time. However, anecdotally, traffic engineers believe that turning drivers start decelerating to intersection entry speed (i.e., turning speed) well before the onset of the yellow indication. If this assumption is true, the extended kinematic equation would overestimate the yellow change interval duration.

- Similar to the original kinematic model, the extended equation also assumes that turning drivers have uniform deceleration and perception-reaction time for all roadways or vehicle types, while research has shown that several factors (e.g., approach speed, travel time to stop line, roadway type, and vehicle type) can influence the deceleration and perception reaction.

PERFORMANCE ASSESSMENT

This section summarizes the findings regarding performance assessment of CCIs.

Safety Performance Measures

Analysts have used several measures to assess the safety performance of the change interval and clearance interval. Researchers can categorize these measures as crash-based measures or as safety surrogate measures.

Crash-based measures related to the CCI include rear-end crashes, opposing left-turn crashes, and right-angle crashes. Surrogate measures to assess the safety performance of the change interval and clearance interval include the red light violation rate and the late exit rate (e.g., proportion of approach vehicles that exit the intersection after the end of the clearance interval) (ITE 2020).

Some performance measures are more appropriate for assessment of the change interval (e.g., red light violation rate), and others are more appropriate for assessment of the clearance interval (e.g., late exits). Some interaction also exists between the two intervals such that a change interval inconsistent with driver needs and expectations may influence measures focused on assessing the clearance interval (ITE 2020). This interaction suggests that a performance assessment should always address both intervals.

Crash-Based Measures

The literature has limited information about the effect of change interval duration on crash frequency. The few identified reports are not in agreement about what crash types are sensitive to change interval duration modifications. The reports further do not agree about the magnitude of the change in crashes associated with the modification. The tendency is to examine the safety effect of an increase in change interval duration. The research team identified no studies that examined the safety effect of a decrease in change interval duration.

Relative to the change interval, the literature has even less information in the literature about the effect on crash frequency of either adding a clearance interval or modifying the clearance interval duration. The few reports the research team reviewed do not agree about what crash types are sensitive to the clearance interval. These reports also do not agree as to whether the clearance interval decreases or increases crashes.

Finally, the crash-based safety studies from the literature review focus on measures associated with the through driver and conflicting movements (including the opposing left-turn movement). The research team identified no studies that examined crashes associated with the left-turn or right-turn movements (and their conflicting movements) and no studies associated with bicycle and pedestrian influences on CCI. Recent research to develop methods for computing the CCIs indicates the durations of these intervals are different from those needed by through movements (ITE 2020). These new methods consider driver and vehicle characteristics that are unique to the turn movement, which suggests that other or additional factors also influence the associated crashes (relative to the through movement).

Safety Surrogate Measures

Safety surrogate measures have proven useful for performance assessment of CCIs. They are well suited to situations where observed crash data are not readily available. Most of the reviewed research focuses on the use of red light violation measures. The research tends to agree that an increase in the change interval is associated with a reduction in red light violation frequency. However, the tendency is to examine the safety effect of an increase in change interval duration, and little information exists on the impacts of excessively long CCIs. The research team identified no studies that examined the safety effect of a decrease in change interval duration.

Very little research has examined safety performance of the clearance interval by using surrogate-based measures. These studies examined the change in performance associated with an increase in the clearance interval duration. The research team found no studies that used safety surrogates to assess the addition of a clearance interval or a decrease in clearance interval duration.

Finally, the surrogate-based safety studies from the literature tend to focus on measures associated with the through driver and its conflicting movements (including the opposing left-turn movement). The research team identified no studies that examined conflicts associated with the left-turn or right-turn movements (and their conflicting movements). Recent research to develop methods for computing the CCIs indicates the durations of these intervals are different from those needed by through movements (ITE 2020). These new methods consider driver and vehicle characteristics that are unique to the turn movement, which suggests that other or additional factors also influence the associated conflicts (relative to the through movement). However, little data exist to verify these issues.

Operations-Based Measures

In contrast to the safety-based measures, the research team found few documents to describe operations-based measures for assessing the change or clearance intervals. Tarnoff (2004) examined the effect of clearance interval duration on vehicle delay for a typical signalized intersection. The study found that vehicle delay increased with an increase in the clearance interval duration. The increase was larger when the volume-to-capacity ratio was large. Additionally, the HCM (TRB 2016) established the relationship between lost time (which is a function of the CCIs) and vehicle delay where vehicle delay increases with an increase in CCI.

Performance Assessment Considerations

The literature has general agreement that an increase in the change interval is associated with a large but short-term reduction in red light violation frequency and that drivers adapt over a period of months to the longer interval such that the reduction rate decreases but is still substantial. The studies cited for this review evaluated sites for which the change interval increased by about 1.0 second, and none of the evaluated intervals exceeded 5.5 seconds in duration. It is unknown whether the level of adaptation would increase (e.g., to the extent that modifying the change interval brings no benefit) if the modifications exceeded these study parameters.

Traffic engineers speculate that some drivers may abuse lengthy change intervals or lengthy clearance intervals that appear consistently in a community or region (Tarnoff 2004; ITE 2020). Engineers believe that drivers adapt to an increase in the interval duration and continue to violate the red indication at a rate that is about equal to that before the increase. Anecdotal information suggests that longer change intervals will increase crash frequency and promote driver disrespect for the traffic control signal. The authors found no research that definitively addresses this issue.

RESEARCH NEEDS AND IDENTIFIED RESEARCH STUDIES

Researchers have assessed the performance of the CCI over the past few decades. The findings have not been conclusive in many areas, including calculation methods and formally recognized performance measures.

The following research studies are based on review of the literature, agency benchmarking results, and input received from the stakeholders:

- Driver Behavior Effects of Long Yellow Change Intervals for Through Vehicles
- Understanding Driving Behavior When Reacting to Yellow Change Intervals for Through Movements
- Understanding Driving Behavior When Reacting to Yellow Change for Turning Movements
- Crash Safety Assessment of Change and Clearance Intervals
- Surrogate Safety Assessment of Change and Clearance Intervals
- Safety Assessment Procedure and Measures
- Investigation of Pairwise Conflict-Zone Method for Red Clearance Intervals and Its Applicability to the U.S. Controllers
- Mobility and Capacity Assessment of Change and Clearance Intervals

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