An Update on Traffic Signal Change and Clearance Intervals

15 December 2023

Description

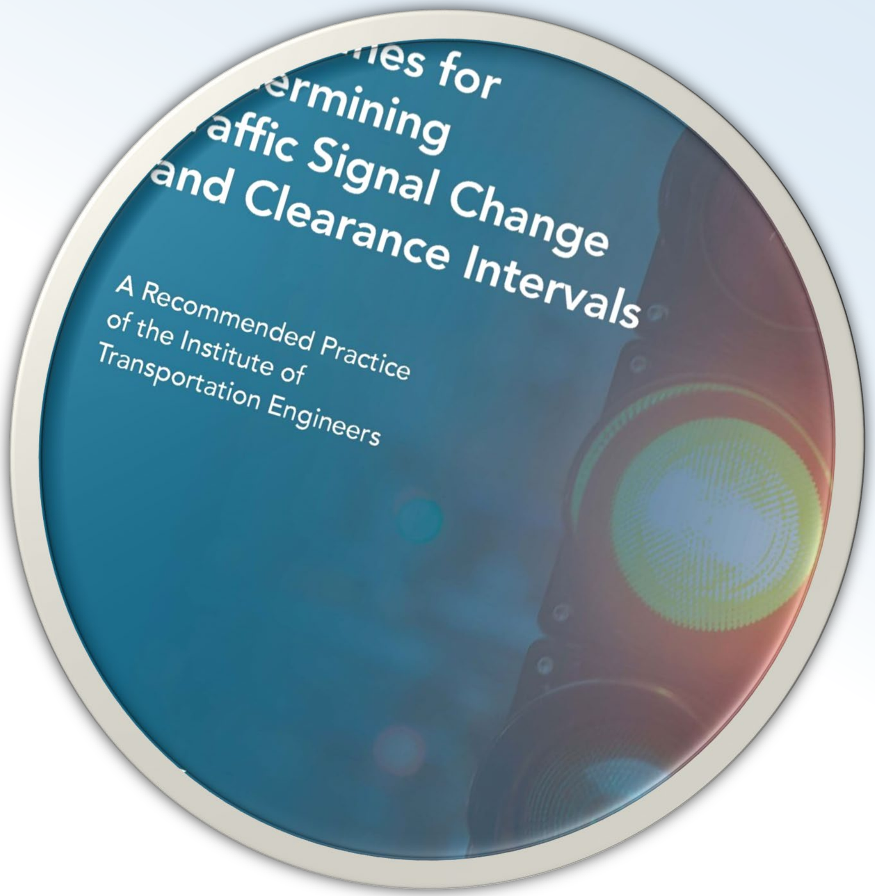
Divergent and strongly held positions characterize any discussion of the procedures for calculating traffic signal change and clearance intervals. Although the extended kinematic equation was recommended by ITE in *Guidelines for Determining Traffic Signal Change and Clearance Intervals* (2020), there remains a strong need to collect primary data to further test this approach and the other research needs identified in the recommended practice. This webinar provides a review of the recommended practice and an update on the current research that is underway along with some observations from agencies' current practice.

ITE Learning HUB

Learning Objectives

- Gain an understanding of the background and key attributes of the extended kinematic equation for traffic signal change intervals in ITE's *Guidelines for Determining Traffic Signal Change and Clearance Intervals* recommended practice.
- Learn about the literature review, study plan, and upcoming survey of practice being performed as part of the *Traffic Signal Change and Clearance Interval Transportation Pooled Fund Study*.
- Explore how transportation agencies are addressing ITE's recommended use of the extended kinematic equation through research and policy considerations.

Development of ITE's 2020 Recommended Practice on Traffic Signal Change and Clearance Intervals



Douglas E. Noble, P.E, PTOE
Senior Director, Management and Operations

An Update on Traffic Signal Change and Clearance Intervals
ITE Webinar

15 December 2023

Overview

- The Backstory
- The Process
- Approach to Document Development
- What Is in the ITE Report?
- Some Important Points for Application and Practice
- Need of More Research
- Looking Forward

ite Learning HUB

The Back Story

- 1960 - original paper by DeGazis, Herman, and Maraduddin proposes a kinematic equation but also notes limitations of their method:
- "…pertains to a single traffic light" (i.e., thru movement)
- Examined speeds below and above speed limit (e.g., up to 1.25 v_0)
- Variations related to divided highways and turning vehicles
- Longer vehicles (i.e., trucks, buses vehicles with trailers) and their maximum deceleration

> The preceding pertains to a single traffic light. Analogous results may be obtained for two closely spaced traffic lights, as in the case of crossing of a divided highway. However, this case is rather complicated and will not be discussed here. There are other variations to the problem of the dilemma zone such as the case of a vehicle approaching an intersection at slow speed with the intention of making a turn. This is a case of known practical difficulty and some information can be obtained from the present analysis with w taken equal to the distance traversed while turning.

> L/v_0 in the computation of $\tau_{\min}$. This means that the required $\tau_{\min}$ is substantially longer for vehicles such as long trucks, buses, or vehicles with trailers, even assuming that these vehicles can stop with the same maximum deceleration $a_2{}^*$ as shorter ones. One may retort that traffic signals should not be designed for these 'unusual' cases. However, these unusual vehicles *are* allowed on the highways, and if the design of the amber phase does not take them into account then the questions raised in the introduction regarding the compatibility of law and physical characteristics become even more acute.

The Back Story

- 1965 – ITE *Traffic Engineering Handbook* (3rd ed.) incorporates DeGazis et al. as minimum duration of yellow interval. Includes 2nd equation that provides time to clear intersection
- 1976 and 1982 Editions of the ITE *Transportation and Traffic Engineering Handbook* carry forward the kinematic equation
- 1982 ITE *Manual of Traffic Signal Design* includes grade factor
- 1982-1989 ITE Committee works to develop recommended practice (not approved)
- 1994 ITE report by a new technical committee presents current methods
- 1999 ITE *Traffic Engineering Handbook* (5th ed.) uses the 1982 version
- 2001 ITE Informational Report on the history of change and clearance intervals

The Back Story

- With the advent of automated enforcement the precision and calculation methods of change intervals began to be challenged.
- Roughly coinciding with the start of the NCHRP Report 731 project, ITE began a forming a committee and process to address issue (again) in a recommended practice.
- Initial work were listening sessions and a joint survey of practice with the NCHRP Report 731 project

The Back Story

What does MUTCD Say?

Section 4D.26 Yellow Change and Red Clearance Intervals

Standard:

01 A steady yellow signal indication shall be displayed following every CIRCULAR GREEN or GREEN ARROW signal indication and following every flashing YELLOW ARROW or flashing RED ARROW signal indication displayed as a part of a steady mode operation. This requirement shall not apply when a CIRCULAR GREEN, a flashing YELLOW ARROW, or a flashing RED ARROW signal indication is followed immediately by a GREEN ARROW signal indication.

02 The exclusive function of the yellow change interval shall be to warn traffic of an impending change in the right-of-way assignment.

03 The duration of the yellow change interval shall be determined using engineering practices.

The Back Story

What does MUTCD Say?

Support:

04 Section 4D.05 contains provisions regarding the display of steady CIRCULAR YELLOW signal indications to approaches from which drivers are allowed to make permissive left turns.

Guidance:

05 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 Back Story

What does MUTCD Say?

Standard:

06 When used, the duration of the red clearance interval shall be determined using engineering practices.

Support:

07 Engineering practices for determining the duration of yellow change and red clearance intervals can be found in ITE's "Traffic Control Devices Handbook" and in ITE's "Manual of Traffic Signal Design" (see Section 1A.11).

Standard:

08 The durations of yellow change intervals and red clearance intervals shall be consistent with the determined values within the technical capabilities of the controller unit.

The Back Story

What does MUTCD Say?

[09] The duration of a yellow change interval shall not vary on a cycle-by-cycle basis within the same signal timing plan.

[10] Except as provided in Paragraph 12, the duration of a red clearance interval shall not be decreased or omitted on a cycle-by-cycle basis within the same signal timing plan.

<u>Option:</u>

[11] The duration of a red clearance interval may be extended from its predetermined value for a given cycle based upon the detection of a vehicle that is predicted to violate the red signal indication.

The Back Story

What does MUTCD Say?

[12] When an actuated signal sequence includes a signal phase for permissive/ protected (lagging) left-turn movements in both directions, the red clearance interval may be shown during those cycles when the lagging left-turn signal phase is skipped and may be omitted during those cycles when the lagging left-turn signal phase is shown.

[13] The duration of a yellow change interval or a red clearance interval may be different in different signal timing plans for the same controller unit.

The Back Story

What does MUTCD Say?

Guidance:

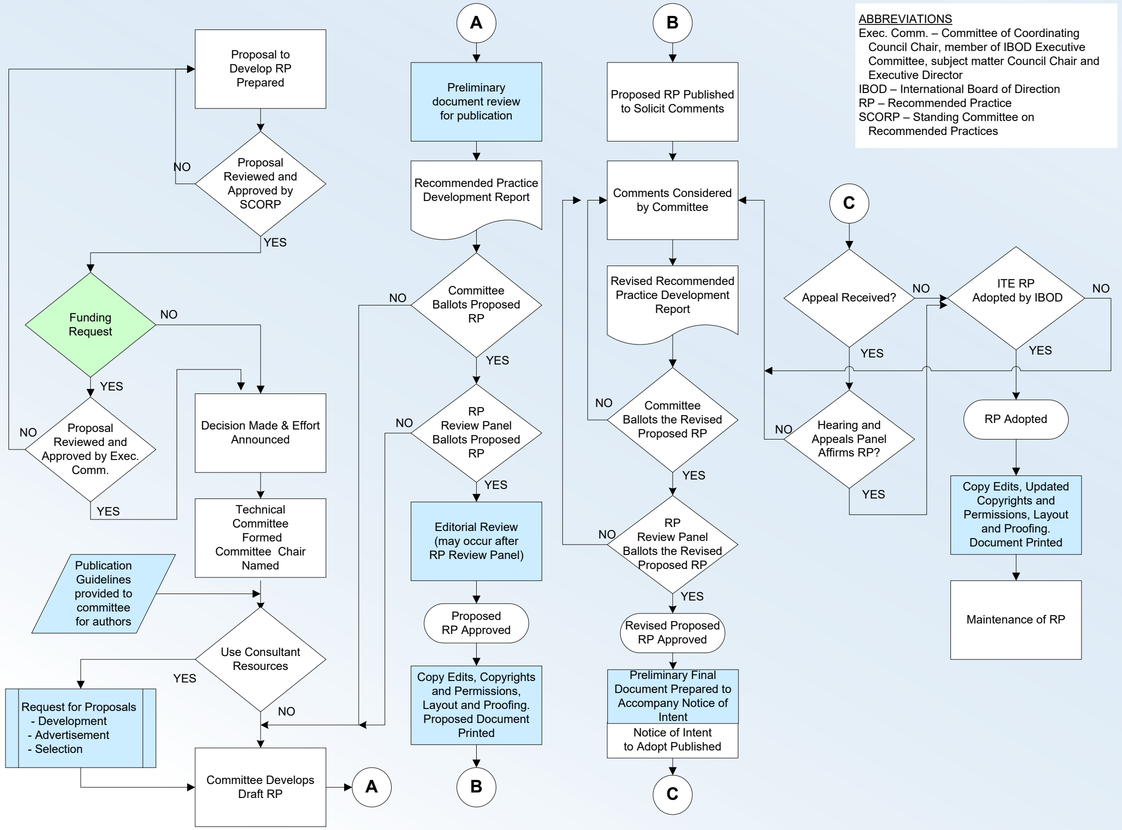
14 A yellow change interval should have a minimum duration of 3 seconds and a maximum duration of 6 seconds. The longer intervals should be reserved for use on approaches with higher speeds.

15 Except when clearing a one-lane, two-way facility (see Section 4H.02) or when clearing an exceptionally wide intersection, a red clearance interval should have a duration not exceeding 6 seconds.

The Process

ITE Recommended Practice Development (generally)

- Project Committee established and develops content
- Peer Review and revisions by Project Committee
- Proposed report issued for public comment
- Comments undergo review and resolution by the project committee and review panel
- Appeal(s), if any
- Adoption by ITE International Board



The Process

<u>This Recommended Practice</u>

- No prior ITE Recommended Practice in this area
- Prior efforts to develop a Recommended Practice could not reach consensus
- Current volunteer-led effort began in 2007
- Survey of current practices conducted in 2009
- Comment / appeal versions of draft RP published in 2015, 2018, 2019
- August 2019 appeals panel meeting to resolve remaining issues
- Final Recommended Practice approved by ITE Board in January 2020
- Final Recommended Practice released on February 28, 2020

Approach to Document Development

- Understanding of what agencies are doing in practice
- Provide summaries of research on the various different approaches to calculating change and clearance intervals
- Consider research and use of different intersection considerations, parameters, and variables
- Draw on the research to make recommendations
- Document broken into State-of-the-Practice and Recommended Method
- Test reaction to variations in research
- Reach consensus of technical committee and review panel
- Incorporate public comments

Purpose and Intended Use

- The recommended practices should yield reasonable times for yellow change and red clearance intervals for traffic signals
- ITE Recommended Practices are intended to provide consensus recommendations based on both theory and best practices, but they must be supplemented by engineering judgement to ensure a balance between sound engineering theory and practical application.
- ITE Recommended Practices are voluntary standards which are adopted at the option of the target audience (in this case agencies which own and operate traffic signals)

Scope of Recommendations

- Calculation method for change and clearance intervals
- Through and turning movements
- Perception-reaction time
- Speeds
- Deceleration
- Intersection Width
- Vehicle Length
- Grade
- Minimum and Maximum Intervals
- Rounding
- Other Road Users
- Special Road Conditions
- Implementation
- Safety
- Driver Behavior

Significant Recommendations

- Use of the Extended Kinematic Equation as Basis for Calculations
- Application to Left Turning Movements
- Application to Right Turning Movements
- Use of Speed Data and Assumptions
- Intersection Width
- Enforcement
- Use of Engineering Judgement

Traditional Kinematic Equation

Yellow Change

$$Y \geq t + \frac{1.47V_{85}}{2a + 64.4g}$$

Red Clearance

$$R = \left[\frac{W + L}{1.47V_{85}}\right] - t_s$$

Where:

Y = minimum yellow change interval (sec.);
t = perception-reaction time (sec.);
V_{85} = 85th percentile approach speed (mph);
a = deceleration (ft./sec./sec.);
g = grade of approach (percent/100, downhill is negative grade);
R = red clearance interval (sec.);
W = distance to traverse the intersection (width), stop line to far side no-conflict point along the vehicle path (ft.);
L = length of vehicle (ft.);
t_s = conflicting vehicular movement start up delay (sec.).

Extended Kinematic Equation

Yellow Change

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

Red Clearance

$$R = \left[\frac{W + L}{1.47V_E}\right] - t_s$$

Where:

Y = minimum yellow change interval (sec.);
t = perception-reaction time (sec.);
V_{85} = 85th percentile approach speed (mph);
V_E = intersection entry speed (mph);
a = deceleration (ft./sec./sec.);
g = grade of approach (percent/100, downhill is negative grade);
R = red clearance interval (sec.);
W = distance to traverse the intersection (width), stop line to far side no-conflict point along the vehicle path (ft.);
L = length of vehicle (ft.);
t_s = conflicting vehicular movement start up delay (sec.).

Calculated Change Interval Times for Left Turn Movements

Approach Speed (V85)	Traditional Kinematic Equation	Extended Kinematic Equation
30 mph	3.2 seconds	3.9 seconds
50 mph	4.7 seconds	6.9 seconds

$t = 1.0$ $a = 10$ ft / sec / sec

$V_E = 20$ mph $g = 0$

Application to Left Turning Movements

- For protected turning movements, calculate change interval, cap at 7.0 seconds if necessary
- For permissive turning movements, calculate change interval for both turning movement (cap at 7.0 seconds if necessary) and through movement, then select appropriate change interval between these two values, using engineering judgement and considering left turn volumes, approach speeds, intersection geometry and other factors as appropriate

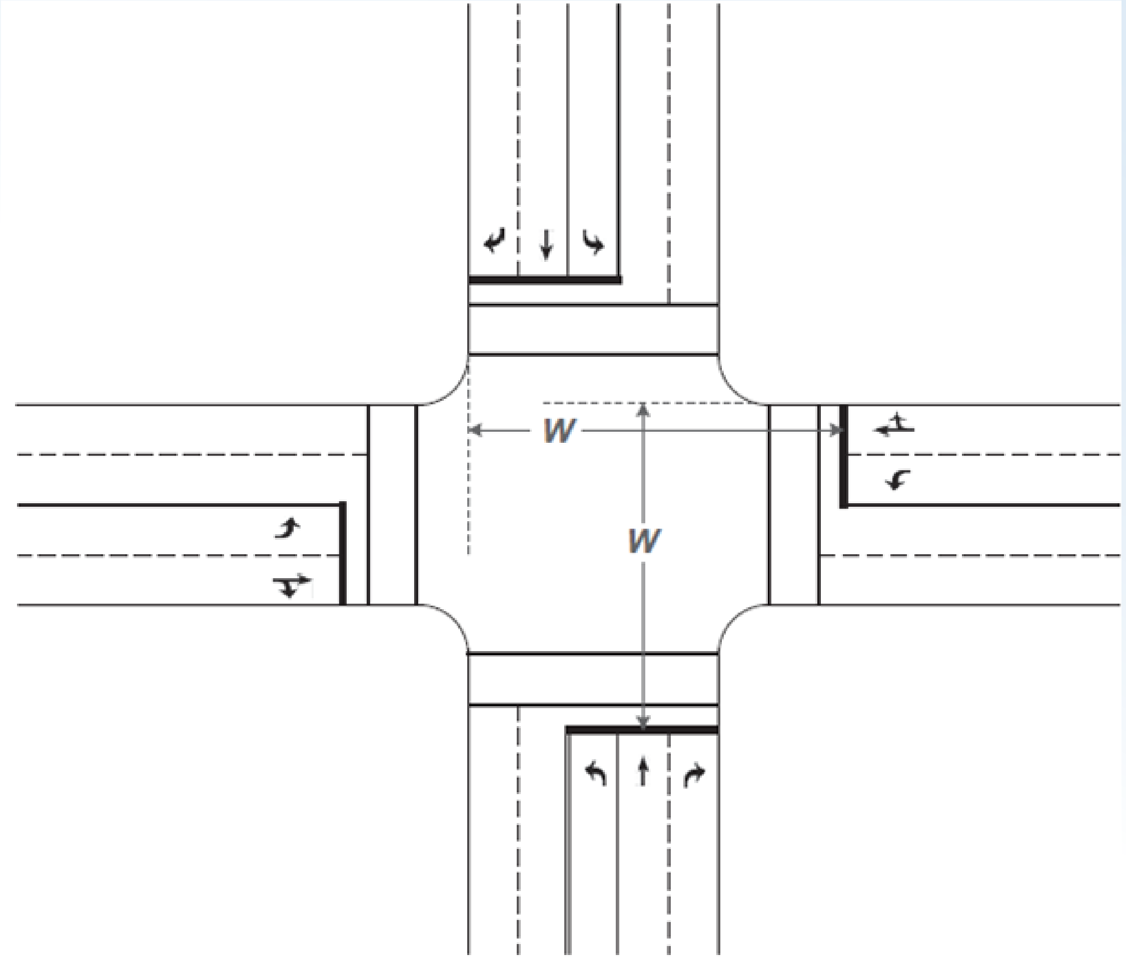
Application to Right Turning Movements

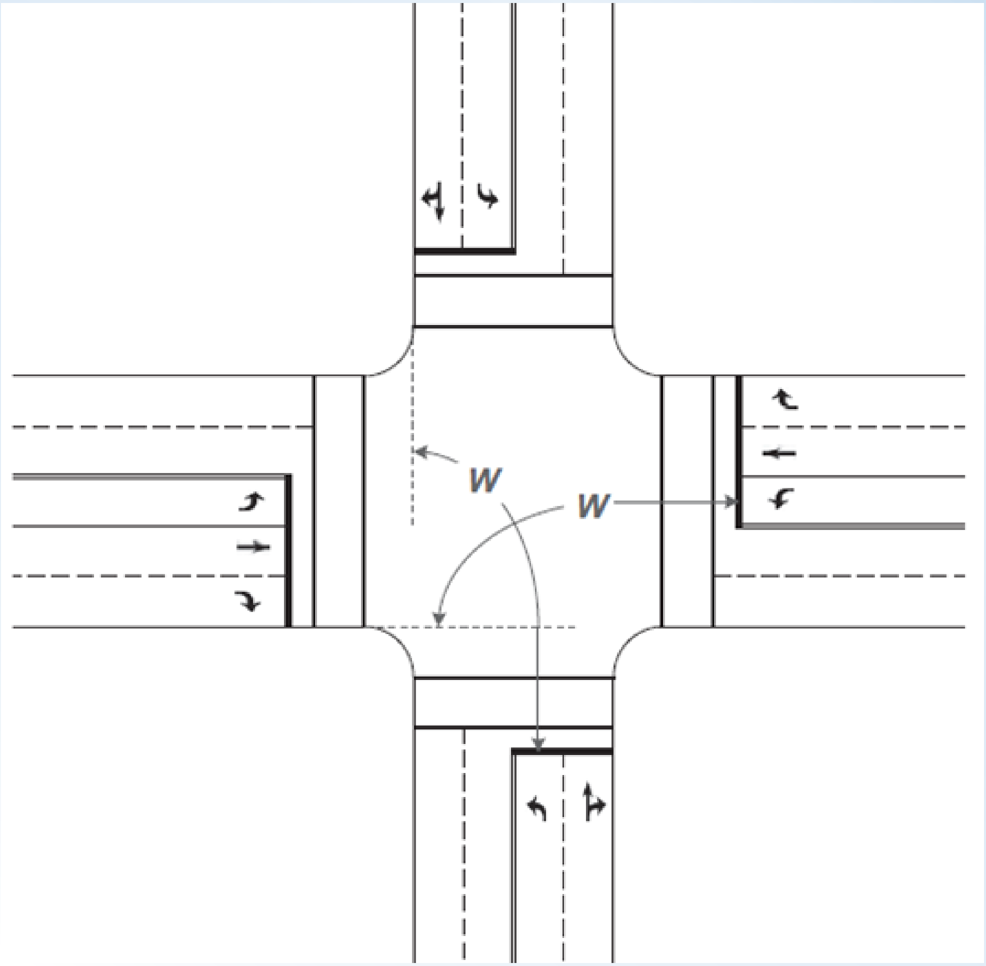
- Due to limited understanding of the complex nature of driver behaviors, interactions, and theoretical formulations of right turn maneuvers, a separate recommendation for calculating change intervals for right turning movements is not made.
- In our judgement, the recommended calculation procedures for through and left turning vehicles should safely accommodate right turning vehicles, but we have recommended additional research on the subject of clearance intervals for right turning movements.

Use of Speed Data and Assumptions

- Due to the significant influence of speed in the calculation of change and clearance intervals, use of actual speed data for approach and intersection entry speeds should be used whenever possible
- Where speed data is not available the following assumptions may be made
  - Through movement approach and intersection entry speed – speed limit plus 7 mph
  - Left turning movement approach speed – speed limit
  - Left turning movement intersection entry speed – 20 mph

Intersection Width





Enforcement

- The Recommended Practice does not cover enforcement actions, either through traditional or automated means.
- However, the Recommended Practice does caution against enforcement of red light violations with zero tolerance due to the wide range of factors and assumptions regarding driver behavior that are used in the calculation of change intervals.
- ITE has developed a proposed policy that strongly supports automated enforcement for purposes of improving safety, but not for a goal of raising revenue

Use of Engineering Judgement

- Emphasis on the use of engineering judgement is woven throughout the Recommended Practice. It is important that professionals using the recommended practices have a full understanding of the concepts and associated assumptions and limitations.
- There is also a strong theme in the Recommended Practice for documentation of decision-making regarding the choice of yellow change and red clearance intervals.

Some Important Points for Application and Practice

- The extended kinematic equation and kinematic equations are deterministic mathematical models of real world activity.
- Extended kinematic equation was judged to have validity on the basis of the underlying theory.
- The formula calculates a **minimum** value… not the value of change and clearance intervals
- The yellow change interval is **not** the time to stop, rather
  the yellow change interval is the time to traverse the braking distance
- Approach speed (or 85th percentile) is **not** the speed limit… (it can be… but…)
- Approach speed and PRT are inversely related

Some Important Points for Application and Practice

- Use of engineering judgment is noted throughout recommended practice
- Document, document, document ! ! !
- Primary data is preferred
- MUTCD states that change and clearance intervals, "… shall be determined using engineering practices."
- Approaches for proxies (surrogates) provided for approach speed and entry (traversal) speed
- What drives the long yellow is speed differential between approach and entry speed… perhaps consideration of lower approach speed thru design techniques.

Need for More Research Identified by ITE

Additional primary data needed for:

- Safety Benefits of Yellow Change and Red Clearance Intervals
- Impact on Driver Behavior and Safety of Longer Yellow Change Intervals
- Perception-Reaction Time and Deceleration for Alerted Drivers for Turning Movements
- Approach and Passage Speed Variations Associated with Left and Right-Turning Movements
- Intersection Passage Speed Variations for Turning Movements
- Data Collection Methods for Capturing Approach and Intersection Entry Speeds
- Others as Described in the Recommended Practice
- Driver Behavior Factors, especially for right-turning vehicles

Need for More Research Identified by ITE

- Approach speeds on “non-posted” roadways and on roadway with speed limits of 35 mph or less
- Easy to implement method to determine the length of travel path through intersections for turning movements and complex intersection geometries
- Effect of weather conditions
- Detector types and impact of real-time data
- Alternative intersections designs

Looking Forward

Current Items That Will Impact Future Work:

- Transportation Pooled Fund Study results
- New edition of MUTCD (soon to be) released
- Public Rights-of-Way Access Guidelines released
- Other agency and university research

ITE's Next Step(s):

- Welcome any research on applications of the extended kinematic equation
- When the Transportation Pooled Fund Study nears completion, ITE will reestablish Technical Committee and Review Panel to begin work on an updated recommended practice.

Resources

Douglas E. Noble, P.E., PTOE
Senior Director, Management and Operations
email: dnoble@ite.org

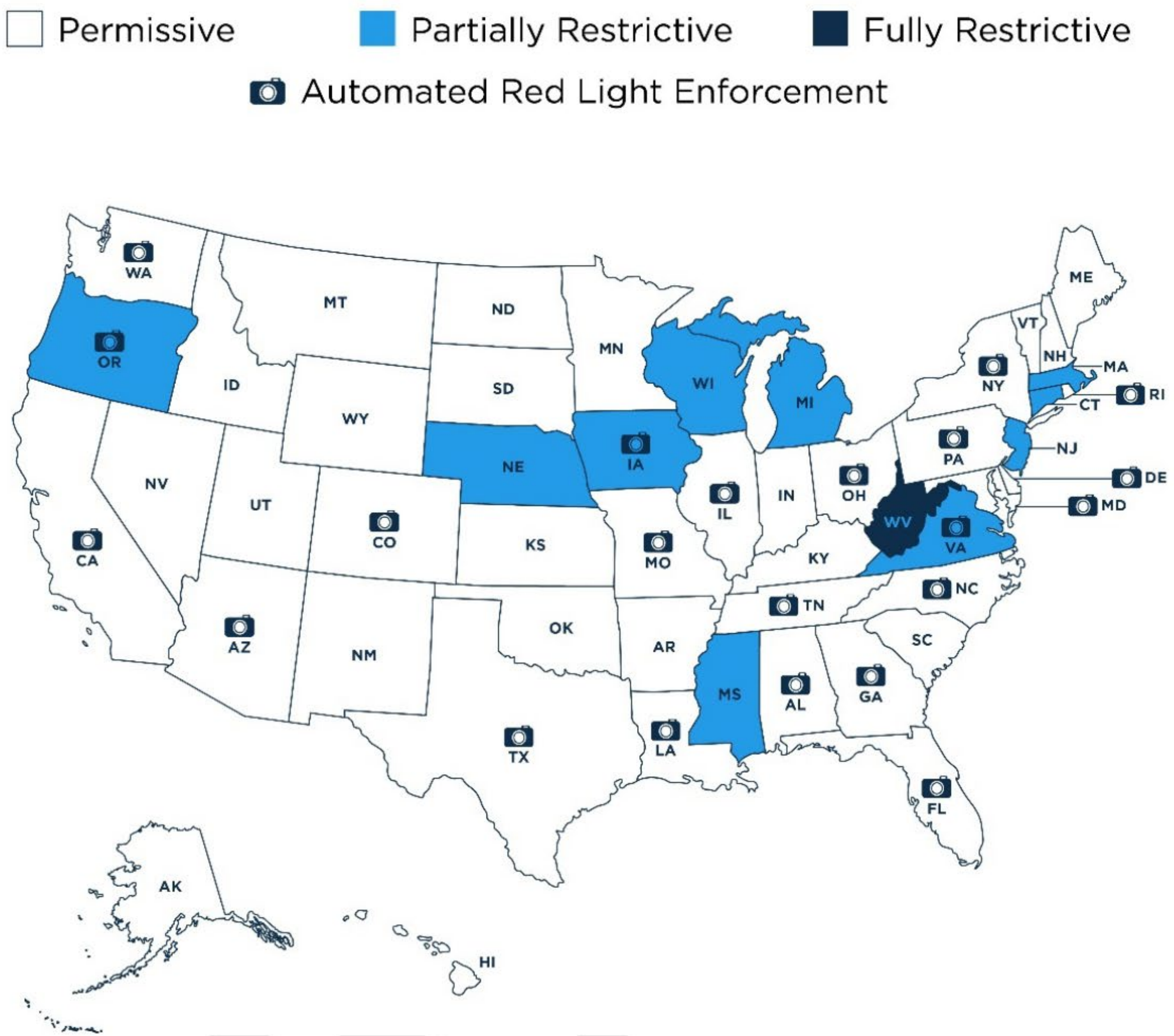
Traffic Signal Change and Clearance Intervals – Agency Perspective

Alan Davis, PE, PTOE

State Traffic Engineer

Change and Clearance Intervals

- State of agency practice
- Agency response to ITE recommended practice
- Agency needs
- What’s next


Permissive
Partially Restrictive
Fully Restrictive
Automated Red Light Enforcement
WA
OR
CA
ID
NV
MT
WY
UT
AZ
CO
NM
ND
SD
NE
KS
OK
TX
MN
IA
MO
AR
LA
WI
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Source: FHWA.

NCHRP 731

Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersection

- The perception-reaction time was confirmed to be 1.0s.
- The deceleration rate was confirmed to be 10 ft/s2.
- The 85th percentile approach speed for through vehicles is closely approximated by adding 7 mph to the posted speed limit. The actual 85th percentile approach speed should be used in the kinematic equation; however, if field data are not available, this estimation is acceptable.
- The 85th percentile approach left-turn speed is closely approximated by subtracting 5 mph from the posted speed limit. This estimation should be used to calculate the yellow change interval. For red clearance interval calculations, the left-turn speed should be considered as 20 mph, regardless of the posted speed limit


NCHRP
REPORT 731
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

GDOT Georgia Department of Transportation

NCHRP 731

Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersection

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

Where:

Y = Yellow Change Interval (sec)

t = perception reaction time (sec) – recommend 1 second

v = 85^{th} percentile approach speed (MPH)*

a = deceleration rate (ft/sec2) – use 10 ft/sec^2

g = grade (ft/ft) – positive for uphill grade, negative for downhill grade, round up to nearest grade

* In lieu of field-measured speed data, the speed limit plus 7 mph should be used as a rule of thumb estimate for the 85^{th} percentile approach speed used to calculate the yellow change interval for through movements. For left-turning movements, the speed limit minus 5 mph should be used to calculate the left-turn yellow change interval duration.

Georgia Department of Transportation

NCHRP 731

Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersection

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

Where:

R = Red clearance interval (sec)

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 edge of the farthest travel lane (ft)

L = Length of vehicle (ft) (recommend using 20 ft)

V = 85^{th} percentile approach speed


NCHRP
REPORT 731
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

ITE Proposed Recommended Practice

DRAFT Guidelines for Determining Traffic Signal Change and Clearance Intervals

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

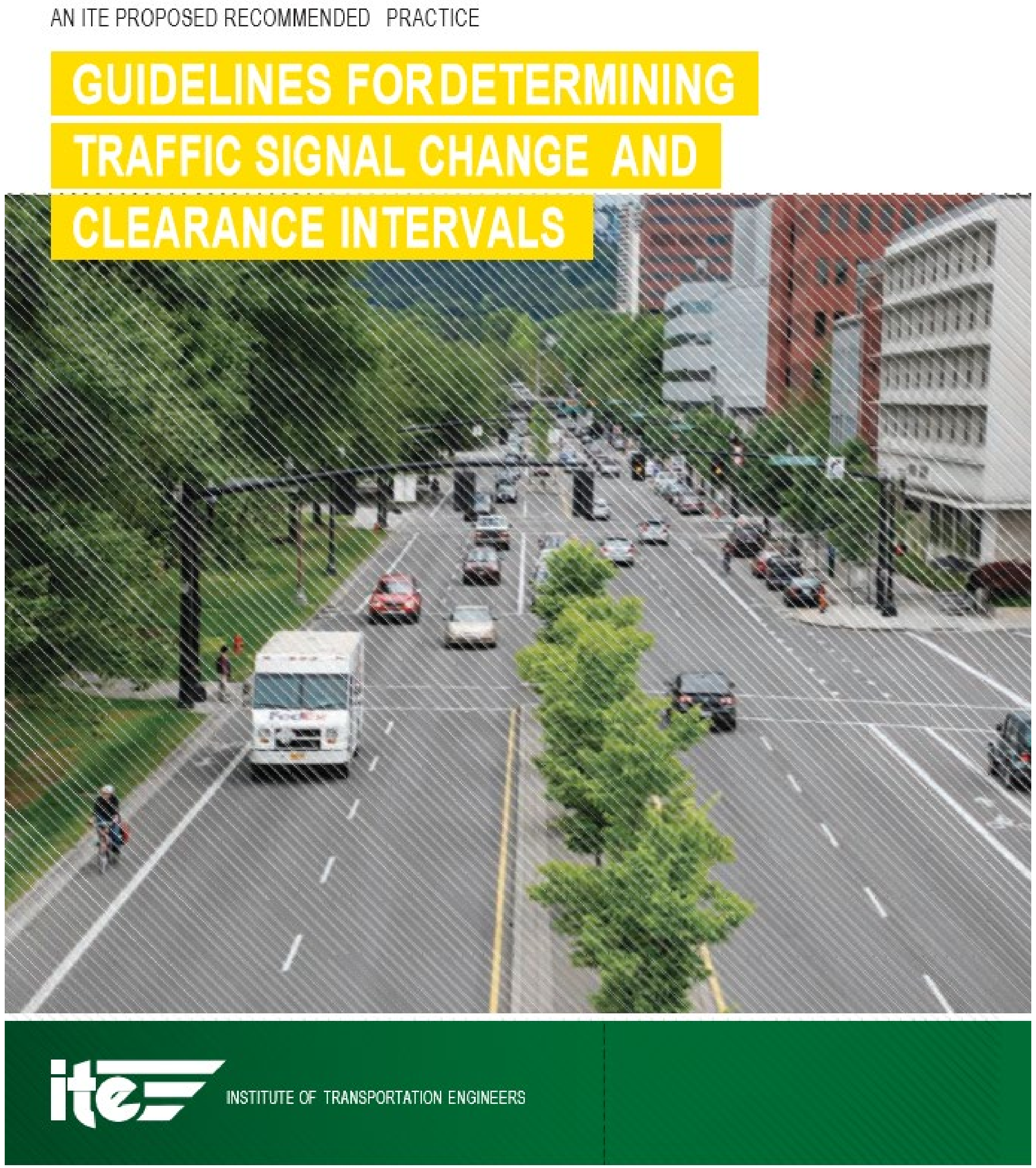
Y = yellow change interval (sec.);

t = perception-reaction time (sec.);

V = 85th percentile approach speed (mph);

a = deceleration rate (ft./sec./sec.);

g = grade of approach (percent/100, downhill is negative grade);



ITE Proposed Recommended Practice

DRAFT Guidelines for Determining Traffic Signal Change and Clearance Intervals

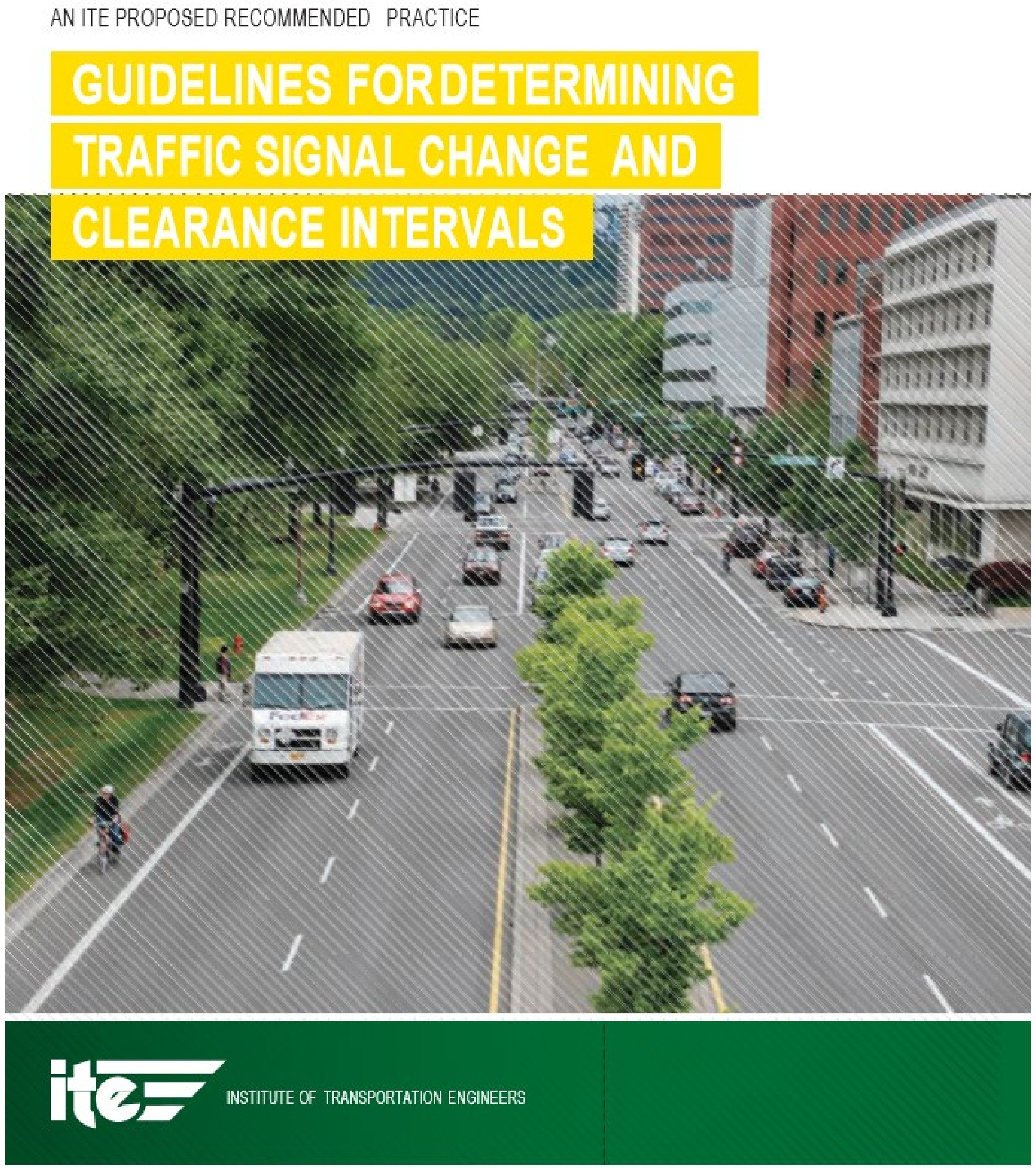
$$R = \left| \frac{W+L}{1.47V} \right| - t_s$$

R = red clearance interval (sec.);

W = width of intersection, stop line to far side no-conflict point (ft.);

L = length of vehicle (ft.); and

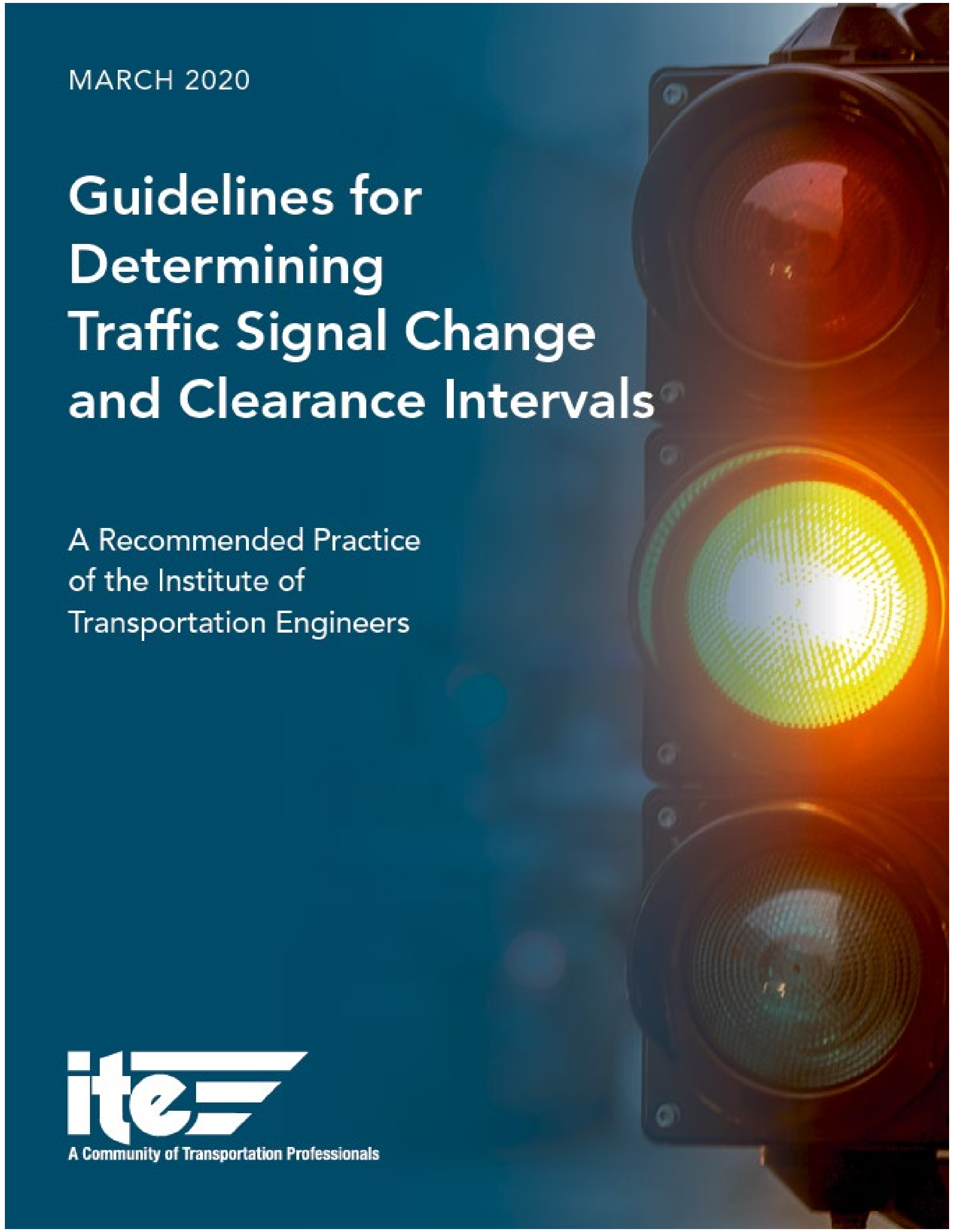
t_s = conflicting movement start up delay (sec.).



ITE Recommended Practice

Guidelines for Determining Traffic Signal Change and Clearance Intervals

- Released March 2020
- Introduced the Extended Kinematic Equation

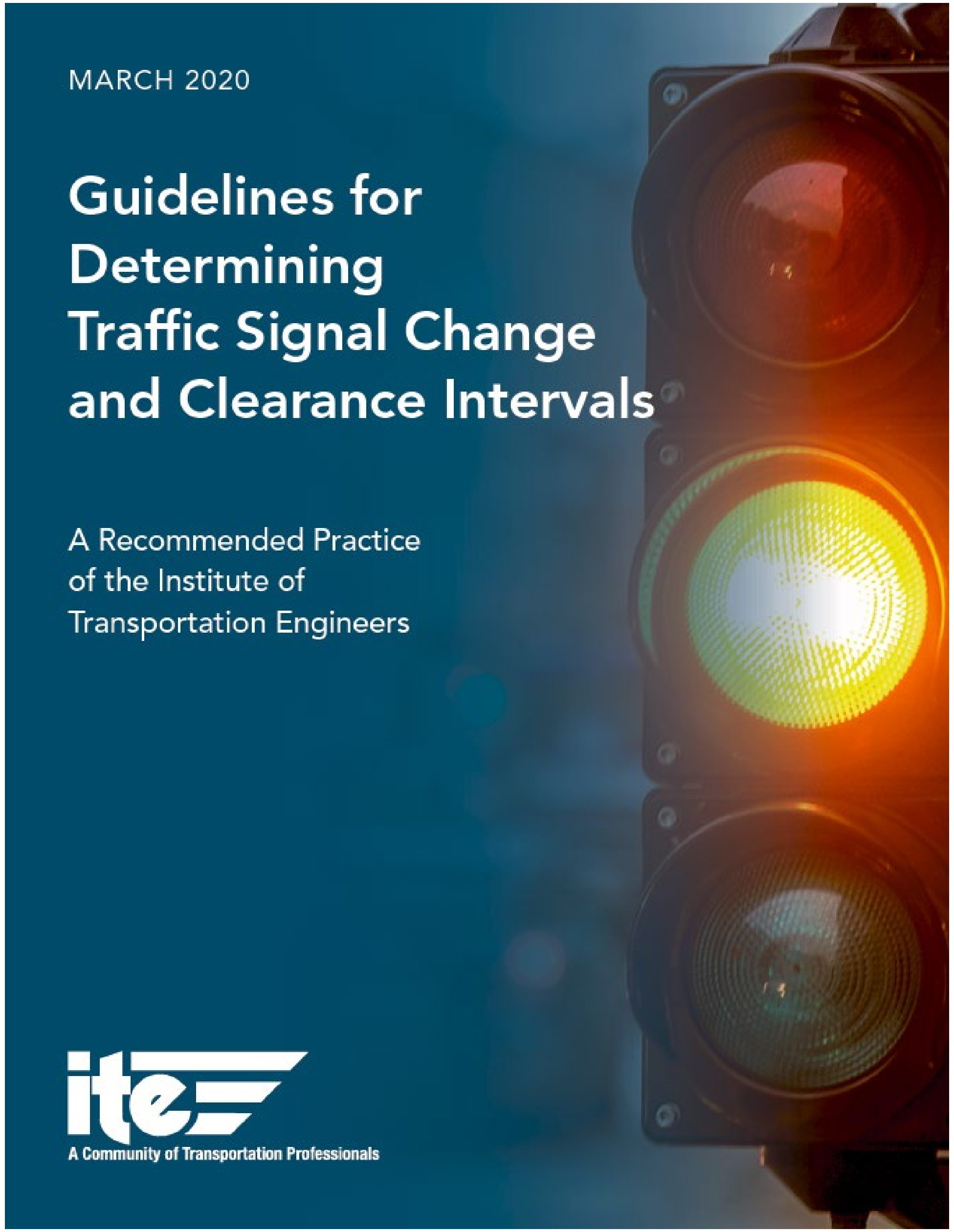


Georgia Department of Transportation

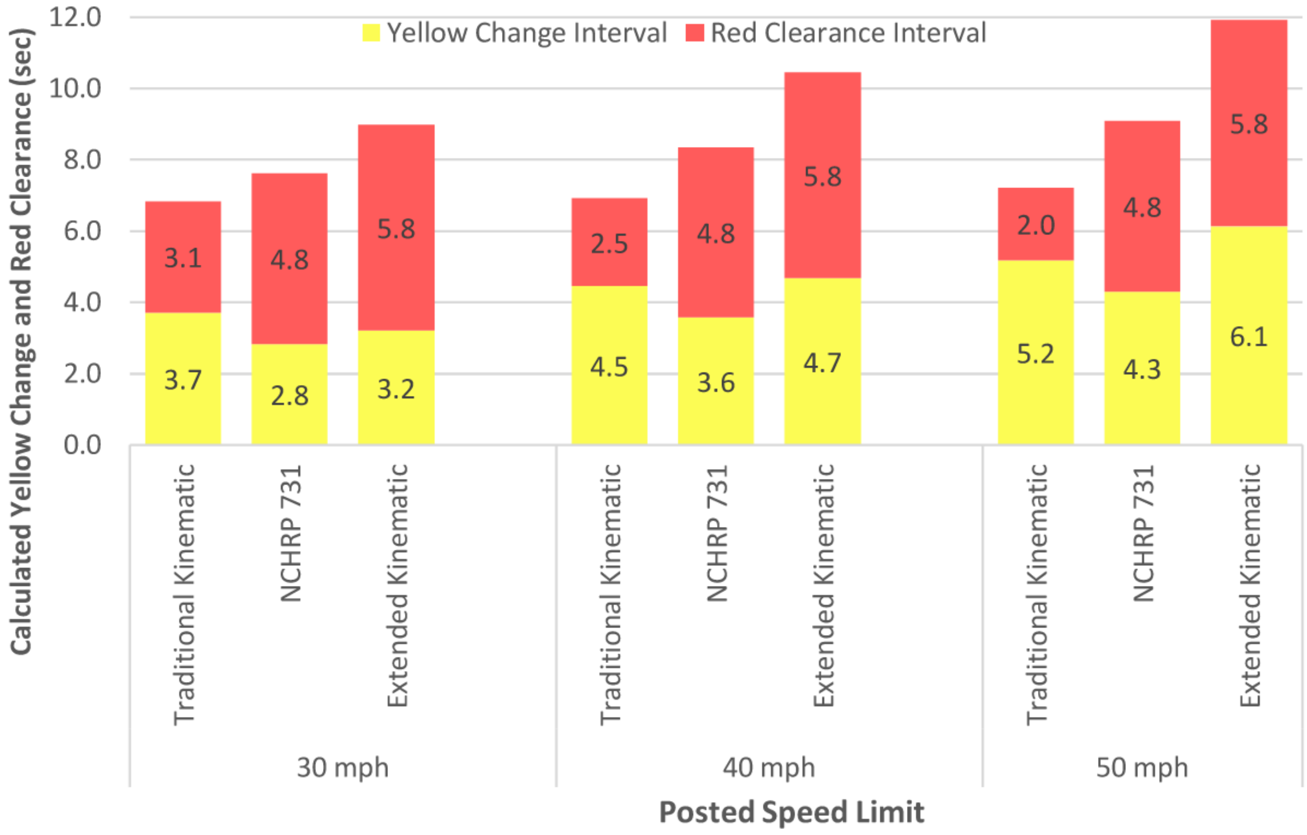
The Extended Kinematic Equation

Guidelines for Determining Traffic Signal Change and Clearance Intervals

- New element to the formula that was not balloted, or peer reviewed.
- Maximum yellow time increased to 7 seconds.
- New speed modification element of intersection entry.
- Results in substantially increased calculated yellow times.
- Conflict with MUTCD.



The Extended Kinematic Equation



Source: FHWA.
mph = mile per hour. NCHRP = National Cooperative Highway Research Program. sec = second.

C. Intersection width = 150 ft.

Georgia Department of Transportation

Letter from AASHTO

Committee on Traffic Engineering

- "CTE's primary concern is the inclusion of the extended kinematic equation in the published guidelines"
- "CTE requests that ITE rescind the guidelines as published"
- "…our Committee will be advising our state agency members to not adopt the guidelines and await completion of upcoming research through pooled fund studies sponsored by the Federal Highway Administration"

AASHTO

Patrick K. McKenna, *President*
Director, Missouri Department of Transportation
Jim Tymon, *Executive Director*

August 28, 2020

Randy McCourt, PE, PTOE
International President
Institute of Transportation Engineers
1627 Eye Street, NW, Suite 600
Washington, DC 20006

Dear Mr. McCourt:

On June 15-16, 2020, the American Association of State Highway and Transportation Officials' (AASHTO) Committee on Traffic Engineering (CTE) convened for their annual meeting. On the agenda was a member presentation and discussion on ITE's recently published *Guidelines for Determining Traffic Signal Change and Clearance Intervals* recommended practice. A brief overview of the history of this subject was provided, as well as details on particular elements of the guidelines that were substantially different from research and practice, namely NCHRP Report 731, *Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections*.

Of concern from this presentation were not just what the guidelines recommended, but also the process by which these guidelines were published. That the Technical Advisory Committee and peer review panel were not reconvened to reach consensus on substantial changes to the recommended practice raises concerns over the review and validity of an important safety aspect of traffic signal operation.

CTE's primary concern is the inclusion of the extended kinematic equation in the published guidelines. The equation itself introduces outcomes that violate allowable yellow change interval in the *Manual on Uniform Traffic Control Devices*, and the lack of technical peer review brings into question its validity. In these calculations, especially at higher speeds for left turns, the length of yellow would be so long that anyone moving through a traffic signal would be at risk of making a different decision from the person following them, thus negating the importance of human factors in setting change and clearance intervals. The goal of setting yellow time should be to maximize safety, not to simply minimize entry after the end of yellow.

In light of upcoming research such as the Solicitation Number: 1536 - Traffic Signal Change and Clearance Interval Pooled Fund Study, and considering both the methodology by which these guidelines were completed and the outcome of their product in the extended kinematic equation, the CTE requests that ITE rescind the guidelines as published. Our Committee will be advising our state agency members to not adopt the guidelines and await completion of upcoming research through pooled fund studies sponsored by the Federal Highway Administration.

Moving Forward

FHWA Sponsored Pooled Fund Research

- Coalition of agencies supporting effort
- Broad spectrum of topics to be researched
- Red light running enforcement
- Permissive yellow vs. restrictive yellow laws
- Leveraging technology to broaden understanding of human factors (e.g. dilemma zone)
- Context

TPF TRANSPORTATION POOLED FUND PROGRAM

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Solicitation Detail View

Traffic Signal Change and Clearance Interval Pooled Fund Study

General Information

Solicitation Number: 1536
Status: Solicitation posted
Date Posted: May 29, 2020
Last Updated: Jun 11, 2020
Solicitation Expires:
Partners: IN
Lead Agency: Federal Highway Administration

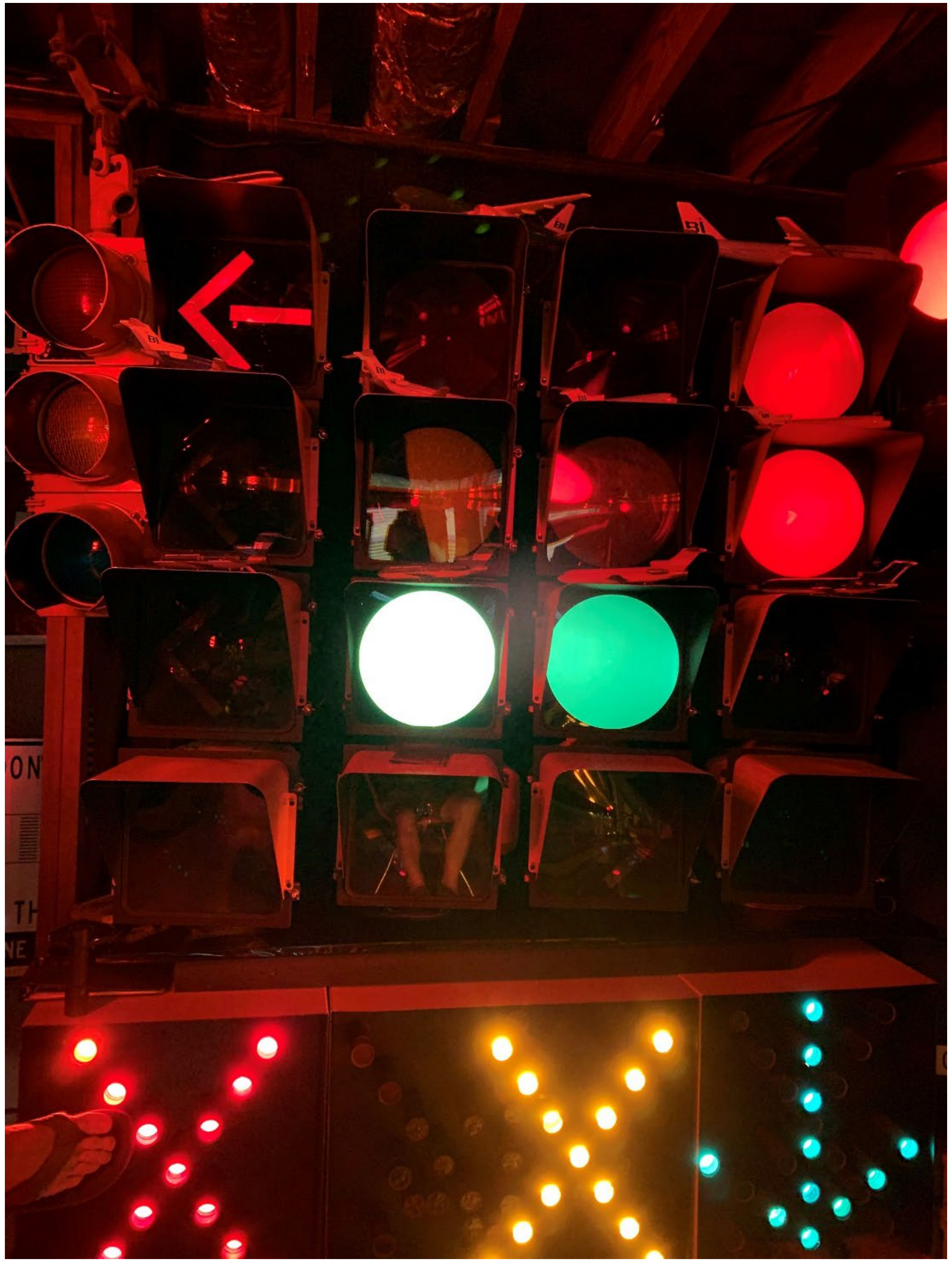
Contact Information:

Lead Agency Contact:
Eddie Curtis
Eddie.Curtis@dot.gov
Phone: 404-780-0927

What do agencies need?

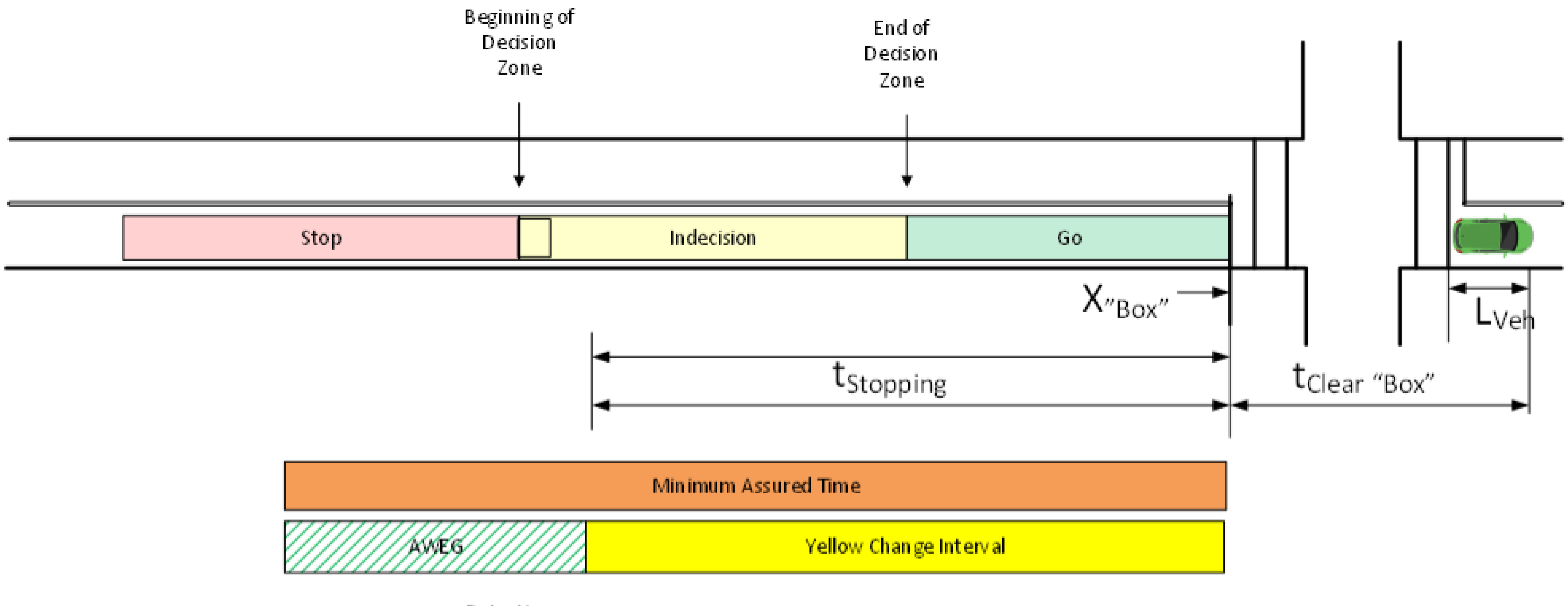
…or want?

- Consistency of implementation and driver expectancy
- “Easy” implementation vs. engineered for the context of every intersection
- Research based guidance to support engineering judgement
- Conclusive product?
- Framework to build on
- Automated enforcement issues



More Needs from Clearance Intervals

Connected Vehicles and Red-Light Violation Warning



Ramp Metering

Virginia DOT

- Green -> Yellow -> Red
  - Uses Operational Yellow which is typically 0.7 seconds

Table 5-4. Recommended Controller Timing for Platoon Metering.

Interval	Vehicles per Cycle					
	1	2	3	4	5	6
Red	2.00	2.00	2.32	2.61	2.86	3.08
Yellow	1.00	1.70	2.00	2.22	2.41	2.58
Green	1.00	3.37	5.47	7.35	9.13	10.83
Cycle Length	4.0	7.08	9.78	12.19	14.40	16.49
Meter Capacity	900	1017	1104	1181	1250	1310

Source: Reference (2).

Traffic Signals Manual *6-23* TxDOT 3/09

The minimum Yellow timing is an important timing factor that affects metering rate for multiple-vehicle-per-green, such as two-vehicle-per-green, type of operations.

The Yellow is typically timed as a constant 2 seconds.

URMS Training Manual, California Department of Transportation, Sacramento, California (2011)

Georgia Department of Transportation

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U.S. Department of Transportation
Federal Highway Administration

An Update on Traffic Signal Change and Clearance Intervals

December 15, 2023

Eddie Curtis, P.E., Federal Highway Administration (FHWA) Office of Operations
Jamie Mackey, P.E., PTOE, Federal Highway Administration (FHWA) Office of Operations

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Desired Outcome

1. Address Research Needs.
2. Improve documentation and consistent implementation of traffic signal Change and Clearance Interval calculation methods.

Pooled Fund Study Participants

- FHWA.
- Connecticut Department of Transportation (DOT).
- Georgia DOT.
- Illinois DOT.
- Indiana DOT.
- Iowa DOT.
- Maryland DOT.
- Mississippi DOT.
- New Hampshire DOT.
- City of Phoenix, AZ.
- City of Mesa, AZ
- City of Seattle, WA.
- New York State DOT.
- North Carolina DOT.
- Oakland County, MI
- Oregon DOT.
- Pennsylvania DOT.
- City of Portland, OR.
- Tennessee DOT.
- Utah DOT.
- Virginia DOT.
- Washington State DOT.
- Maricopa County, AZ.
- Nebraska DOT.

Phase I: Project Objectives

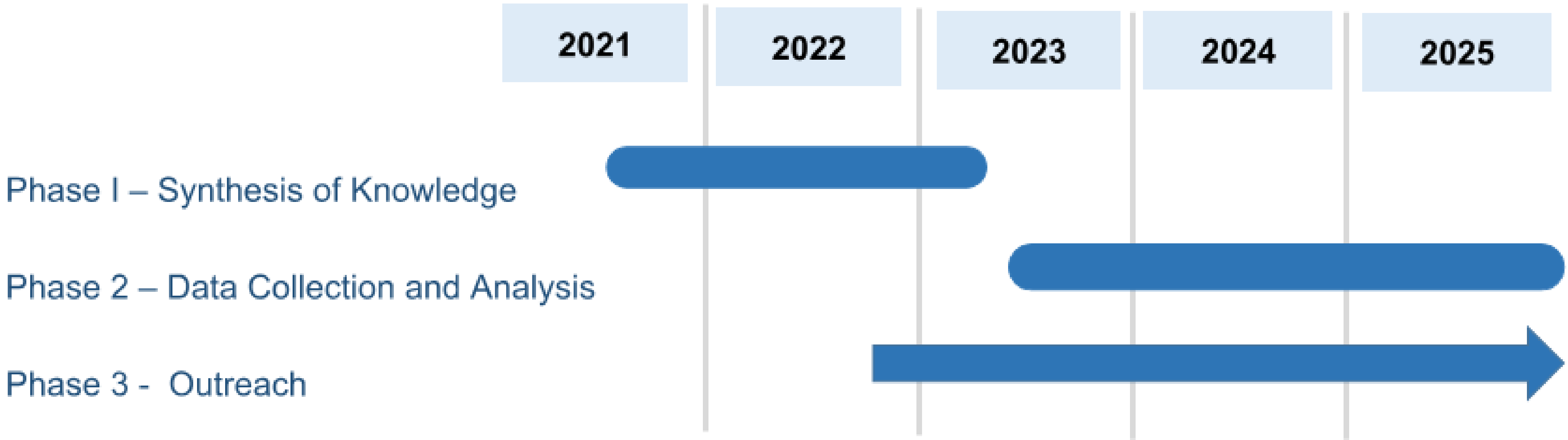
- Literature Review
  - Published
  - Unpublished
- Benchmarking Report
- Research Plan
- Data Collection Methods Analysis
- Synthesis Report

Phase 1: Research Team

- Eddie Curtis, FHWA (Project Manager)
- Jocelyn Bauer, Leidos (Prime)
- David Hale, Leidos (Prime)
- Burak Cesme, Kittelson
- Aleksandar Stevanovic, University of Pittsburgh
- Christopher Day, Iowa State University
- Bastian Schroeder, Kittelson
- Tom Urbanik, Kittelson
- Jim Bonneson, Kittelson

Approach and Schedule

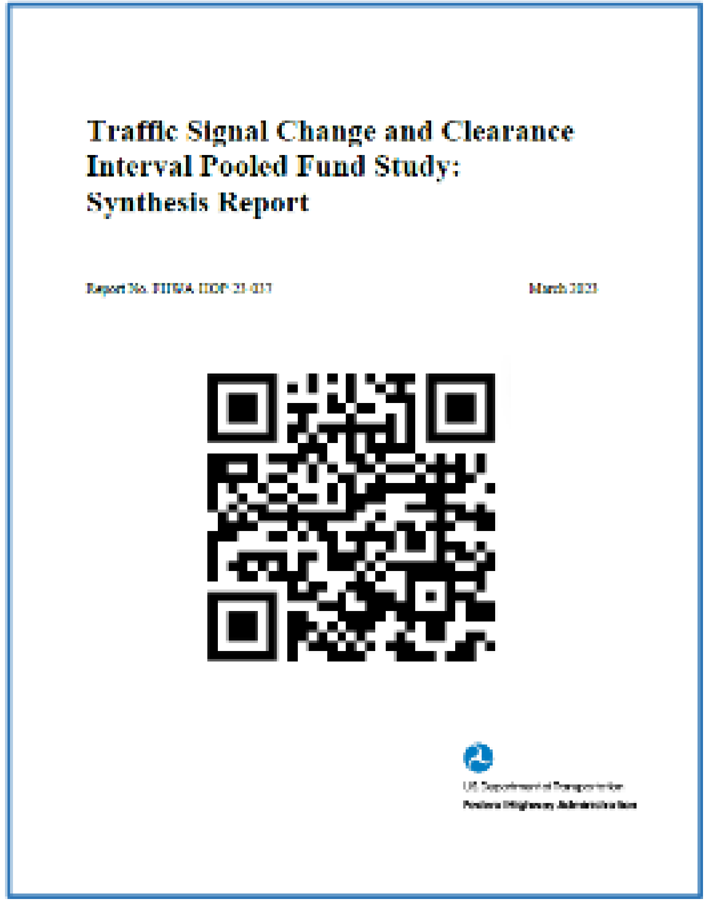
Summer 2021 - Summer 2025



Source: FHWA.

Accessing the Report

https://www.pooledfund.org/Details/Study/697


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

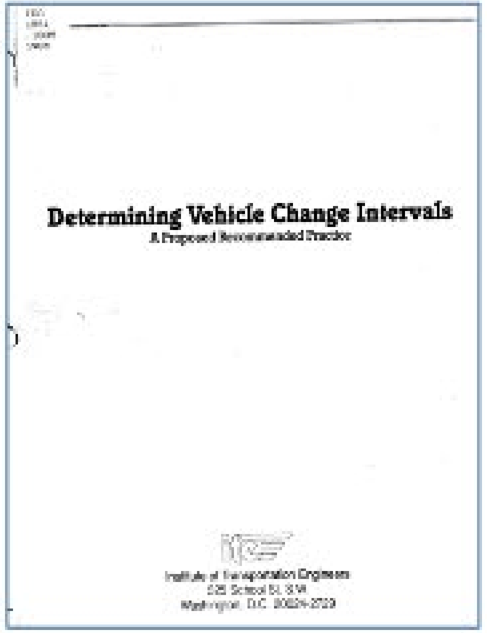
March 2023

Literature Review: Key Documents

1959

Source: Gazis, Herman, and Maradudin, 1959.

1985

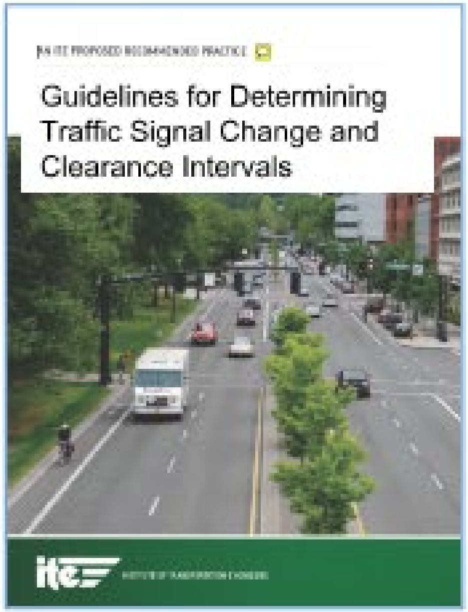


Source: ITE, 1985.

2012

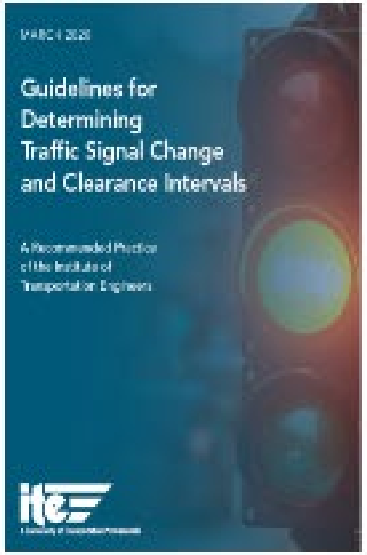
Source: NCHRP Report 731, 2017.

2017



Source: ITE, 2017.

2020



Source: ITE, 2020.

Summary of Methods for Determining CCI

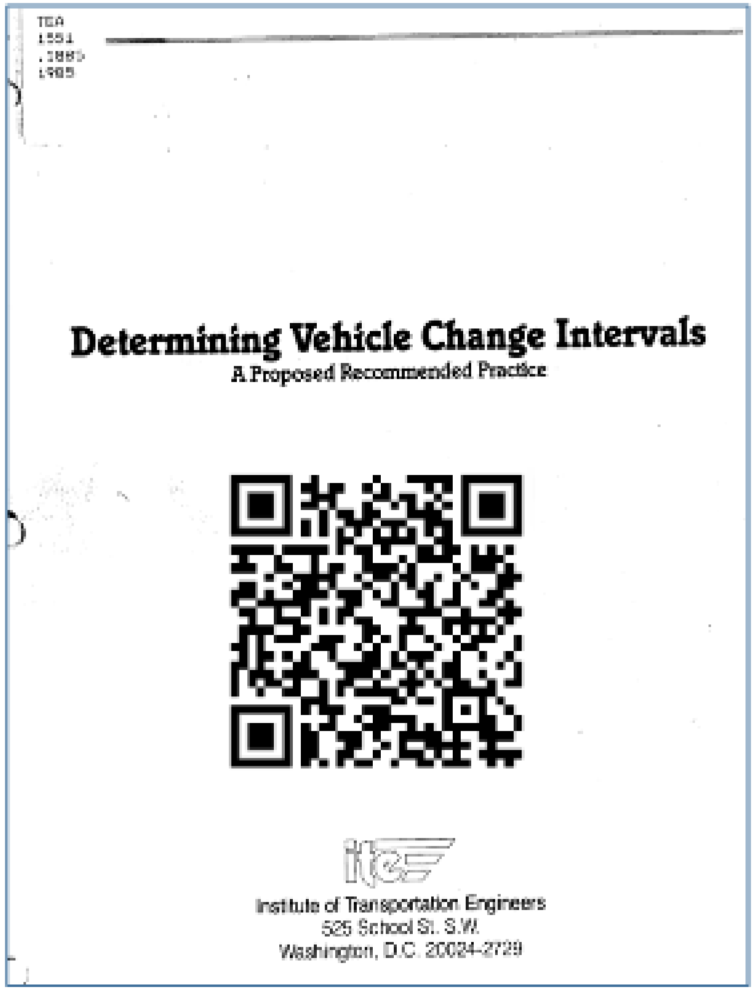
- The kinematic model, originally developed by Gazis, Herman, and Maradudin (1960), is one of the most common methods used.
- To address limitations of the kinematic model, researchers studied driver behavior and stopping probability functions at the onset of yellow.
- The Institute of Transportation Engineers (ITE) introduced the extended kinematic equation to address the oversimplification of the kinematic equation for turning vehicles.

1985 Literature Review and Deliberations (1/2)

Goal: Defensible Methodology

Objectives:

- Appear reasonable.
- Easy identification of violators.
- Safety superior to efficiency.
- Field work, changes to equipment, and other costly procedures to be avoided.

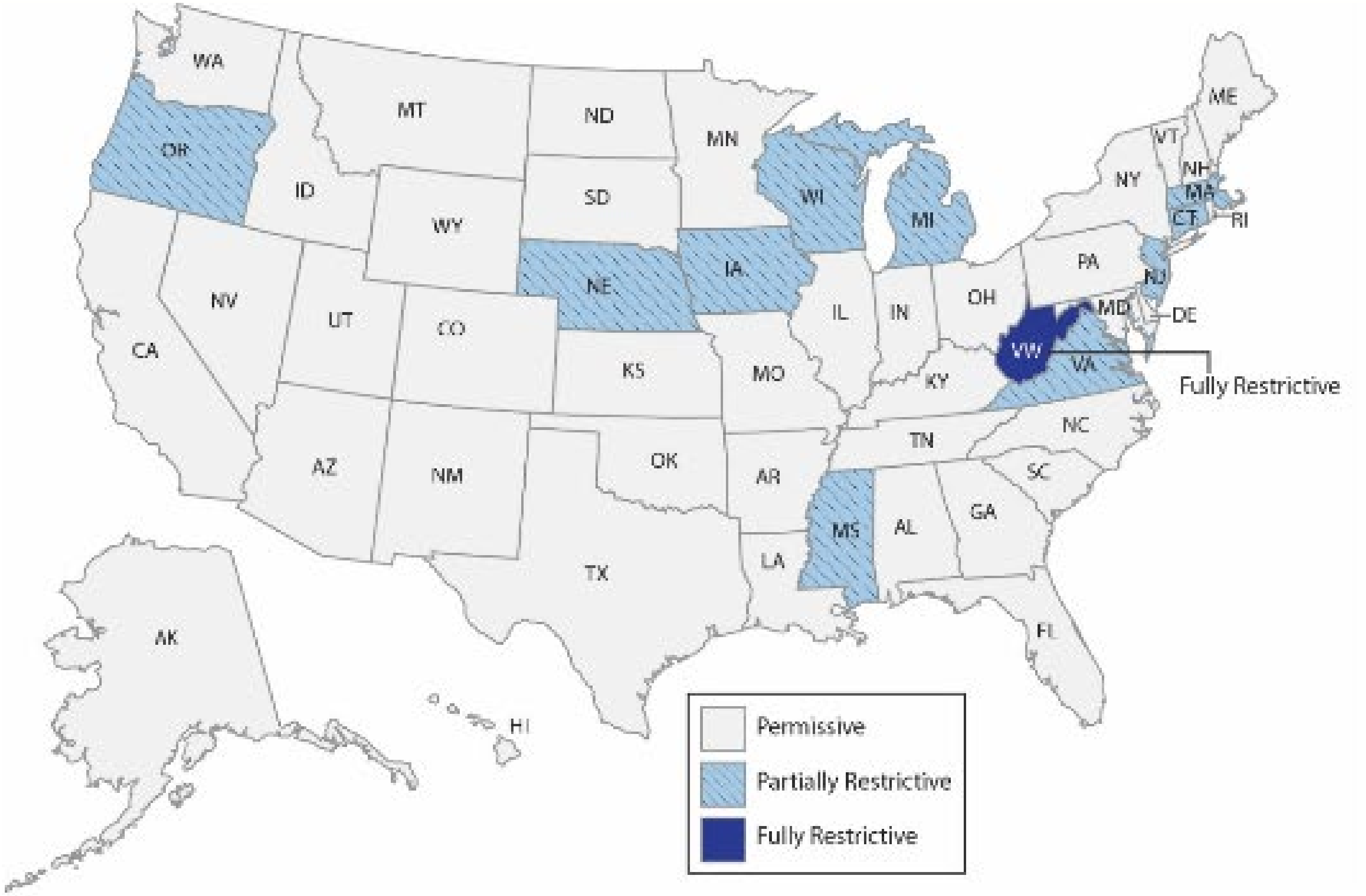


1985 Literature Review and Deliberations (2/2)

Conclusions:

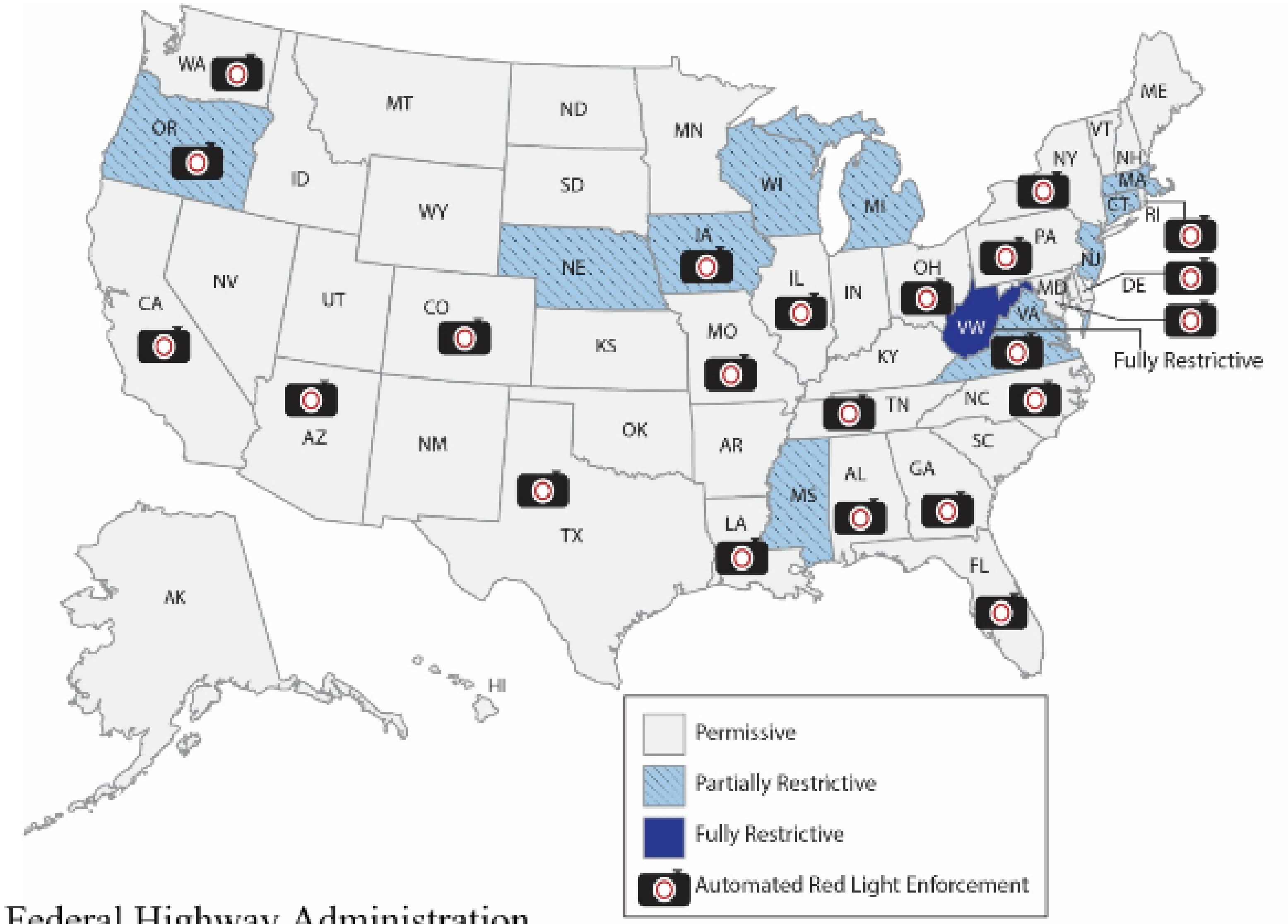
1. The Stopping Probability Model is the most theoretically correct model, but data to implement do not yet exist.
2. Yellow interval is timed for the driver who decides not to stop and **should not provide time to stop as some have incorrectly proposed.**
3. The **kinematic model is a compromise** attempt to estimate stopping probability, based on many assumptions.
4. The problem associated with applying the probability of stopping model is the absence of valid data.

Restrictive Vs Permissive



Source: Federal Highway Administration.

Automated Enforcement



Source: Federal Highway Administration.

Research on Factors Affecting CCI

Category	Characteristic	Selected Authors Who Have Identified the Characteristic as Influencing Change Period Duration: Motion Kinematics	Probability of Stopping
Road design	Approach grade[a]	McGee et al. (2012)	Chang, Messer, and Santiago (1985)
	Intersection width[a]	McGee et al. (2012)	Bonneson and Son (2003)
Vehicle characteristics	Vehicle length	McGee et al. (2012)	None found
	Vehicle type (car, truck)	None found	Gates et al. (2007)
	Progression quality (signal coordination)	None found	Li et al. (2010)
Driver characteristics	Perception-reaction time	McGee et al. (2012)	None found
	Deceleration	McGee et al. (2012)	None found
	Approach speed[a]	McGee et al. (2012)	Sheffi and Mahmassani (1981)
	Intersection entry speed	ITE (2020)	None found
	Conflicting start-up delay	ITE (2020)	None found
	Gender	None found	El-Shawarby et al. (2011)
	Age	None found	El-Shawarby et al. (2011)
	Distance to stop line	None found	Chang, Messer, and Santiago (1985)
Signal control	Signal phase/movements	McGee et al. (2012)	None found
	Change interval duration	None found	Gates et al. (2007)
	Actuated versus pretimed	None found	Van der Horst (1988)
	Signal back plate presence	None found	Bonneson and Son (2003)
Environment	Precipitation level	None found	Li, Rakah, and El-Shawarby (2012)
	Presence of conflicting vehicle, bike, or pedestrian	None found	Gates et al. (2007)

[a]Characteristics are common to both model categories. ITE = Institute of Transportation Engineers.

Source: FHWA – TPF-5(470).

Research on Factors Affecting CCI

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[a] Characteristics are common to both model categories. ITE = Institute of Transportation Engineers.

Source: FHWA – TPF-5(470).

Kinematic Models (1/2)

- Originally intended to provide insights into the challenges for a national method to compute CCI durations.
- Use a deterministic approach (except for approach speed).
- Assume ideal or reasonable driving behavior.
- Assume a constant or uniform deceleration.

Kinematic Models (2/2)

- A sample kinematic model: Traffic Engineering Handbook

$$y = t + \frac{V}{2a + 64.4g} + \frac{W + L}{V}$$

Typically used for yellow change interval

Typically used for red clearance interval

ITE, *Traffic Engineering Handbook*, fifth edition,1999.

y = CCI (sec)
t = perception-reaction time (sec)
V = speed of clearing vehicle (mph)
a = deceleration (ft/sec^2)
g = grade of approach (in decimal form)
W = intersection width (ft)
L = vehicle length (ft)

Key Findings on Perception-Reaction Time

- ITE recommendation—of 1.0 sec for average perception-reaction time is consistent.
- Inconclusive results found between younger and older drivers.
- Perception-reaction time decreases as approach speed increases.
- Previous research focused on through vehicles, not turning vehicles.

Key Findings on Deceleration

- Mean deceleration is largely influenced by:
  - **Approach speed**: Increase in approach speed leads to greater deceleration.
  - **Travel time to stop line is** more aggressive driving with shorter travel time to the stop line.
- ITE recommendation of 10 ft/sec^2 mean deceleration is consistent when approach speed is 35–40 mph. When speed is >40 mph, mean deceleration is underestimated.
- Male drivers typically have a slightly greater deceleration than female drivers.

Key Findings on Approach Speed

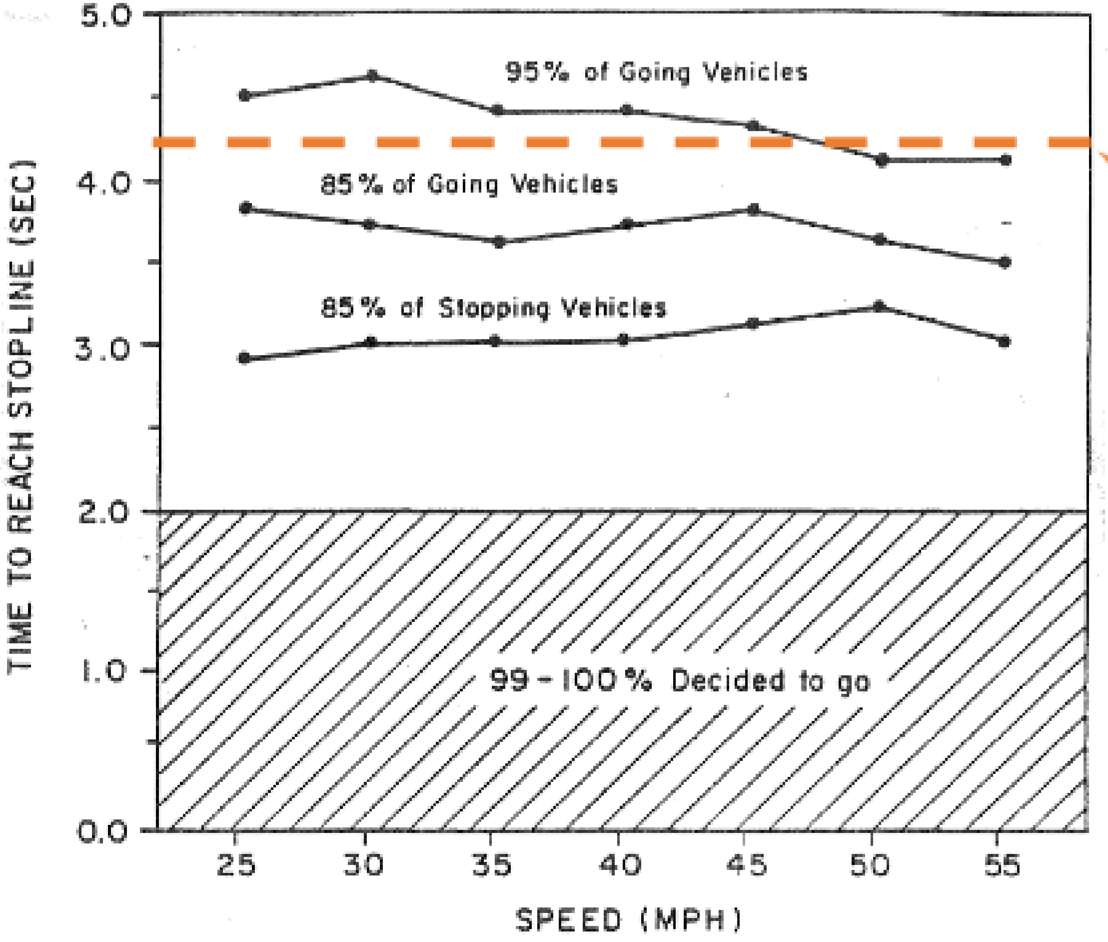
- Approach speed recommendation for through vehicles is well established:
  - Use the 85th percentile speed when field measured.
  - Otherwise, use posted speed + 7 mph.
- Less attention to turning drivers, but some guidance on approach and entry speed for left turns (e.g., *National Cooperative Highway Research Program (NCHRP) Report 731: Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections* suggests 20 mph for approach speed and approach speed – 5 mph for entry speeds) based on limited research.

Limitations of Kinematic Equation

- Mostly a deterministic approach (except for approach speed).
- Unrealistic assumptions:
  - Reasonable driver behavior with specific values.
  - Constant deceleration and perception-reaction time of driver at the onset of a yellow light.
- Effects of different vehicle types or contexts ignored.
- No account given for the difference between the fact that intersection entry speed is different than the intersection approach speed for turning vehicles.

Behavioral Studies (1/3)

Driver's decision to stop or go by time and approach speed



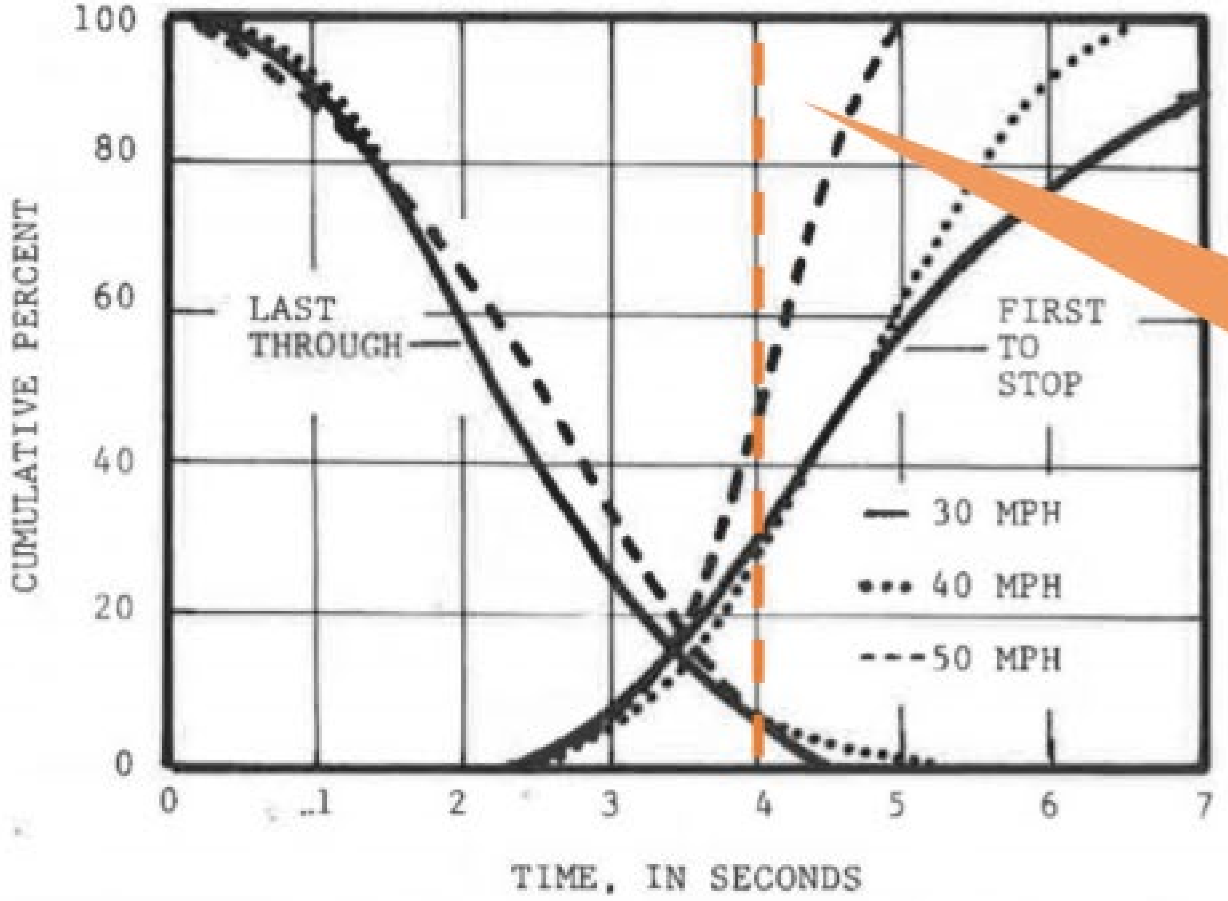
Took less than 4.5 sec for 95% of the going vehicles, regardless of approach speed

Source: Chang, Messer, and Santiago, (1985).

U.S. Department of Transportation
Federal Highway Administration

Behavioral Studies (2/3)

Driver's decision to stop or go by time and approach speed



About 95% of the last vehicles through the intersection are 4 sec or less from the intersection at the start of a yellow signal light.

Source: Wortman and Fox, 1986.

Behavioral Studies (3/3)

Minimum yellow change intervals based on the 90th percentile stopping probability

Source	Speed Miles Per Hour									
	10	15	20	25	30	35	40	45	50	55
Olson and Rothery					4.1		4.3		5.1	
Williams	6.3	5.7	4.9	4.3						
Parsonson					4.0	4.1	4.3	4.5	4.8	5.0
Herman					4.0	4.2	4.4	4.8	5.0	
Minnesota					3.2	3.5	3.7	3.9	4.1	4.6
Zegeer						5.0	4.8	4.9	4.8	4.8
Sheffi and Mahmassani						4.7	4.8	4.9	5.0	5.1
Chang						5.0	4.7	4.4	4.2	4.0
ITE Original Kinematic Equation Level Grade, t = 1 sec, = 10 ft/sec^2	1.7	2.1	2.5	2.8	3.2	3.6	3.9	4.3	4.7	5.0

Source: FHWA – TPF-5(470).

$$y = t + \frac{V}{2a + 64.4g} + \frac{W + L}{V}$$

Extended Kinematic Equation

ITE 2020 Recommended Practice:

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

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

Source: ITE, 2020.

- Y = minimum yellow change interval (sec)
- t = perception-reaction time (sec)
- V_{85} = 85th-percentile approach speed (mph)
- V_E = intersection entry speed (mph)
- a = deceleration (ft/sec^2)
- g = approach grade (percent divided by 100)
- R = red clearance interval (sec)
- W = distance to traverse the intersection (width), stop line to far side no-conflict point along the vehicle path (ft)
- L = length of vehicle (ft)
- t_s = conflicting vehicular movement start up delay (sec)

Concerns With the Institute of Transportation Engineer's 2020 Recommended Practice

- Assumes turning drivers maintain their approach speed during perception-reaction time.
  - However, anecdotally, engineers believe deceleration starts well before the yellow indication.
- Assumes drivers preparing to turn decelerate at the same rate as when deciding to stop in response to yellow.
  - However, anecdotally, engineers believe most drivers decelerate more gently when preparing for a turn than they do stopping for onset of yellow.
- Change intervals longer than the accepted limit for turning vehicles.
- In the absence of field data, recommendations for approach and entry speed do not consider site characteristics (e.g., number of turn lanes, turn bay length).
- All the other limitations of the original kinematic equation.

Comparison of Methods for CCI Calculation

Intersection Width = 100 ft

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

Source: FHWA – TPF-5(470).

*Calculations assume 1 sec of perception-reaction time, a deceleration of 10 ft/sec^2, zero grade, and 20-ft vehicle length

Performance Assessment (1/2)

- Assess CCIs from the perspective of performance:
  - Crash-based metrics
    E.g., rear-end crashes, opposing left-turn crashes, right-angle crashes.
  - Surrogate safety metrics
    E.g., red signal violation rate, late exit rate.
  - Operational metrics
    E.g., vehicle delay.
  - Driver adaptation to long yellow durations.

- Motivation: No current method considers all variables.

Performance Assessment (2/2)

Category	Variable	Variables Found In...	
		Kinematic Models	Behavioral Models
Road design	Approach grade	Yes	Yes
—	Intersection width	Yes	Yes
Vehicle characteristics	Vehicle length	Yes	No
—	Vehicle type	No	Yes
—	Progression quality	No	Yes
—	Perception-reaction time	Yes	No
—	Deceleration	Yes	No
—	Approach speed	Yes	Yes
—	Intersection entry speed	Yes	No
—	Distance to stop line	No	Yes
Signal control	Left phase, thru phase	Yes	No
—	Actuated, pretimed	No	Yes

— = no data

Source: FHWA – TPF-5(470).

Summary of Unpublished Research

- Unpublished research is mainly centered around the extended kinematic equation.
- The extended kinematic equation is an advancement to the traditional kinematic equation, but it also generated the following concerns:
  - The assumption that turning drivers maintain their approach speed during the perception-reaction time is questionable.
  - The assumption that drivers decelerate when preparing to turn at the same deceleration when they are at the critical distance and encounter a yellow signal is also questionable.

Proposed Research Studies (1/2)

#	Research Study Name	Priority	Collection Campaigns	Hypotheses (Paraphrased) (Tests Will Try to Reject)
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
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
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
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

Source: FHWA – TPF-5(470).

EKE = extended kinematic equation. FI = fatal injury. KE = kinematic equation. RLR = red light running.

Proposed Research Studies (2/2)

#	Research Study Name	Priority	Collection Campaigns	Hypotheses (Paraphrased) (Tests Will Try to Reject)
5	Surrogate Safety Assessment of CCIs	5	IV (and I)	1. Longer yellow = more RLR (thru) 2. Longer yellow = more late exits (thru) 3. Shorter clearance = more late exits (thru) 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)
6	Safety Assessment Procedure and Measures	2	N/A	N/A
7	Investigation of Pair-Wise Conflict-Zone Method for Red Clearance Intervals and Applicability to U.S. Controllers	7	V (and II)	1. U.S. controllers cannot support this method
8	Mobility/Capacity Assessment of CCIs	8	I, II, IV	1. Longer yellow/red increase capacity 2. Longer yellow/red increase mobility 3. Longer delays = less RLR 4. Capacity cannot increase?

Source: FHWA – TPF-5(470).

N/A = not applicable.
RLR = red light running.

Potential Data Sources (1/2)

Category of Data	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; GPS data	In-vehicle video; CAN bus and similar	In-vehicle video; virtual vehicle instrumentation
Vehicle: broadcasted	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.

Source: FHWA – TPF-5(470).

Potential Data Sources (2/2)

- Vehicle trajectories are the most relevant data for capturing driver behavior with respect to CCIs.
- Analysts can obtain those trajectories through many different datasets.
- Trajectory data must include signal state change times.
- Contextual data (e.g., speed limits, lane configuration, weather, lighting, pedestrian and bike presence) are also key.
- Analysts could potentially combine different datasets to develop a full picture of the operation.

Proposed Data Collection Approach

Study	Preferred Method	Alternative Method
Driver Behavior Effects of Long Yellow Intervals for Through Vehicles	Vehicle trajectories and signal state data	Naturalistic driving data; connected vehicle (CV) data[1] combined with signal state data or equivalent record of start of yellow times
Understanding Driving Behavior When Reacting to Yellow Indication for Through Movements	Vehicle trajectories and signal state data	CV data combined with signal state data or equivalent record of start of yellow times
Understanding Driving Behavior When Reacting to Yellow Indication for Turning Movements	Vehicle trajectories and signal state data	CV data combined with signal state data or equivalent record of start of yellow times
Crash Safety Assessment of CCIs	Crash data	None
Surrogate Safety Assessment of CCIs	Vehicle trajectories and signal state data	None
Safety Assessment Procedure and Measures	Agency survey to identify locations	None
Investigate Pair-Wise Conflict Zone Method for Red Intervals and Applicability to U.S. Controllers	Microsimulation	None
Mobility/Capacity Assessment of CCIs	Microsimulation	Signal state data or commercial CV data

Source: FHWA – TPF-5(470).

[1]Also referred to as Basic Safety Message (BSM) data.

Agency Benchmarking (1/2)

Topic Area	Description
General information	• Name of agency, agency type, survey respondent name
Agency characteristics	• Number of signals managed • Controller precision of CCI durations • Number of traffic engineers and technicians
General policies	• Method used to determine CCI duration • Allocation of time between yellow and red intervals • Practices, laws, and procedures that dictate CCI methods • Minimum and maximum values for yellow and red intervals and total period • Frequency of review of CCI durations
Variables	• Use of variables (e.g., deceleration rate, perception-reaction time) • Variation of variables due to site condition (e.g., curvature) • Vehicle speeds used for different movement types • Procedure and frequency for field data collection of speed • Procedure for measurement of intersection width and grade

Source: FHWA – TPF-5(470).

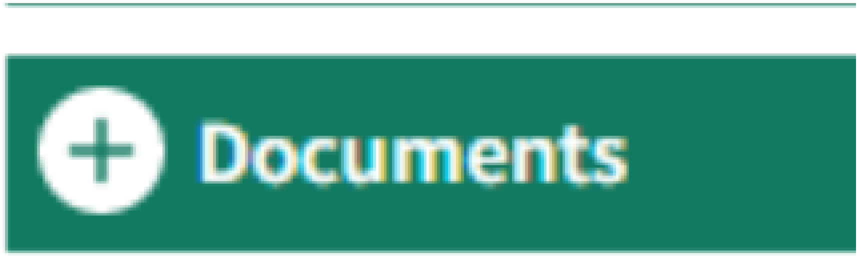
Agency Benchmarking (2/2)

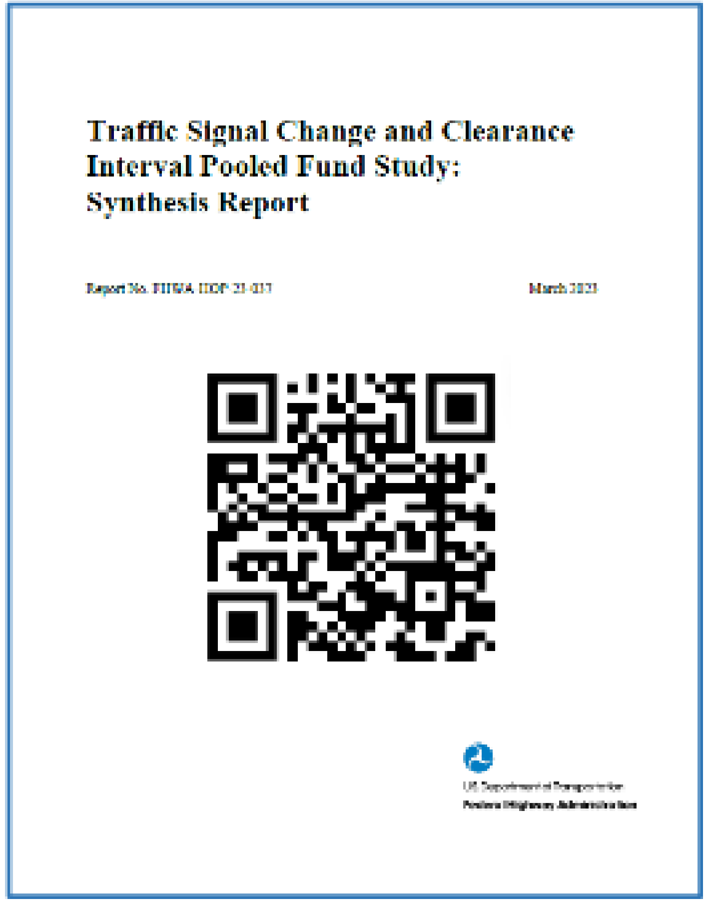
Topic Area	Description
Special conditions	• Procedure for calculation of CCI durations for site characteristics
Automated enforcement	• Use and count of automated enforcement devices • Duration of grace period • Case studies relevant to automated enforcement
Bicycle clearance	• Procedure for determining CCI duration for bicycle phases
Practice adjustments	• Recent changes to CCI timing practices • Data sources used to refine or evaluate CCIs • Case studies related to impact of CCIs

Source: FHWA – TPF-5(470).

Accessing the Report

https://www.pooledfund.org/Details/Study/697

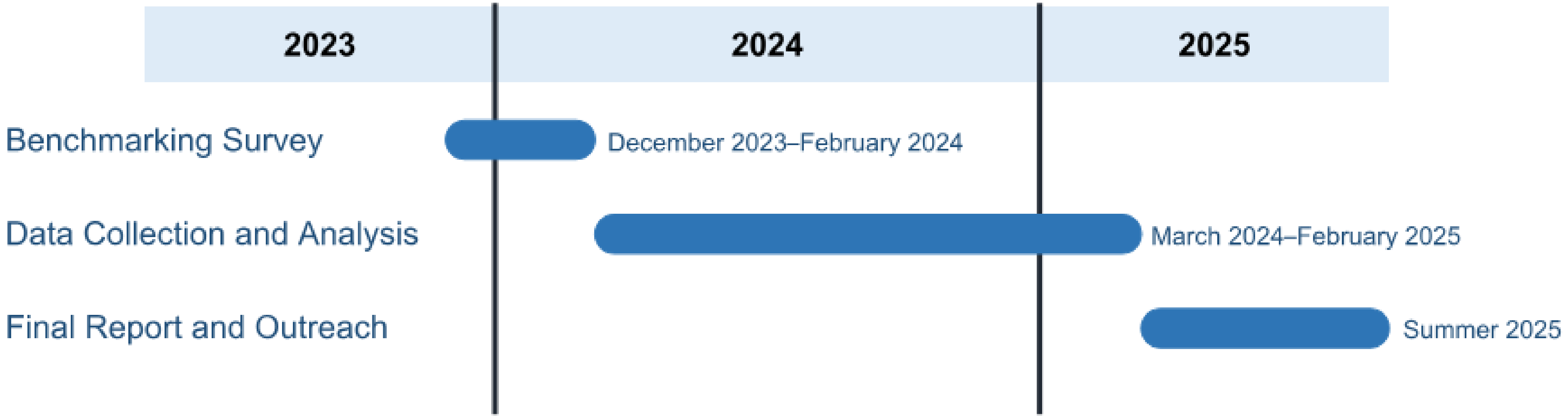




Pooled Fund Study—Phase 2

October 2023–March 2025

Purpose: Clarify assumptions and develop methodology for agencies to develop and justify their CCI-setting process



Source: FHWA.

Phase 2—Agency Benchmarking

December 2023–February 2024

- Purpose of benchmarking survey:
  - Document the state-of-the-practice.
  - Identify barriers to achieving nationally accepted guidelines.
  - Distribute state-of-the-practice information to State, metropolitan, and international agencies.
- Benchmarking survey results will be available via Microsoft® Power BI dashboard with interactive charts, maps, tables, and measures to review.

Phase 2—Data Collection and Analysis

March 2024–February 2025

- Purpose:
  - Collect data to develop well-supported methodology.
  - Test assumptions in existing methodologies.
- Develop a research work plan starting with eight research studies identified in Phase 1.
- Execute data collection.
- Archive data.

Phase 2—Outreach

Summer 2025

- Purpose: Engage interested parties to ensure acceptance of the final methodology.
- Audience 1: Agencies—benefits, impacts, motivation, resources needed.
- Audience 2: Researchers—technical details, remaining research needs.
- Additional external presentations planned throughout the project.

Contact Information

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