Bicycle-Specific Traffic Signals: Results from a State-of-the-Practice Review

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ABSTRACT

This paper presents the results of a survey of North American jurisdictions with known installations of bicycle-specific traffic signals and a review of available engineering guidance. Surveys were sent to agencies in 21 jurisdictions (19 in the United States and two in Canada) that requested detailed engineering aspects of the signal design such as placement, mounting height, lens diameter, backplate color, type of actuation, interval times, use of louvers, and performance. We reviewed guidance documents produced by the National Association of City Transportation Officials (NACTO); American Association of State Highway and Transportation Officials (AASHTO); Transportation Association of Canada (TAC); the CROW design manual for bicycle traffic; and the Canadian, U.S. and Californian manuals on uniform traffic control devices. Responses were received for 63 intersections and 149 separate signal heads. The survey results highlight the current treatments and variations of similar designs. A subsequent review of the documents generally revealed consistent guidance with regard to the design of bicycle-specific traffic signals. The guidance on bicycle signals has grown substantially in recent years, and it is likely that there will be less variety in future designs.

INTRODUCTION

Increasing cycling as a regular mode of transportation has many personal and environmental benefits that have been noted in recent literature *(1)*. These benefits, paired with growing concerns about pollution and traffic congestion from personal car use, have motivated many municipalities to provide increased choices in infrastructure and bicycle-specific facilities (especially for new or less-confident riders) *(1, 2)*. Although cyclists are willing to travel out of their way to utilize bicycle infrastructure, minimizing trip distance and improving connectivity are other important factors in route choice *(2)*. Cohesion between network components and direct routes are essential elements of a bicycle network, as documented in the *Dutch Design Manual for Bicycle Traffic (3)*.

Difficult connections or crossing opportunities create discontinuities in the bicycle network and decrease perceived cyclist safety and comfort *(4)*. Safety, or the perception thereof, has been cited as another significant factor in people's decision to cycle *(5–7)*. Further, difficult connections obstruct direct routes or decrease their attractiveness to less-confident riders by increasing the overall stress level of an otherwise low-stress route *(8)*. Insecurities about safety and gaps in connectivity at intersections pose barriers to cycling that could be alleviated by selected application of bicycle signals.

Bicycle-specific traffic signals are heads used at intersections with conventional signals to specifically control cyclists' movement. They are typically not viewable by motorists or they are distinguished from other signal heads through special signing, bicycle indications, or signal housing color. They are common elements in the European network, where cycling is popular *(9)*. Under the control of a bicycle-specific traffic signal, cyclist movements may occur concurrently with other compatible vehicle phases or exclusively on a separate phase. In Europe, bicycle signals are most commonly used to implement leading intervals, to signalize bike-only approaches, and to separate conflicts between turning motorists and through cyclists. Presently, bicycle-specific signals are limited to displaying only 8-inch or 12-inch circular or arrow indications by the *Manual on Uniform Traffic Control Devices* (MUTCD) *(10)*. California *(11)* has specified that bicycle-specific traffic signals shall display red, yellow and green symbols. Thus, the use of bicycle-specific signals in the U.S. has been limited to a small number of jurisdictions. They are included in the MUTCD for Canada *(12)*.

This paper's purpose is to present the existing state of the practice that relates to bicycle-specific signals. The primary focus of the synthesis was the U.S. (though information is included from installations and guidance from Canada). The remainder of this paper is organized as follows: First, a short synthesis of the engineering guidance documents that address bicycle-specific signals is presented. Definitions in vehicle codes are included. It should be noted that there is very little in terms of published literature that relates to bicycle-specific signals. We have not reviewed the related literature in this paper due to space limitations, but present it elsewhere *(13, 14)*. Second, the results of a survey of jurisdictions with known installations of bicycle-specific signals are presented. Surveys were sent to agencies in 21 jurisdictions (19 in the U.S. and two in Canada) that requested detailed engineering aspects of the signal such as placement, mounting height, lens diameter, backplate color, type of actuation, interval times, use of louvers, and performance. A total of 63 intersections and 149 separate signal heads are included in this paper, which concludes with a summary and some discussion of future research needs.

ENGINEERING GUIDANCE DOCUMENTS

The following documents were reviewed with respect to their engineering guidance:

- *Guide for the Development of Bicycle Facilities* (AASHTO, 2012)
- *California Manual on Uniform Traffic Control Devices* (MUTCD) (Caltrans, 2012)
- *Urban Bikeway Design Guide* (NACTO, 2011)
- *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA, 2009)
- *Traffic Signal Guidelines for Bicycles* (Transportation Association of Canada (TAC), 2004)
- *Manual of Uniform Traffic Control Devices for Canada*, 2008 update (TAC, 2008)
- *Design Manual for Bicycle Traffic* (CROW, 2007)

The review categories are arranged in the same order as the state-of-the-practice review presented in the next section.

Physical Elements

As suggested by NACTO *(15)*, much of the guidance about regular traffic signals can be considered when designing bicycle-specific signals. In this review, only specific references in the documents to bicycle-specific signals or cyclists are identified.

Signal Head

Lens Size. The MUTCD permits the use of an 8-inch circular indication for the “sole purpose of controlling a bikeway or a bicycle movement” in *Section 4D.07 Size of Vehicular Signal Indications (10, pp 457)*. This wording is also consistent in the California MUTCD. The Canadian MUTCD states that standard bicycle signal lenses are 200-millimeter (8-inch) circular lenses. When the lens is more than 30 meters (98.4 feet) away from stopped cyclists, 300-millimeter (12-inch) lenses may be considered.

Use of Bicycle Insignia in Lens. In the MUTCD, the use of the red-yellow-green bicycle stencil in lenses is not allowed. The California manual, however, requires the use of the bicycle insignia by stating that “only green, yellow and red lighted bicycle symbols shall be used to implement bicycle movement at a signalized intersection” *(11, pp 896)*. The bicycle stencil faces left. TAC guidance from *Traffic Signal Guidelines* incorporates the guidance from Quebec with the stencil facing left. The NACTO design guidance features an illustration of the bicycle signal head with the insignia facing right. The direction of the stencil is a detail that most likely does not affect comprehension or operation, but does highlight design differences. The MUTCD does allow sign symbols to be reversed if “the reverse orientation might better convey to road users a direction of movement” *(10, pp 35)*. None of the documents provide guidance on indications that could be used to indicate protected movements. *Traffic Signal Guidelines*, however, notes that bicycle signals are intended to signal permissive movements only, with all bicycle movements being permitted unless there is signage to indicate otherwise.

Optional Elements – Color and Backplates. Both the NACTO and TAC *Guidelines* documents suggest that the color of the signal housing be different than vehicle signal housing for presumed improved visibility. TAC guidance suggests that bicycle signals be black (opposite the yellow housings for motorist signals) to further distinguish their special use.

Placement and Mounting

The placement and mounting height of the bicycle signal head will clearly depend on the particular intersection and the movement being controlled. The guidance in the reviewed document is summarized in the following sections.

Visibility for the Cyclist The NACTO design guidance explicitly states that signal heads are to be "placed in a location clearly visible to oncoming bicycles"*(15, pp 132)* with near-side placement as an "optional" enhancement to visibility. This guide's illustrations display the bicycle signal mounted over the pedestrian head.

TAC guidance also suggests supplemental near-side displays for very wide intersections, or those with complex geometry, and specifies that one signal head should be installed in the field of vision of cyclists or within 30 meters (98.4 feet) of the stop bar for easy perception and identification of the signal. As an alternative to 300-millimeter (12-inch) lenses for signal heads more than 30 meters away from stopped cyclists, bicycle signals may be placed in both the road median and at the far edge of very wide intersections. TAC *Guidelines* also suggest mounting heights for bicycle signals similar to pedestrian signal heads on the opposite side of an intersection. Bicycle signals placed over the travelled part of the roadway should be mounted at the standard signal height above the roadway 4.5 meters (14.8 feet).

The Canadian MUTCD has similar guidance to TAC *Guidelines* and states that a bicycle signal head should be "mounted within the cone of vision of cyclists and preferably within 30 m upstream of the stop bar" with vertical mounting preferred *(12)*. The guidance on this characteristic is that the minimum height for a bicycle signal over a roadway is 4.5 meters (14.8 feet).

The AASHTO and CROW guidance do not provide any specific guidance on signal head placement.

Visibility to Other Modes One design concern for bicycle-specific signals is the possibility that motorists will confuse the indication with ones meant for motor vehicles. To help limit vehicle driver confusion with the signal indication, NACTO *(15)* suggests that a bicycle signal head and motor vehicle head should be separated by 2 feet horizontally. The MUTCD *(10)* requires that when these are used, "signal faces shall be adjusted so bicyclists for whom the indications are intended can see the signal indications. If the visibility-limited signal faces cannot be aimed to serve the bicyclist, then separate signal faces shall be provided for the bicyclist" *(10, pp 816)*. It should be noted that this assumes that bicycle insignia are not being used in the lens faces of the bicycle signal heads.

Operational Elements

Detection, Phasing, Restricted Movements, Accompanying Signage

The guidance on the placement and use of detection for bicycles (not necessarily at bicycle-specific signals) is fairly robust. AASHTO *(16)*, NACTO *(15)*, California MUTCD *(11)*, and TAC *(12, 17)* all provide guidance on placement, type, location and use of the bicycle-detection pavement stencil shown in the MUTCD.

When the bicycle-specific signal is used to separate through-bicycle movements from turning cars, it is often desirable to restrict vehicles from making what would normally be a legal maneuver (e.g., right turn on red). Only NACTO offers guidance on this issue. Its guide states that "if the bicycle signal is used to separate through bicycle movements from right turning vehicles, right turn on red shall be prohibited if it is normally allowed *(15, pp 132)*."

To help identify the bicycle-signal head as for cyclists only, NACTO recommends a supplemental "Bicycle Signal" sign below the head.

Timing of Intervals for Bicyclists

A number of the referenced documents include guidance on timing intervals for bicyclists. Of concern are minimum green times, adequate clearance intervals, and length of cycles. Implicit in all of the guidance documents is the wide variance in the performance characteristics of cyclists in terms of speed, acceleration and braking capabilities.

The MUTCD provides no specific guidance on timing issues for bicycles; it only states that on bikeways, "signal timing and actuation shall be reviewed and adjusted to consider the needs of bicyclists" *(10, pp 816)*. The Canadian MUTCD does not include guidance on timing issues.

AASHTO, California MUTCD and NACTO contain formulas for the length of timing intervals that is generic for accommodating bicycles at all traffic signals. The AASHTO guide contains equations to determine minimum green time for cyclists starting from stop and clearance intervals based on crossing time for rolling cyclists. AASHTO provides a formula to estimate minimum green time for bicycles from a standing position:

$$BMG + Y + R_{clear} = PRT + \frac{V}{2a} + \frac{(W + L)}{V}$$

where:

BMG = Bicycle minimum green interval (sec)

PRT = Perception and reaction time, 1 (sec)

Y = Length of yellow interval (sec)

R_{clear} = Length of red interval (sec)

W = Intersection width (feet)

L = Typical bicycle length = 6 (feet)

a = Bicycle acceleration = 1.5 (feet/sec^2)

V = Bicycle crossing speed = 14.7 (feet/sec)

This guide also states that "the yellow interval is based on the approach speeds of automobiles, and therefore, should not be adjusted to accommodate bicycles" *(16, pp 4-46)*. The guide suggests modifying the all-red time or, if that is insufficient, providing for extension time using dedicated bicycle-detector and -controller settings to add sufficient time to clear the intersection.

The California MUTCD provides provisions on the minimum-timing parameters. The manual specifies that the sum of the minimum green, plus the yellow-change interval and any red-clearance interval, should be sufficient to allow a cyclist riding a bike 6 feet long to clear the last conflicting lane at a speed of 10 mph (14.7 feet/second), plus an additional, effective start-up time of six seconds, according the formula:

$$G_{min} + Y + R_{clear} > 6\,\text{sec} + \frac{(W + 6\,ft)}{14.7\,ft/sec}$$

where:

G_{min} = Length of minimum green interval (sec)

Y = Length of yellow interval (sec)

R_{clear} = Length of red interval (sec)

W = Distance from limit line to far side of last conflicting lane (feet)

The AASHTO and California formulas estimate similar numbers. With the default AASHTO values of perception-reaction (one second), speed (14.7 feet/second), and acceleration (1.5 feet/second^2), the first two terms of the AASHTO equation are approximately six seconds (see Figure 2A).

For rolling cyclists, AASHTO presents an equation for determining the rolling crossing time. A cyclist who enters the intersection just at the end of green should have sufficient time to clear the intersection during the yellow change and all-red clearance intervals. Rolling time is presented as the sum of the braking distance, intersection width, and length of bicycle divided by the assumed rolling speed (suggested as 10 mph or 14.7 feet/second):

$$BCT_{rolling} = PRT + \frac{V}{2a} + \frac{BD + W + L}{V}$$

$$BD = PRT * V + \frac{V^2}{2a}$$

where:

- BCT = Bicycle crossing time (sec)
- PRT = Perception and reaction time, 1.0 (sec)
- BD = Braking distance (feet)
- W = Intersection width (feet)
- L = Typical bicycle length = 6 (feet)
- a = Bicycle deceleration rate for wet pavement = 5 (feet/sec^2)
- V = Bicycle crossing speed = 14.7 (feet/sec) or 10 miles per hour (mph)

Similarly, NACTO requires that an "adequate clearance interval (i.e., the movement's combined time for the yellow and all-red phases) shall be provided to ensure that bicyclists entering the intersection during the green phase have sufficient time to safely clear the intersection before conflicting movements receive a green indication" *(15, pp 132)*. An equation is provided to calculate the total clearance interval using the intersection width (*W*) and cyclist velocity (*V*):

$$C_i = 3 + \frac{W}{V}$$

In determining this minimum interval, field investigation of bicyclists' speed is recommended. The guide suggests intervals sufficient for 15th percentile speeds should be used. Absent field data, NACTO suggests that "14 feet per second (9.5 miles per hour) may be used as a default speed" *(15, pp 132)*.

Intersection width is defined differently in the California MUTCD and NACTO guidance. NACTO defines the width from the intersection entry (i.e., stop-line or crosswalk in the absence of a stop-line) to halfway across the last lane carrying through traffic. California defines width as the limit line to the far side of the last conflicting lane. For presentation purposes, in Figure 4b the width was adjusted for consistency assuming a 12-foot lane. The values produced by the AASHTO and NACTO clearance interval formulas are nearly identical (see Figure 4b). It should be noted, however, that the values determined by these equations exceed the yellow and all-red practical maximums for vehicles, for all except the narrowest intersections. This implies that detection and extension designs may be needed at some wide intersections.

The CROW manual does not provide formulas for minimum times, but does include suggested design values for speed (20 kilometers/hour)(12.4 mph), acceleration (0.8 to 1.2 meters/second^2)(2.6 to 3.9 feet/second^2), deceleration (1.5 meters/second^2)(4.9 feet/second^2), and perception-reaction time (1s). The guide acknowledges the variety in speed and acceleration because of cyclist characteristics and road conditions. Related to timing practices in general, CROW states that a basic premise of the guide is that bicycles should have to stop as little as possible. An average wait time of less than 15 seconds is considered good, with an absolute maximum wait time (in built-up areas) of 90 seconds

Finally, TAC guidelines *(17)* Sections 4.1.3 and 4.1.4 discuss timing and phasing for bicycle signals, respectively. The average typical cruising speed of a cyclist is given to be 20 kilometers/hour (12.4 mph), and it is suggested that cyclists in mixed traffic are adequately served by existing green times for the majority of cases. Recognizing the additional time for cyclists to begin pedaling from start, the document recommends an absolute minimum green time of five seconds. It is also suggested that minimum vehicular greens at very wide crossings or on uphill gradients be extended to accommodate cyclists. Recommendations for clearance intervals state that yellow times should remain unchanged - since cyclists can more easily stop than motor vehicles - and that, if needed, all-red displays can be extended to accommodate slower cyclists. For exclusive bicycle phasing, the recommended minimum green time is 10 seconds for most intersection widths. For very wide intersections where cyclists must accelerate from a stop, an additional five seconds can be allocated to the minimum green time for a total of 15 seconds.

Warrants

The California MUTCD provides a *Bicycle Signal Warrant* which states that "a bicycle signal should be considered for use only when the volume and collision or volume and geometric warrants have been met" *(11, pp 831)*. These are identified as:

- Volume - based on the number of bicycles per peak hour (at least 50) and the number of vehicles at the peak hour entering the intersection;
- Collisions - when two or more bicycle/vehicle collisions of types susceptible to correction by a bicycle signal have occurred over a 12-month period, and the responsible public works official determines that a bicycle signal will reduce the number of collisions; and
- Geometric (a path connection or to allow a movement not open to vehicles).

The manual states that a bicycle signal should be used only after other alternatives have been used. The California Vehicle Code further states that "a bicycle signal may be used only at those locations that meet geometric standards or traffic volume standards, or both, as adopted by the Department of Transportation *(18)*."

NACTO doesn't explicitly discuss warrants for bicycle signals, but cyclist safety is cited as an important consideration for the installation of any type of traffic signal – specifically where conflicting traffic speed and/or volume is high enough to hinder cyclists' crossing of an intersection. Maintaining the flow of bicycle traffic is another reason for a signal's installation. Section 4.1.6 of TAC's guidelines discusses justifications for the installation of a bicycle signal. Although several key factors to consider are detailed in the report, no thresholds or minimum number of cyclists are given to warrant a bicycle signal. There is a strong emphasis on the use of engineering judgment in conjunction with the key factors: safety, traffic/cycling volumes, conflicting movements, and public input. The Canadian MUTCD states that bicycle signals should only be installed if standard vehicle displays cannot adequately control bicycle movement and assign right-of-way. CROW states that bicycle signals can be considered if the crossing movement of cyclists is hindered by cross-traffic speed and/or volume, but only if other measures are unfeasible at that location.

Enabling Legislation

Two states' legislation was identified in the review. Based on discussions with engineers in these jurisdictions, the legislation was needed to define cyclists' legal actions when facing a traffic signal with green, yellow or red bicycle indications. California defines the requirements of a cyclist in Section 21456.3 Transportation Bicycle Signals of the California Vehicle Code *(18)*. The language describes allowable actions when facing a green bicycle signal, a steady-yellow bicycle signal, and red-signal indications. The code allows legal right turns on red after the cyclist stops completely and yields right of way to pedestrians. In 2011, Oregon Senate Bill 130 amended state statute to describe cyclists' requirements when facing bicycle-signal indications *(19)*. The requirements are very similar to California's, but adopted for consistency with Oregon's vehicle code. The Canadian MUTCD also defines the expected actions based on the bicycle-signal indications.

SURVEY OF PRACTICE

Based on the authors' knowledge and information from the Federal Highway Administration on the current experiments, targeted surveys were sent out to agencies in 21 jurisdictions with known bicycle-signal installations (19 in the U.S. and two in Canada). Surveys were distributed online. There are likely other installations of bicycle-specific signals that were not captured in this survey. These jurisdictions are shown in Figure 2. Jurisdictions that responded to the survey are shown with black labels; those that did not are grey. The per-city response rate for the survey, including data gathered for Portland, was 71%.

In all, 63 intersections (36 Canadian and 27 U.S.) and 149 separate signal heads are included in the results that follow. The labels in Figure 4 also include the number of bicycle-specific signal heads reported in survey results. It should be noted that although a response from Tucson, AZ., was collected, information about the signals in that jurisdiction were not included in the results. Tucson has designed special signalized intersections called "TOUCAN"s that only serve bicycle and pedestrian traffic on the side-street approaches. With no potential for confusion among motorists or bicyclists, these types of signals were not the focus of this survey.

All statistics reported in this synthesis are based on received responses and site visits only. For tables, the columns labeled "unknown" indicate that the jurisdiction did not provide this information. Because each bicycle signal installation is unique, the analysis should not be construed to show consensus for any one design approach or treatment. Instead, the purpose is to highlight the current various treatments and, when available, show the variations of similar designs.

Motivations and Decision Criteria

As part of the survey, jurisdictions were asked to provide a narrative for the motivations to install bicycle signals. Reasons could be grouped into five categories:

1. Cyclist non-compliance with previous traffic control
2. Presence of a contra-flow bicycle movement
3. A diagonal (or otherwise unique) cyclist path through the intersection
4. Safety concerns for cyclists
5. Other

As shown in Table 6, bicycle signals are most commonly installed when cyclists are moving against motorist traffic, taking a non-standard path through an intersection, or when there are safety concerns for cyclists at that intersection. The many contra-flow responses are from installations in Vancouver, BC and Montreal, QC, with two-way cycle tracks. Reasons falling into the "other" category were few. For two signals, infrastructure updates gave the agencies an opportunity to install the signal. Three more signals were installed for experimental reasons.

Two agencies in Portland and Eugene, OR., have independently developed warrants for implementation of bicycle signals. Jurisdictions in California refer to the California MUTCD to warrant a bicycle signal installation.

Physical Elements

Signal Head

Five characteristics of the bicycle signal heads were described in this synthesis: backplate presence and color, signal housing color, lens size, traits of the insignia, and the presence of louvers or a visibility limited indication. Table 2 presents a summary of survey results for these characteristics.

Standard signal housing colors, yellow and black, made up the majority of housing colors for reviewed signals. Eight signal heads from San Francisco were reported as being "Dark Green" and appear in Table 2's "Other" column. The reported color of backplates, when present, varied between black and yellow, although the vast majority of bicycle signals have no backplates. Pictures of the various housing and backplate combinations are shown in Figure 6f.

It should be noted that these elements reflect local design practice. For example, the housing color of bicycle signal heads in Vancouver, BC (yellow) matched the motorist signals. In the survey, it was more common for U.S. jurisdictions to use different color housing than motor vehicle signals. The majority of U.S. signal lenses were 12 inches; Canadian signals were more likely 8 inches. This corresponds to guidance in Canadian MUTCD and the fact that signal heads are often placed on both sides of the intersection.

As one way to differentiate the bike signal from motorist signals, many bicycle signal heads display an insignia (or stencil) of a bicycle in the lens. The majority of installed bicycle signals have some sort of insignia on the lenses. Interestingly, there is variation in the directions the insignia face. Canadian signals were more uniform in their use of a left-facing lens insignia (in Montreal and Vancouver). Within and between U.S. cities, there is variation with the application of lens insignia. Also, two basic forms of the insignia were found: a realistic outline of a bicycle and a more abstract one (see Figure 6c).

Most of the surveyed signal heads did not use louvers or other modifiers to restrict the visibility of the bicycle signal to be viewed by cyclists only. Generally, when louvers were employed, it was at intersections with major safety concerns and/or where the bicycle signal aligned with the motorist signal and might be easily confused. Louvers were not heavily utilized in either of the surveyed Canadian jurisdictions.

Placement and Mounting

In the U.S., vehicle traffic signals are located on the far side of the intersection unless there are sight-distance issues. This practice has been followed with installations of bicycle signal heads. About 19% of the U.S. sample and 64% of the Canadian intersections had signal heads placed on both the near and far side of the intersection. Near side-only bicycle signals are commonly found in Europe, but no near side-only signals were found in our North American survey. Note that these near-side heads are typically smaller and lower in Europe. Pictures of some typical mounting locations are shown in Figure 6a and b.

The reported mounting heights of bicycle signals varied widely, from 7 to 19 feet (measured from pavement elevation at the bicycle stop bar). The mounting height partially correlated with the intersection placement of the signals – intersections with signals on both near and far sides tended to have lower mounting heights. Lower mounting heights were also common when the bicycle signal was mounted on the same pole as the pedestrian indication. Mounting heights are summarized in Table 8.

Operational Elements

Detection, Phasing, Restricted Movements, Accompanying Signage

All of the signalized intersections in Vancouver and Montreal do not include detection. Forty-four percent of U.S. signals were on recall with no detection. For the remaining intersections, with some form of detection, loop detection was the most common. For intersections with loop detection, most used the bicycle-detector pavement marking found in the MUTCD. Some U.S. locations also included push-button actuations (see Figure 6d). The MUTCD placard sign for "to request green" was commonly used. Two jurisdictions (Austin, TX., and Portland, OR.) reported experimenting with a detection feedback indication, which illuminates when the controller detects the presence of cyclists. A close-up of Portland's installation is shown in Figure 3d.

Based on submitted timing plans, commentary from the survey and Internet research, the phasing for the majority of the signals could be determined. In the U.S., 59% of the intersections provided for an exclusive phase for bicycle movement. It was also very common to restrict conflicting motor vehicle movements (70% of the U.S. and 56% of the Canadian intersections). Finally, nearly 74% of the U.S. signals included some form of accompanying signage to provide additional information that the signal head controlled bicycle movements. The signs were generally consistent (see Figure 3e), though Long Beach, CA., added lettering to the signal backplate. Some jurisdictions created guidance signs intended for cyclists instructing on use of the signal (See Figure 3e).

Timing of Intervals for Bicyclists

Survey respondents were asked to report the minimum green, yellow and red times for bicycle signals (see Table 10). Because a comparison of minimum times also needs to account for intersection width, these minimum times were normalized based on the "standing start" equation for bicycle minimum green time from AASHTO's 2012 guide. The guide-suggested values for PRT (1 second), L (6 feet), and a (1.5feet/second^2) were used in these calculations (T). Intersection widths were obtained from Google Earth. These normalized values are presented in Table 10. Although timing information could not be determined for all signals, analysis of the data revealed a range of assumed cyclist speeds.

CONCLUSION

This review has highlighted both the guidance available to engineers and planners and the types of designs being implemented by jurisdictions of bicycle-specific signals. The availability of engineering guidance has improved substantially over the past few years with the release of the California MUTCD, NACTO's *Urban Bikeway Design Guide*, and AASHTO's guidance. While there are minor differences, there is generally consistent guidance. To some extent, the guidance documents reflect the lessons learned by the surveyed jurisdictions since installation of the bicycle-specific signals is limited to those places willing to experiment. The survey of practice found a variety in some design elements: lens size, use of insignia, utilization of louvers, mounting location, and the means to designate that the signal head is for bicyclists. Some consensus appears on the use of the lens insignia and accompanying signage. Given the accelerated deployments of bicycle-specific signals and the new guidance documents, it is likely that there will be less variety in future designs. Adoption of minimum guidance in the U.S. MUTCD would also likely improve consistency and practice

Research Needs

The review highlighted a few clear knowledge gaps that warrant further research. First, the timing of minimum green and clearance intervals is challenging based on the wide variety of cyclists' abilities. Descriptive data on cyclist performance characteristics like speed, acceleration, start-up lost time, and saturation flow rate that affect intersection clearance time are important for effective timing of intervals to accommodate cyclists. Second, quantitative research on the safety effectiveness of bicycle-specific signals is lacking. This is a key gap in the knowledge needed to create standards for the operation of bicycle-specific signals. Finally, operational compliance of cyclists with bicycle-specific signals is another empirical data gap.

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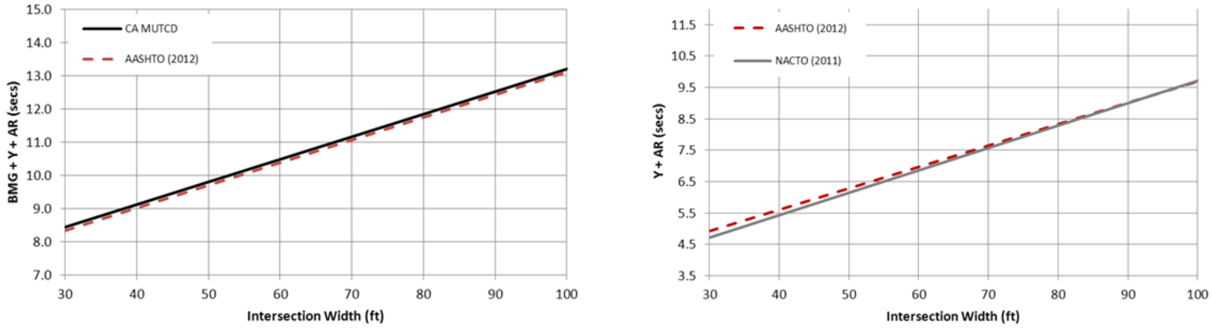
LIST OF FIGURES



a) Comparison of BMG + Y + AR

b) Comparison of Y+ AR

FIGURE 4 Graphical Comparison of Timing Formulas

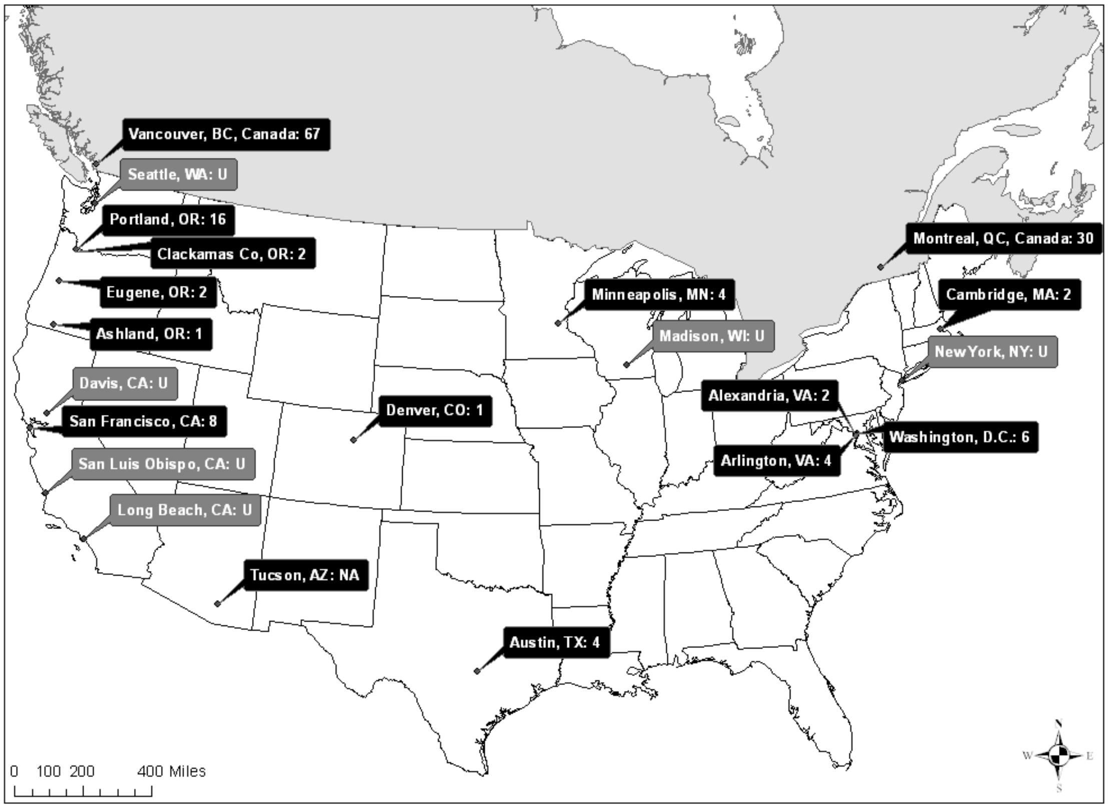


FIGURE 5 Jurisdictions Identified with Bicycle-specific Signals and Survey Respondents

Note: numbers following the ":" denote the number of reported signal heads at that location. "U" denotes a non-response for that location. "NA" denotes a response from Tucson on their TOUCAN signals which is shown for completeness

FIGURE 6 Photographs of Various Elements of Bicycle-Specific Traffic Signals

LIST OF TABLES

TABLE 6 Motivations for Installation

Motivations	Number of Intersections			Percent of Sample		
	US	Canada	Total	US	Canada	Total
Non-compliance	3	0	3	8%	-	3%
Contra-flow	6	36	42	17%	69%	48%
Unique path	13	3	16	36%	6%	18%
Safety	9	12	21	25%	23%	24%
Other	4	1	5	11%	2%	6%

Note: percentages do not add to 100% as more than one motivating reason per intersection could be cited

TABLE 7 Elements of the Signal Head

Characteristic		**Number of Signal Heads**			**Percent of Signal Heads**		
		US	**Canada**	**Total**	**US**	**Canada**	**Total**
Backplate Color	Black	18	0	18	35%	-	12%
	Yellow	10	0	10	19%	-	7%
	No backplate	24	97	121	46%	100%	81%
	Unknown	0	0	0	-	-	-
Housing Color	Black	32	37	69	62%	38%	46%
	Yellow	12	60	72	23%	62%	48%
	Other	8	0	8	15%	-	5%
	Unknown	0	0	0	-	-	-
Lens Size	12"	35	7	42	67%	7%	28%
	10"	0	0	0	-	-	-
	8"	9	90	99	17%	93%	66%
	Other	2	0	2	4%	-	1%
	Unknown	6	0	6	12%	-	4%
Bicycle Insignia	Faces Left	19	79	98	37%	81%	66%
	Faces Right	20	0	20	38%	-	13%
	No Insignia	12	18	30	23%	19%	20%
	Unknown	1	0	1	2%	-	1%
Utilization of Louvers	Yes	38	17	55	73%	18%	37%
	No	13	80	93	25%	82%	62%
	Unknown	1	0	1	2%	-	1%

Note: All percentages are rounded to the nearest integer.

Note: Percentages based on total number of surveyed signal heads, 149.

TABLE 8 Placement and Mounting

Characteristic		**Number of Intersections**			**Percent**		
		US	**Canada**	**Total**	**US**	**Canada**	**Total**
Intersection Placement[*]	Near side-only	0	0	0	-	-	-
	Far side-only	22	13	35	81%	36%	56%
	Both	5	23	28	19%	64%	44%
	Unknown	0	0	0	-	5%	-
Mounting Height	< 10 ft	13	0	13	25%	-	9%
	10-14.9 ft	19	93	112	37%	96%	75%
	15+ ft	8	4	12	15%	4%	8%
	Unknown	12	0	12	23%	-	8%

[*] *Percentages based on total number of surveyed intersections, 63.*

TABLE 9 Operational Elements

Design Element		**Number of Intersections**			**Percent of Intersections**		
		US	**Canada**	**Total**	**US**	**Canada**	**Total**
Detection Type	Loop	7	0	7	26%	-	11%
	Video	2	0	2	7%	-	3%
	Loop & Push-Button	4	0	4	15%	-	6%
	Push-button Only	2	0	2	7%	-	3%
	No Detection/ Recall	12	36	48	44%	100%	76%
	Unknown	0	0	0	-	-	-
Phasing Type	Exclusive	16	13	29	59%	36%	46%
	Concurrent	7	23	30	26%	64%	48%
	Leading interval	1	0	1	4%	-	2%
	Unknown	3	0	3	11%	-	5%
Restricted Movements	Yes	19	20	39	70%	56%	62%
	No	6	16	22	22%	44%	35%
	Unknown	2	0	2	7%	-	3%
Accompanying Signage	Yes	20	9	29	74%	25%	46%
	No	6	27	33	22%	75%	52%
	Unknown	1	0	1	4%	-	2%

*One reviewed signal, from Portland, OR., with a leading interval for cyclists is included.

Note: Percentages based on total number of surveyed intersections, 63.

Note: The definition for "Exclusive" includes those signals that are concurrent with pedestrian traffic but not motorist traffic.

TABLE 10 Assumed Cyclist Speeds, Derived from Minimum Green Times and Intersection Widths

Statistic		**US**	**Canada**	**Total Sample**
Minimum Green Time (sec)	Mean	10.6	8.2	9.7
	Median	10	7	9
	Low	4	5	4
	High	19	25	255
Intersection width (ft)	Mean	77.6	77.5	77.5
	Median	80	75	75
	Low	30	58	30
	High	110	135	135
Assumed Cyclist Speed (ft/s)	Mean	8.2	8.8	8.5
	Median	6.5	7.2	7.2
	Low	2.1*	4.6	2.1*
	High	18.7	17.4	18.7
% of sample with available timing information		78%	36%	54%

*Extreme low due to one location with a narrow intersection width and lengthened bicycle indication to be concurrent with pedestrian indication. Next lowest value was 3.8 ft/s