Methodology for Estimating Bicyclist Acceleration and Speed Distributions at Intersections

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As cities across North America install infrastructure to accommodate a growing number and variety of bicyclists, installation of bicycle-specific traffic signals is a common design element. A recent survey showed a lack of consistency in design and timing. In particular, minimum green signal timing is highly dependent on the assumed acceleration and speed performance of bicyclists, but no detailed methodology exists to estimate these performance values. Recently, AASHTO, the California Department of Transportation, and the National Association of City Transportation Officials issued documents that required the provision of an adequate clearance interval and recommended that, in the determination of this minimum interval field, an investigation of bicyclist speed be conducted. Even if detailed video trajectories are available, the determination of a value for field speed and acceleration is not trivial, because values of speeds and accelerations are a function of time and individual bicyclist performance. The purpose of the research reported here was to develop and apply a general methodology to estimate bicyclist acceleration and speed for traffic signal timing applications. With the use of physical equations of motion, this research analytically derived expressions that could be used to classify an individual bicyclist's performance as a function of the observed acceleration profile. The analysis indicated that four basic acceleration profiles were possible and that the profiles could be obtained with a parsimonious field data collection method. The methodology was applied successfully to two intersections in Portland, Oregon. A detailed statistical analysis showed that the results were intuitive and that the methodology successfully categorized bicyclist performance variations as a result of topography or demographic characteristics.

Many cities in North America are making significant investments in bicycling infrastructure to improve cycling conditions. These investments are motivated in part by research that indicates that, to grow bicycle ridership, facilities need to be designed to accommodate all riders, particularly those demographic groups that might not otherwise choose to cycle in the typical urban setting because to do so would be a stressful experience (*1*).

Most bicycle–vehicle crashes in urban areas occur at intersections (*2*). Thus, traffic signal timing plays a significant role in the effort to make cycling a safe and attractive option for city travel. The setting of many timing parameters involves a delicate balance, because urban intersections must accommodate motor vehicles, pedestrians, and cyclists, and the performance of these users varies between and within groups. If movements are separated by users (e.g., a bicycle-specific phase) it becomes important to have field-observed performance values for safety and efficiency. For example, unnecessarily long minimum green times to accommodate cyclists can lead to excessive delays and increased emissions from motor vehicles. Yet inadequately short bicycle-specific minimum green times can create stressful, uncomfortable, and even unsafe bicycle environments (*3*). Because there may be performance differences associated with cycling demographics, it is possible that only strong or high-performance bikers may be capable of the acceleration and speed necessary to clear an intersection safely in situations in which clearance and green time may be minimal. A user that requires more time to cross comfortably (e.g., child, older cyclist) may be caught midway through an intersection when opposing traffic receives a green. Not only is such a situation unsafe, it also can be a deterrent to bicycling as a viable alternative mode.

To meet the needs of bicycle riders and other intersection users adequately, it is vital to understand the performance of bicycle riders. Extensive literature and reports on the basis of professional experience describe operational strategies and design issues with respect to traffic signals for motorized vehicles and pedestrians. In contrast, the literature and reports on engineering experience for bicycle-specific signal design are newer and relatively scarce. A recent survey indicated a lack of consistency across North American cities with respect to bicycle signal design, detection, and timing parameters (*4*). In particular, the survey found a wide range of assumed bicycle speeds (from 2.2 to 18.7 ft/s) across bike signals in North American cities.

A relatively wide range of published cyclist performance data (e.g., on perception–reaction times, rolling speed, accelerations) can guide the selection of basic signal parameters (e.g., minimum green, yellow, and all-red clearance intervals; extension times). AASHTO, the California Department of Transportation (Caltrans), and the National Association of City Transportation Officials (NACTO) now require that an adequate clearance interval be provided. Furthermore, they recommend that, in the determination of the minimum interval, a field investigation of bicyclist speeds be conducted (*5–7*). These guides suggest that intervals sufficient for 15th percentile speeds should be used. Absent field data, the guides suggest that a value of approximately 15 ft/s may be used as a default speed. AASHTO also recommends that extended crossing times should be given to some types of riders [e.g., young riders near schools (*5*, Sec. 4.12.4, p. 4-44)].

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Transportation Research Record: Journal of the Transportation Research Board, No. 2387, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 66–75.
DOI: 10.3141/2387-08

Although these guidance documents (*5–7*) recommend field-obtained values and 15th percentile speeds, no consistent methodology is available to determine field speeds or acceleration. As discussed later in this paper, the determination of field bicyclists' acceleration and cruising speed is not a trivial exercise. In the literature, no comprehensive mathematical framework has yet appeared to estimate bicycle rider acceleration and cruising speeds at intersections.

The purpose and main contribution of the research reported here was to develop and apply a general mathematical framework to estimate bicyclist acceleration and cruising speed for traffic signal timing applications to data that could be extracted from a simple video data collection procedure.

Because the simultaneous estimation of acceleration and cruising speed values is not trivial, the methodology contained in this paper can be used to estimate acceleration and cruising speed distributions in intersections with unique or special characteristics.

Through the analysis of physical equations of motion, this research analytically derived expressions that could be used to classify an individual bicyclist's performance as a function of the observed acceleration profile. In turn, the acceleration profile could be used to classify the individual bicyclist's performance at an intersection and the performance given different demographics and acceleration and speed distributions. Finally, recommended minimum green times obtained from current guidance documents were compared with field estimations with the use of 85th percentile crossing times.

LITERATURE REVIEW

The recently released 2012 AASHTO *Guide for the Development of Bicycle Facilities* provides a revised treatment of the information that relates to bicyclist types and minimum green crossing time. The three classes of cyclists (A, B, and C) presented in the 1999 guide have been replaced by two new classes, namely "Experienced and Confident" and "Casual and Less Confident" (*5*). The new guide presents timing issues separately for standing and rolling bicyclists. For stopped bicyclists, the guide presents the equations to determine the minimum green required for a cyclist to start from stop and clear the intersection width. To estimate minimum green crossing times, acceleration and crossing speeds must be known. For a bicycle that starts from a stopped position, the default acceleration value is 1.5 ft/s^2; the default rolling speed is 10 mph or 14.7 ft/s.

For rolling cyclists, the guide also presents an equation to determine the rolling crossing time. A cyclist that enters an intersection just at the end of green should have sufficient time to clear the intersection during the yellow change and all-red clearance intervals. The 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 ft/s). The new AASHTO guide states that "the yellow interval is based on the approach speeds of automobiles, and therefore, should not be adjusted to accommodate bicycles" (*5*, p. 4-46). The guide suggests the modification of the all-red time or, if that is insufficient, to use a dedicated bicycle detector and controller settings to extend time sufficiently to clear the intersection.

A speed of approximately 10 mph (14.7 ft/s) is now cited in the latest bicycle design guides as an assumed rolling speed (*5–7*). The NACTO guide 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." In the determination of this minimum interval, field investigation of bicyclists' speed is recommended. The guide suggests that intervals sufficient for 15th percentile speeds should be used. Absent field data, the NACTO guide suggests that "14 feet per second (9.5 miles per hour) may be used as a default speed" (*7*).

The AASHTO guide provides a formula to estimate minimum green for bicycles from a standing position (*5*):

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

where

BMG = bicycle minimum green interval (s),
PRT = perception–reaction time (1 s),
Y = length of yellow interval (s),
R_{clear} = length of all-red clearance interval (s),
W = intersection width (ft),
L = typical bicycle length (6 ft),
a = bicycle acceleration (1.5 ft/s^2), and
V = bicycle crossing speed (14.7 ft/s).

The *California Manual on Uniform Traffic Control Devices* provides detection guidance and provisions on the minimum timing parameters (*6*). The manual states that, "for all phases, the sum of the minimum green, plus the yellow change interval, plus any red clearance interval should be sufficient to allow a bicyclist riding a bicycle 6 feet long to clear the last conflicting lane at a speed of 10 mph (14.7 ft/s) plus an additional effective start-up time of six seconds," according to the following formula:

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

where G_{min} is the length of the minimum green interval (seconds) and W is the distance from the limit line to the far side of the last conflicting lane (feet).

The AASHTO and Caltrans formulas estimate similar numbers. With the default AASHTO values of perception–reaction (1 s), speed (14.7 ft/s), and acceleration (1.5 ft/s^2), the first two terms of AASHTO Equation 1 are approximately 6 s:

$$\text{PRT} + \frac{v}{2a} \approx 6\text{ s}$$

Empirical evidence indicates that a wide range of acceleration and speed performance may need to be accommodated on the basis of individual locations (*8–11*). Most published studies have used different measurement techniques to derive these values. Wachtel et al. conducted one of the first studies of bicyclists' minimum green time, and highlighted that the most common signal timing issue related to vehicle–bicycle collisions: a cyclist lawfully enters an intersection on a yellow phase and is hit by a motorist on the intersecting street, who restarts or accelerates into the intersection upon receipt of a green phase (*8*). In this situation, the clearance time is not sufficient for a cyclist at cruising speed to travel safely across the intersection. Another signal timing issue can occur at the start of a green phase at an actuated signal. A signal that provides only a minimum green time designed for motor vehicles (a result of low vehicle demand) may not be long enough to accommodate a cyclist's need to react, accelerate, and traverse the intersection, especially at wide intersections and in situations in which multiple cyclists have formed a queue.

A handful of studies have measured average speeds and accelerations and compared them with the guidance documents. Pein measured the average speed and approximated the acceleration of cyclists on multiuse paths and at three-leg intersections (*9*). Rubins and Handy measured intersection clearance times for cyclists in Davis, California, from stopped, slowed, and rolling positions across a wide age range (*10*). A study conducted in Portland, Oregon, found statistically significant performance differences between male and female bicyclists, and also when flat and uphill intersections were compared (*11*). Pein investigated trail users, and collected data from active and passive study participants on skateboards, kick scooters, tandem cycles, manual and power wheelchairs, electric bicycles, inline skates, and hand cycles, among several other emerging trail user vehicle types (*9*). In his study of the cyclist group, Pein found that, after an initial increase in the acceleration rate, the rate decreased with increasing speed, which was counter to the AASHTO equation, which assumes a constant acceleration (*5, 9*). More recently, researchers have used video-image and processing software to extract each cyclist's trajectory through an intersection (*12–13*). The trajectories were synchronized to signal phases and were used to determine start-up time and cruising speed through intersections. The studies presented evidence that performance varied by intersection population. At a location populated mainly by recreational cyclists and families, speeds were found to be slower than at a location largely made up of commuting college students.

Bicyclist demographics do affect performance (*11, 14, 15*). Research by Navin found that young males achieved higher speeds than average when they climbed on a grade (*15*). A UK study found no statistically significant difference between male and female speeds on flat roadways but significantly lower speeds (for females) on uphill roadways (*16*).

ACCELERATION AND SPEED DETERMINATION

The determination of field bicyclist acceleration and speed is recommended by the guidance documents as well as through the use of 15th percentile speeds. No methodology to determine field speeds or acceleration is provided, however. Automated methods to extract object trajectories from video data are possible, although not widely available (*17*).

Even if detailed video trajectories are available, the determination of a value for field speed and acceleration is not trivial, because values of speeds and accelerations are a function of time and individual bicyclist performance. For example, when a bicyclist starts in a standing position, the initial speed is zero; it takes time t_c to reach cruising speed. The change of speed is, in turn, a function of the acceleration a from time zero t_0 (the time when bicyclist movement is imminent) to time t_c. As expected from physics and real observations, the value of acceleration is not a constant but tends to decrease as speed increases (*11*). Many potential acceleration values can be observed in a second-by-second trajectory analysis. To compare against guidance acceleration and speed values a consistent methodology is necessary, one derived from fundamental physics equations of motion, to obtain representative average acceleration and speed values.

Again, it is not trivial to obtain representative average acceleration and speed values. For an individual bicyclist, it is possible to observe the time t_1 to cover a given distance d_1 from a standing position. If the goal is to obtain an average acceleration, denoted a, and a cruising speed v_c, and if constant acceleration is assumed, the time to reach cruising speed is $t_c = v_c/a$. The distance traveled is equal to

$$d_c = \frac{1}{2a}(t_c)^2 = \frac{(v_c)^2}{2a}$$

The time elapsed up to the first observations is equal to

$$t_1 = t_c + (t_1 - t_c) = t_c + \frac{(d_1 - d_c)}{v_c} \qquad (1)$$

Replacement of $v_c = t_c a$ and $d_c = (v_c)^2/2a$ into Equation 1 yields

$$t_1 = \frac{v_c}{a} + \frac{d_1 - \frac{(v_c)^2}{2a}}{v_c}$$

$$t_1 = \frac{v_c}{2a} + \frac{d_1}{v_c} \qquad (2)$$

In Equation 2, two values are known from measurement (t_1, d_1) and two unknowns, v_c and a. Thus the problem is indeterminate. It is not possible to estimate both values simultaneously. This indetermination can be broken if another observation is taken. In addition to (t_1, d_1), it is possible to obtain a second pair of observations timing the cyclists' time t_2 to cover a given distance d_2 from a standing position and a start at time–distance (t_0, d_0).

Without loss of generality, it is assumed that $t_1 < t_2$ and $d_1 < d_2$. With the observations (t_1, d_1) and (t_2, d_2) it is possible to have four acceleration profiles on the basis of the point at which each bicycle rider has finished acceleration (i.e., the cyclist has reached a cruising speed). These cases are described in the following list:

Case 1. The cyclist reaches cruising speed within, at, or before he or she reaches the time–distance (t_1, d_1).
Case 2. The cyclist reaches cruising speed after (t_1, d_1) but before he or she reaches (t_2, d_2).
Case 3. The cyclist reaches cruising speed after (t_2, d_2).
Case 4. The cyclist does not have a nondecreasing speed profile.

To simplify the notation and expressions, the prime symbol is introduced to denote the differences. For example, the partial time ($t_{2'}$) and distance ($d_{2'}$) between Observations 1 and 2 are denoted as

$$t_{2'} = t_2 - t_1$$
$$d_{2'} = d_2 - d_1$$

Similarly, the partial time ($t_{1'}$) and distance ($d_{1'}$) between Observations 0 and 1 are denoted as

$$t_{1'} = t_1 - t_0$$
$$d_{1'} = d_1 - d_0$$

Determination of Case 1

The cyclist reaches cruising speed within, at, or before the cyclist reaches the time and distance (t_1, d_1). Thus it is possible to solve the indeterminacy, because the second period is traveled at a cruising speed as

$$v_c = \frac{(d_2 - d_1)}{(t_2 - t_1)} = \frac{d_{2'}}{t_{2'}} \tag{3}$$

If Equation 3 is replaced into Equation 2, the value of a is obtained as

$$t_1 = \frac{d_{2'}}{2at_{2'}} + \frac{d_1 t_{2'}}{d_{2'}}$$

$$a = \frac{d_{2'}}{2t_{2'}\left(t_1 - \dfrac{d_1}{d_{2'}}t_{2'}\right)}$$

$$t_c = \frac{v_c}{a} \tag{4}$$

Given that accelerations cannot be negative, Case 1 holds when this obvious inequality is valid as follows:

$$\frac{d_{2'}}{d_1} > \frac{t_{2'}}{t_1}$$

Determination of Case 2

The cyclist reaches cruising speed after (t_1, d_1) but before he or she reaches (t_2, d_2). In Case 2, it is possible to estimate the acceleration in the first period as follows:

$$a = \frac{2d_1}{(t_1)^2} \tag{5}$$

However, t_c and v_c are still unknown. In this case, v_c is reached in the time interval [t_1, t$_2$], and Equation 2 must be written as follows:

$$t_2 = \frac{v_c}{2a} + \frac{d_2}{v_c} \tag{6}$$

Expression of Equation 6 as a second-order equation is as follows:

$$\frac{(v_c)^2}{2a} - t_2 v_c + d_2 = 0$$

In its replacement, the following is obtained:

$$v_c = at_2 \pm \sqrt{(at_2)^2 - 2ad_2} \tag{7}$$

To obtain real roots, the term inside the square root must be positive as follows:

$$(at_2)^2 - 2ad_2 > 0$$

$$t_2^2 > \frac{2d_2}{a}$$

From the analysis of Equation 7 only one root may be feasible. This root is infeasible as

$$v_c = at_2 + \sqrt{(at_2)^2 - 2ad_2} \tag{8}$$

This equation is proved because the cruising speed must satisfy $v_c \le at_2$ (i.e., in Case 2 the cruising speed is assumed to be reached in the time interval [t_1, t_2]).

For the only potentially feasible root (Expression 9), the feasibility constraint indicates that the cruising speed is reached in the time interval [t_1, t_2] as shown in Expression 10.

$$v_c = at_2 - \sqrt{(at_2)^2 - 2ad_2} \tag{9}$$

$$t_1 a \le v_c \le t_2 a \tag{10}$$

Determination of Case 3

In Case 3, the cyclist reaches cruising speed after (t_2, d_2). Thus two average accelerations may occur in each period, a_1 and a_2:

$$d_1 = \frac{1}{2a}(t_1)^2 \tag{11}$$

$$d_{2'} = v_1 t_{2'} + \frac{a_2 (t_{2'})^2}{2} \tag{12}$$

From Equation 11, the following is known:

$$a_1 = \frac{2d_1}{(t_1)^2} \tag{13}$$

From Equation 12, the following is obtained:

$$a_2 = \frac{2(d_{2'} - a_1 t_1 t_{2'})}{(t_{2'})^2}$$

Because $a_2 > 0$, a feasibility constraint is that

$$d_{2'} > 2a_1 t_1 t_{2'},\ d_{2'} > v_1 t_{2'} \tag{14}$$

The distance traveled in the interval [t_1, t_2] must be longer than the distance that would be traveled if the speed at time t_1 was maintained (i.e., if $a_2 = 0$). If this condition does not hold, the bicyclist is decreasing speed (i.e., $a_2 < 0$), and the speed profile is no longer a nondecreasing function of time. This situation is not what is usually expected from a cyclist that crosses an intersection from a standing position; a bicyclist's intuitive behavior would be to break to reach a standing position. This latter case naturally brings up the final case.

Determination of Case 4

Given a cyclist in a standing position, Cases 1 to 3 have assumed a positive acceleration until the cyclist eventually reaches cruising speed (i.e., the speed profile is nondecreasing). However, in Case 4 the cyclist does not have a nondecreasing speed profile and does not fit any of the previous cases. For example, the cyclist may accelerate to a maximum speed and then decelerate to a final cruising speed.

Distributions of Acceleration and Speed

With the use of two time and distance measurements and the formulas presented in this section, it was possible to classify a bicyclist's performance case, acceleration, and cruising speed value. This framework was applied to two intersections in Portland, Oregon, with data collected previously (*11*). Each bicycle crossing time was allocated to an acceleration case, and then average acceleration and cruising speed values were calculated for each bicycle rider. Through the aggregation of individual rider performance values, it was possible to put together distribution functions of average acceleration and cruising speeds. These distributions could be used to calculate average and 15th percentile values. The speed and acceleration distributions were a function of the intersection width and the chosen values for (d_1, d_2). For the sake of consistency, this research made use of $d_1 = d_2$ in all the case studies and calculations. Field data descriptions, results, and insights are provided in the following sections.

DESCRIPTION OF CASE STUDY

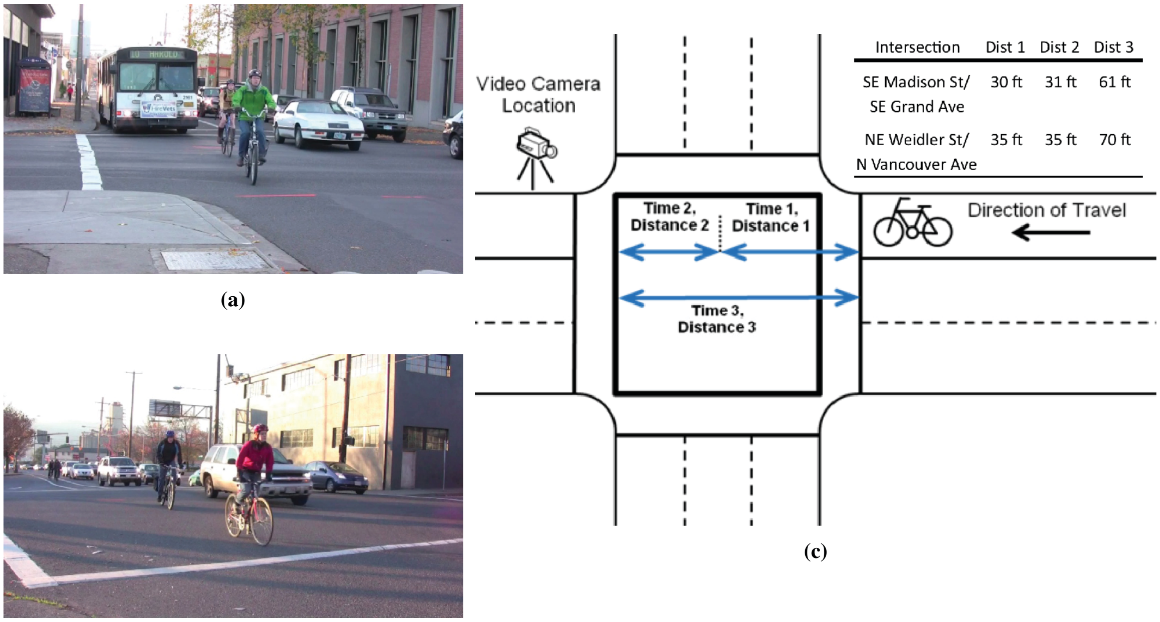
This case study included two intersections. Data were collected during the winter and summer, and these particular intersections were chosen because they were located along popular commute routes and had good pavement conditions at the time of data collection.

The first investigation, referred to here as the "flat" intersection study, was conducted at the intersection of Southeast Madison Street and Grand Avenue in Portland. Crossing-time data were collected for cyclists that traveled on Madison Street westbound and crossed Grand Avenue. Because the intersection of Madison Street and Grand Avenue was located along a popular morning commute route, data collection took place during the expected peak hours of 7 and 10:30 a.m.

The second investigation, referred to here as the "grade" intersection study, took place at the intersection of Northeast Weidler Street and North Vancouver Avenue in Portland. Crossing-time data were collected for cyclists that traveled uphill on Weidler Street eastbound and crossed Vancouver Avenue. This intersection was located along a popular commute route out of downtown Portland, and the collection period coincided with the expected afternoon peak hour period between 3 and 6:30 p.m.

Crossing-time data were obtained through video footage of the data collection. For each study, a video camera was located at the far side of the intersection (relative to the direction of bike traffic), on the sidewalk adjacent to the bike lane. This position provided a view of the cyclists as they approached the intersection, stopped at the near side of the intersection on a red light, and traveled through the intersection on a green light.

Figure 1 shows the view from the video camera at each intersection and a diagram of the field setup. For consistency, researchers collected data only from the cyclists that (*a*) came to a complete



Intersection	Dist 1	Dist 2	Dist 3
SE Madison St/ SE Grand Ave	30 ft	31 ft	61 ft
NE Weidler St/ N Vancouver Ave	35 ft	35 ft	70 ft

(a)

(b)

(c)

Intersection	Female		Male		Total	
	Winter	Summer	Winter	Summer	Winter	Summer
SE Madison St/ SE Grand Ave	50	52	50	97	100	149
NE Weidler St/ N Vancouver Ave	42	29	47	55	89	84

(d)

FIGURE 1 Data collection setup and summary: video camera perspective of (*a*) level intersection study on Madison Street and (*b*) grade intersection study on Weidler Street; (*c*) field setup diagram with intersection distance measurements; and (*d*) summary of cyclists by group (dist = distance; SE = southeast; st = street; NE = northeast; N = north; ave = avenue).

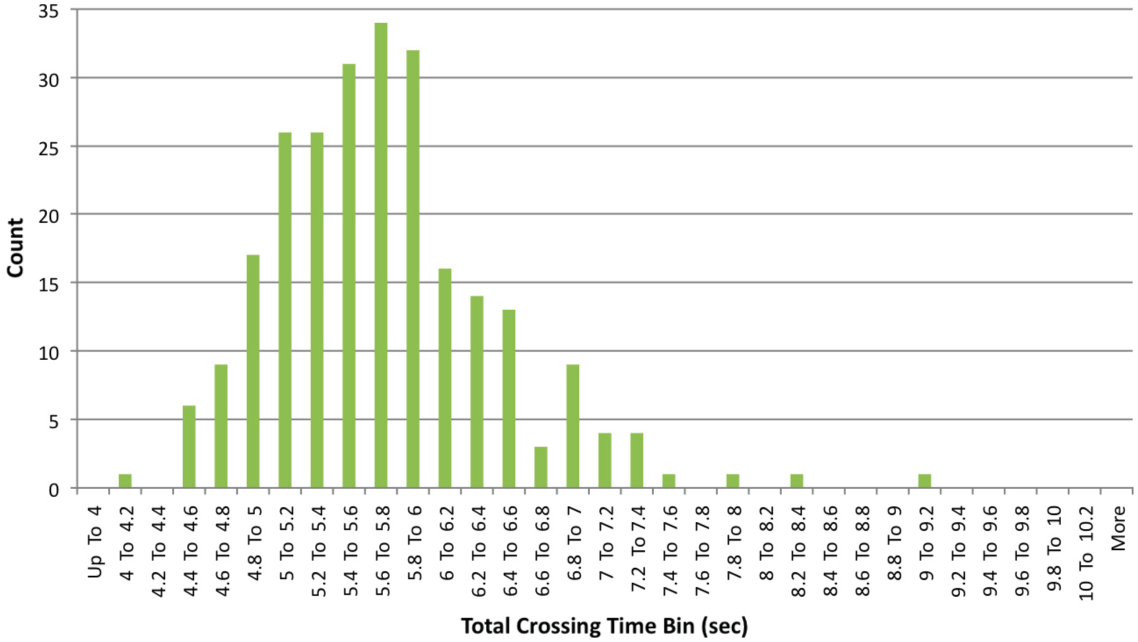


FIGURE 2 Total crossing time for flat intersection (n = 249).

stop at the intersection, (b) stopped at the first crosswalk line and were the first cyclists in a queue, and (c) had at least one foot on the ground. These parameters allowed researchers to capture the reaction and start-up time required for a cyclist from the same reference point, and eliminated cyclists that balanced on their bike before they received a green. Perception and reaction time was not included in the following measurements.

Each intersection was divided into two sections: a painted pavement line midway through the intersection that separated Distances 1 and 2 ($d_{1'}$ and $d_{2'}$ with the notation in the previous section). Distance 3 = $d_{1'} + d_{2'}$ referred to the entire intersection and was the sum of the previous two. During each data collection, two collectors were present to film and collect rider and bicycle characteristics.

Figures 2 and 3 present the total crossing time ($d_{1'} + d_{2'}$) distributions with the same scale to facilitate comparisons. As shown in the figures, the crossing times were skewed toward the left. Both the flat and grade intersections showed a long tail of cyclists, which fell to the right and had longer than average crossing times. It was easily observed that the flat intersection had shorter crossing times and less spread standard deviation than the grade intersection.

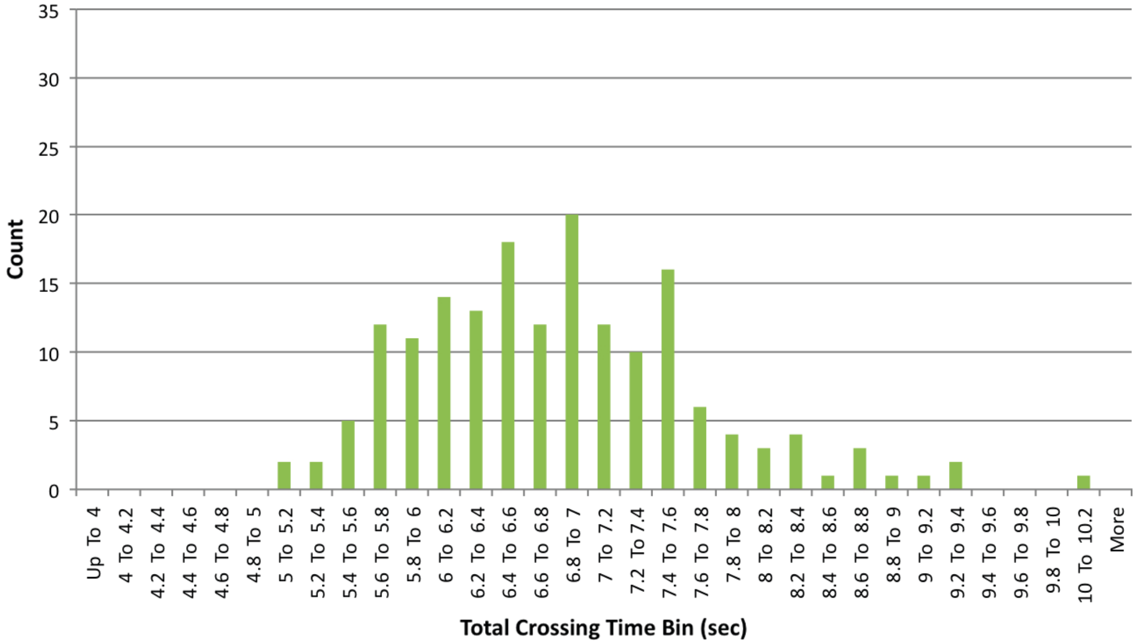


FIGURE 3 Total crossing time for grade intersection (n = 173).

TABLE 1 ***t*-Test Between Mean Crossing Times and Noncentral *t*-Test Between 85th Percentile Crossing Times: Flat Intersection**

Crossing Time[a]	*t*-Test Between Mean Crossing Times (s)				*t*-Test Between 85th Percentile Crossing Times (s)				
	μ_{female}	μ_{male}	*t*-Statistic	*p*-Value	$\mu_{\text{female,85th}}$	$\mu_{\text{male,85th}}$	*t*-Statistic	$t_{0.05,247}$	*p*-Value
$t_{1'}$	3.71	3.61	1.41	1.61 E–01	4.05	4.15	–1.43	–1.19	7.95 E–02
$t_{2'}$	2.22	2.05	4.92***	1.00 E–04	2.45	2.25	5.60***	2.34	9.58 E–07
$t_{1'} + t_{2'}$	5.93	5.65	3.07**	2.40 E–03	6.49	6.31	1.97**	0.54	1.10 E–03

[a] Female versus male.
* >95% significance; ** >99% significance; *** >99.9% significance.

TABLE 2 ***t*-Test Between Mean Crossing Times and Noncentral *t*-Test Between 85th Percentile Crossing Times: Grade Intersection**

Crossing Time[a]	*t*-Test Between Mean Crossing Times (s)				*t*-Test Between 85th Percentile Crossing Times (s)				
	μ_{female}	μ_{male}	*t*-Statistic	*p*-Value	$\mu_{\text{female, 85th}}$	$\mu_{\text{male, 85th}}$	*t*-Statistic	$t_{0.05,171}$	*p*-Value
$t_{1'}$	4.84	4.39	4.79***	1.00 E–04	5.65	4.90	7.83***	4.75	5.24 E–06
$t_{2'}$	2.49	2.14	6.72***	1.00 E–04	2.85	2.49	6.87***	1.82	1.53 E–10
$t_{1'} + t_{2'}$	7.34	6.53	6.59***	1.00 E–04	8.35	7.39	7.88***	2.95	6.06 E–10

[a] Female versus male.
* >95% significance; ** >99% significance; *** >99.9% significance.

ACCELERATION AND PERFORMANCE

Tables 1 and 2 show results from the statistical analysis of crossing times at the flat and grade intersections, respectively. Comparisons were made with the unpaired *t*-test and noncentral *t*-test, and the female and male demographics were studied.

The comparison of gender groups at the flat intersection (Table 1) shows that the mean and 85th percentile crossing times were statistically significantly different. Females had a longer crossing time at a significance level greater than 99% only in the second interval.

The comparison of gender groups at the grade intersection (Table 2) shows that the mean and 85th percentile crossing times $t_{1'}$, $t_{2'}$ and $t_{1'} + t_{2'}$ were statistically significantly different. Females had a longer crossing time at a significance level greater than 99.9%. These results suggest that males tend to achieve higher acceleration and speeds on grades, which is consistent with previous results in the literature.

The results here seemed to indicate that males tended to go faster in the second period in the flat intersection and in both periods in the grade intersection. The interpretation of the differences between groups was facilitated when the acceleration cases developed earlier were applied. The results are shown in Table 3. At the flat intersection, males had a greater tendency to keep increasing their speed in the second half of the intersection (more Case 2 and 3 types). As expected, both groups at the grade intersection required more time to reach cruising speeds. At the flat intersection, both groups tended to achieve a cruising speed in the second part or even after the intersection. The chi-square tests indicated a significant difference (>99%) between the distribution of acceleration cases at the flat and grade intersections (Case 4 observations were zero and were not included in the chi-square test).

TABLE 3 **Acceleration Case by Gender**

Intersection	Group	Percentage by Case			
		1	2	3	4
Flat	Female	98	2	0	0
	Male	82	12	6	0
Grade	Female	45	51	4	0
	Male	46	44	10	0

At the flat intersection, most cyclists reached cruising speed in the first half of the intersection (Case 1), with a few cyclists in Case 2, and even fewer in Case 3. However, at the grade intersection most cyclists were identified as Case 1. Compared with what occurred in the flat intersection, a greater percentage of cyclists still accelerated through the second half of the intersection. Thus the grade must have had an impact on riders. Cyclists continued to accelerate over a longer distance on a grade.

Figures 4 and 5 present histograms of accelerations for the flat and grade intersection studies. It was clear that the values of the acceleration at the flat intersection were significantly higher than those at the grade intersection. Tables 4 and 5 show that at the flat intersection there was no statistically significant difference between the male and female cyclist mean and 15th percentile acceleration for both study periods. However, the mean cruising velocities showed a statistically significant difference (with 99.9% significance) in both study periods; male cyclists achieved greater speed than female cyclists. As indicated previously, this finding suggested that, although the rate of acceleration was not significantly different, male cyclists continued to accelerate for a longer period of time than female cyclists and reached a greater cruising speed. This finding was consistent with the finding of acceleration case distributions discussed previously in which a greater percentage of male cyclists were identified as Case 2 and Case 3 at the flat intersection, and who reached cruising speed

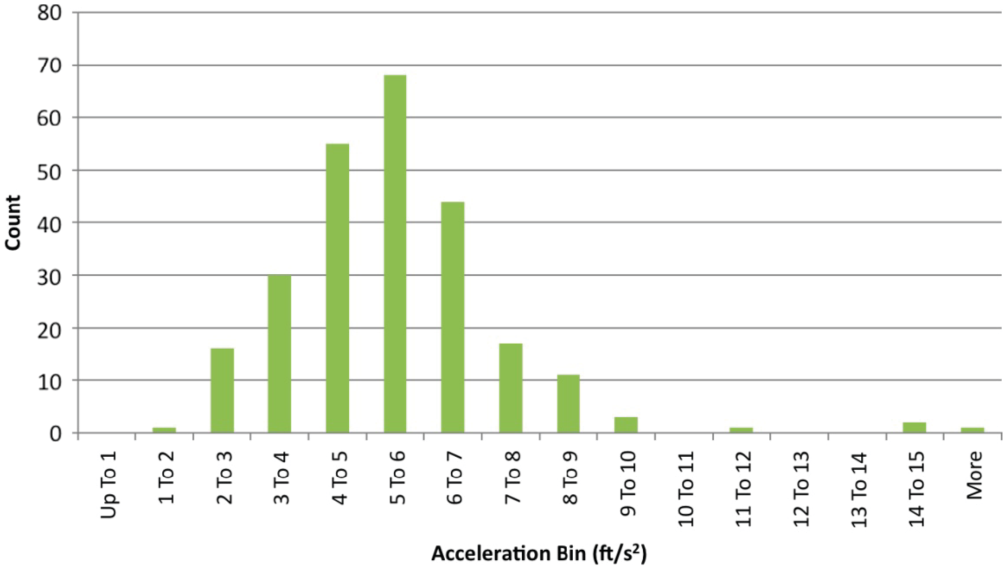


FIGURE 4 Accelerations for flat intersection (n = 249).

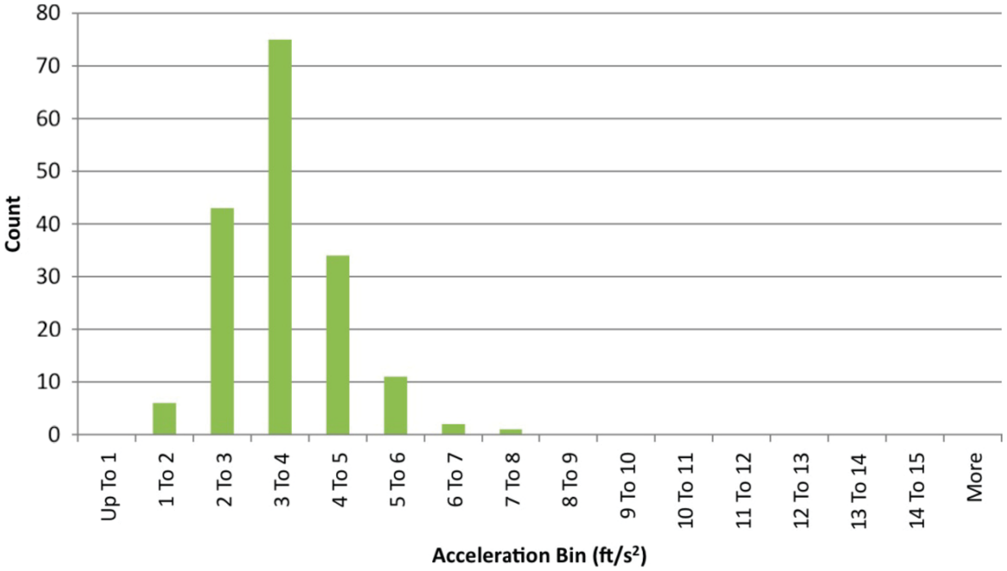


FIGURE 5 Accelerations for grade intersection (n = 172).

TABLE 4 Unpaired t-Tests Between Mean Acceleration and Cruising Speed

	Level Intersection				Grade Intersection			
Condition[a]	μ_{female}	μ_{male}	t-Statistic	p-Value	μ_{female}	μ_{male}	t-Statistic	p-Value
Winter								
a	4.90	5.06	0.60	5.51 E–01	3.34	3.78	2.40*	1.84 E–02
V_c	13.61	15.24	5.28***	0	14.26	16.23	4.19***	7.00 E–05
Summer								
a	5.36	6.15	1.56	1.20 E–01	2.90	3.88	4.40***	3.00 E–05
V_c	13.77	14.87	3.45***	7.40 E–04	15.22	17.71	4.34***	4.00 E–05

[a]Female versus male.
* >95% significance; ** >99% significance; *** >99.9% significance.

TABLE 5 Noncentral *t*-Tests on 15th Percentile Acceleration and Cruising Speed

	Level Intersection					Grade Intersection				
Condition[a]	$\mu_{\text{female,15th}}$	$\mu_{\text{male,15th}}$	*t*-Statistic	$t_{0.05,98}$	*p*-Value	$\mu_{\text{female,15th}}$	$\mu_{\text{male,15th}}$	*t*-Statistic	$t_{0.05,86}$	*p*-Value
Winter										
a	3.76	3.35	–1.52	–0.47	2.76 E–01	2.49	2.91	2.30**	1.56	9.10 E–03
V_c	11.85	13.64	5.78***	2.17	5.28 E–07	12.73	13.70	2.06***	–0.48	1.80 E–05
Summer										
a	3.98	4.05	0.14	0.22	5.91 E–02	2.00	2.94	4.22***	1.49	1.54 E–05
V_c	12.50	13.33	2.61***	0.81	3.29 E–04	12.04	14.93	5.03***	2.37	2.73 E–05

[a] Female versus male.
* >95% significance; ** >99% significance; *** >99.9% significance.

in the second half of the intersection or beyond. At the grade intersection, there were statistically significant differences; male cyclists achieved greater acceleration. This finding seemed to verify the physical impact of the hill on acceleration and cruising speed, which was evident when performance by gender was examined.

DISCUSSION OF RESULTS

Current AASHTO (*5*) and Caltrans (*6*) guidelines recommend field measurements or an acceleration of 1.5 ft/s^2 and a bicycle cruising speed of 14.7 ft/s. A recent survey found that the assumed speed was 18.7 ft/s in the timing plans for some bicycle-specific signals (*5*).

In the Portland case, the application of the AASHTO and Caltrans guidelines resulted in 10.6 s and 11.2 s for the flat and grade intersections, respectively. The flat intersection had a width of 61 ft, and the grade intersection had a width of 70 ft. The field measurement of the 85th percentile of crossing times indicated that these values were 6.4 s and 7.8 s, respectively, for the flat and grade intersections. If 1 s for perception–reaction time was added (as suggested by AASHTO), the crossing time was estimated to be 7.4 s and 8.8 s, respectively (Figures 2 and 3).

A comparison of the acceleration and speed values from Table 5 and the existing guidelines indicated that the biggest difference was found in the value of acceleration (higher in the field) and that the speeds in the field actually were less than 14.7 ft/s for riders that started from the stopped position. The application of an assumed speed of 14.7 ft/s (higher than the field-observed 15th percentile of 13 ft/s) over a wider intersection also helped to reduce the difference between calculated and field minimum green crossing times. The existing guidelines call for 3.2 and 2.4 s longer green times for the flat and grade intersections, respectively. The existing guidelines add 30% and 21% more crossing times than the 85th percentile does for flat and grade intersections, respectively. AASHTO's recommended values are closer to the 98th percentile, but they are still higher than the observed 98th percentile. Adequate yellow and all-red time also is critical to ensure the safety of bicyclists that start to cross the intersection as the signal turns yellow.

In the Portland case, longer green times were not an issue because these intersections had a high volume of cyclists. It also was clear that the engineer should provide signal times that would be appropriate under less favorable conditions (e.g., weather, bicycle queuing). In some cases, however, such additional times, could have a significant accumulated impact on vehicle delays, fuel consumption, and emissions if the green time was provided at a minor crossing (with no pedestrian crossing request) and the red was extended for the main congested arterial.

The methodology proposed in this paper can be used to estimate field distributions of acceleration and cruising speeds and to justify longer crossing times when a special type of rider needs special accommodation (e.g., young riders near schools). It is always good practice to add room for additional safety through the use of lower-than-AASHTO-suggested acceleration or crossing speed. However, it is recommended that the additional safety be justified through field estimations of acceleration and speed distributions, especially if safer and more comfortable bicycle traffic signal designs generate high costs in delays, fuel consumption, and emissions.

CONCLUSIONS

The research described in this paper demonstrates how field-collected observations from a basic video setup can be used to successfully estimate design acceleration and speed values with the use of equations of motion. It shows that it is not trivial to obtain distributions of cyclists' acceleration and speed distributions. The proposed analytical procedure allows for further statistical analysis of cyclist acceleration and cruising speed performance by demographic group and intersection grade (if these data are collected), or to justify longer crossing times when a special type of rider needs special accommodation (e.g., young riders near schools; older riders near a retirement home). Findings from the statistical analysis were intuitive and consistent with the expected performance of bicycle riders by gender and intersection grade.

The existing policy guidelines [i.e., AASHTO, Caltrans, and NACTO (*5–7*)] require that an adequate clearance interval be provided, and they recommend that, in the determination of this minimum interval, bicyclist speeds undergo field investigation. Clearly, as other work has shown, the performance values derived for a particular intersection crossing location depend on intersection location, the type of cyclist, and the time of the data collection. Traffic engineers should be cognizant of this dependency when they deploy data collection equipment and reduce data for analysis. In particular, field estimations of acceleration and speed distributions should be provided if bicycle traffic signal designs that exceed AASHTO-recommended values result in high costs in terms of delays, fuel consumption, and emissions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Oregon Transportation, Research, and Education Consortium, the Oregon Department of Transportation, and FHWA for sponsoring parts of this research.

Ryan Conrad provided assistance with data collection and analysis of the crossing time data for the initial study (*11*).

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The Bicycle Transportation Committee peer-reviewed this paper.