A Methodology to Estimate Bicyclists’ Acceleration and Speed Design Values to Calculate Minimum Green Times at Signalized Intersections

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ABSTRACT
As cities across North America install new infrastructure to accommodate a growing number and variety of bicyclists, installation of bicycle-specific traffic signals is a common design element. A recent survey has shown that there is a lack of consistency in their design and timing. In particular, minimum green signal timing is highly dependent on the assumed acceleration and speed performance of bicyclists’ but there is no detailed methodology to estimate these performance values. The purpose of this research is to develop and apply a general methodology to estimate bicyclists’ acceleration and speed for traffic signal timing applications. Utilizing physical equations of motion, this research analytically derives expressions that can be used to classify individual bicyclist’s performance as function of the observed acceleration profile. The analysis indicates that four basic acceleration profiles are possible and the profiles can be obtained using a parsimonious field data collection method. The methodology is successfully applied to two intersections in Portland, Oregon. A detailed statistical analysis of the results shows that the results are intuitive and that the methodology successfully categorizes bicyclists’ performance variations due to topography or demographic characteristics. The case study shows that formulas contained in the guidance documents tend to overestimate minimum green crossing times.

Keywords: bicycle performance, speed, acceleration, minimum green time
1. INTRODUCTION

Many cities in the North America are making significant investments in bicycling infrastructure to improve cycling conditions. This is in part motivated by research that indicates that in order to grow bicycle ridership facilities should be designed to accommodate all riders, particularly those demographic groups that may not otherwise choose to cycle in the typical urban setting because riding is a stressful experience (1).

A majority of bicycle-vehicle crashes in urban areas occur at intersections (2). Thus, traffic signal timing plays a significant role to make cycling a safe and attractive option for people as a means to travel around the city. Because urban intersections must accommodate motor vehicles, pedestrians, and cyclists and the performance of these users varies between and within groups, the setting of many timing parameters is a delicate balance. 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. On the other hand, inadequately short bicycle-specific minimum green times can create stressful, uncomfortable and even unsafe bicycle environments (3). Because there may be performance differences among cycling demographics, it is possible that only strong or high performance riders may have the acceleration/speed necessary to clear an intersection safely in situations where clearance and green time may be minimal. However, a user who requires more time to cross comfortably (such as a child or older cyclist) may be caught midway through the intersection when opposing traffic receives a green. This situation is not only unsafe but can also be seen as a deterrent to bicycling as a viable mode choice alternative.

To adequately balance the needs of the population of bicycle riders and other intersection users, it is vital to understand the performance of bicycle riders. There is extensive literature and professional experience describing operational strategies and design issues of traffic signals for motorized vehicles and pedestrians. In contrast, the literature and engineering experience for bicycle-specific signal design is newer and relatively scarce. A recent survey (4) indicates there is a lack of consistency across North American cities regarding bicycle signal design, detection, and timing parameters.

There is a relatively wide range of published cyclist performance data (perception-reaction times, rolling speed, and accelerations) that can be used to guide the selection of basic signal parameters such as minimum green, yellow and all red clearance intervals, and extension times. The new AASHTO (5), Caltrans (6), and NACTO (7) documents require that an adequate clearance interval shall be provided and that in determining this minimum interval, field investigation of bicyclists’ speeds is recommended. The guide suggests intervals sufficient for 15th percentile speeds should be used. Absent field data, the guides suggest that a value of approximately 15 ft/sec may be used as a default speed.

While the guidance documents (5-7) recommend field obtained values and 15th percentile speeds, there is no consistent methodology to determine field speeds or acceleration. Furthermore, as later discussed in this research, the determination of field bicyclists’ acceleration and cruising speed is not a trivial exercise. In the literature, there is no comprehensive mathematical framework to estimate bicycle riders acceleration and cruising speeds at intersections.

The purpose and main contribution of this research is to develop and apply a general mathematical framework to estimate bicyclists’ acceleration and cruising speed for traffic signal timing applications to data that can be extracted from a simple video data collection procedure.
By analyzing physical equations of motion, this research analytically derives expressions that can be used to classify individual bicyclist’s performance as function of the observed acceleration profile. In turn, the acceleration profile can be used to classify the individual bicyclist’s performance at an intersection and the performance of different demographics and acceleration/speed distributions. Finally, recommended minimum green times obtained from current guidance documents are compared to field estimations using 85th percentile crossing times.

2. LITERATURE REVIEW

The recently released 2012 AASHTO Guide for the Development of Bicycle Facilities provides a revised treatment of the information that relates bicyclists’ 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 named “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. Both acceleration and crossing speeds must be known to estimate minimum green crossing times. For a bicycle starting from a stopped position the default acceleration value is 1.5 ft/s²; the default rolling speed is 10 mph or 14.7 ft/s.

For rolling cyclists, the guide also 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. 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” (pp 4-46). The guide suggests modifying the all-red time, or if that is insufficient, to provide for extension time using a dedicated bicycle detector and controller settings to add sufficient time to clear the intersection.

A speed of approximately 10 mph (14.7 ft/sec) is now cited in the latest bicycle design guides AASHTO (5), Caltrans (6), and NACTO (7) documents as an assumed rolling speed. The NACTO (6) 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 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, the NACTO guide suggests that “14 feet per second (9.5 miles per hour) may be used as a default speed.”

The AASHTO guide (4) provides a formula to estimate minimum green for bicycles from a standing position:

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

where:

- \(BMG\) = Bicycle minimum green interval (sec)
- \(PRT\) = Perception and reaction time, 1 (sec)
- \(Y\) = Length of yellow interval (sec)
- \(R_{\text{clear}}\) = Length all red clearance interval (sec)
- \(W\) = Intersection width (feet)
\[ L = \text{Typical bicycle length} = 6 \text{ (feet)} \]
\[ a = \text{Bicycle acceleration} = 1.5 \text{ (feet/sec}^2\text{)} \]
\[ V = \text{Bicycle crossing speed} = 14.7 \text{ (feet/sec)} \]

The California Manual on Uniform Traffic Control Devices (6) provides detection guidance and also provides provisions on the minimum timing parameters. 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 6 seconds, according the formula:

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

where:

- \( G_{\text{min}} \) = Length of minimum green interval (sec)
- \( Y \) = Length of yellow interval (sec)
- \( R_{\text{clear}} \) = Length of red clearance 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 (1 second), speed (14.7 ft/sec), and acceleration (1.5 ft/sec^2), the first two terms of the AASHTO equation (1) are approximately 6 seconds.

\[ PRT + \frac{V}{2a} \approx 6 \text{ sec}. \]

Empirical evidence indicates that there is wide range of acceleration and speed performance that may need to be accommodated based on individual locations (8-11). Most published studies have used different measurements techniques to derive these values. Wachtel et al. (8), one of the first studies about bicyclists’ minimum green time, highlights that the most common signal timing issue related to vehicle-bicycle collisions; that of a cyclist hit after lawfully entering an intersection on a yellow phase by a motorist on the intersecting street restarting or accelerating into the intersection upon receiving a green phase. 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. If the signal provides only a minimum green time designed for motor vehicles (a result of low vehicle demand), the green time may not be long enough to accommodate the time needed for cyclists to react, accelerate and traverse the intersection, especially at wide intersections and/or in situations where multiple cyclists may have formed a queue.

A handful of studies have been conducted to measure average speeds and accelerations and compare them to the guidance documents. Pein measured the average speed and approximated the acceleration of cyclists on multi-use paths (MUPs) and at 3-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 when comparing flat and uphill intersections (11). An FHWA report
investigated trail users, collecting data from active and passive study participants using skateboards, kick scooters, tandem cycles, manual and power wheelchairs, electric bicycles, inline skates, hand cycles, among several other emerging trail user types (12). When studying the cyclist group, the study found that after an initial increase in the acceleration rate, the rate decreases with increasing speed—counter to the AASHTO equation, which assumes a constant acceleration (5). More recently researchers used video image and processing software to extract each cyclist’s trajectory through the intersection (13-14). The trajectories were synchronized to signal phases and were used to determine startup time and cruising speed through intersections. The study presented evidence that performance varies by intersection population; e.g., at a location populated mainly by recreational cyclists and families, speeds were found to be slower than a location largely made up of commuting college students.

Bicyclists’ demographics do affect performance (11,15, 16). Research by Navin found that young males achieve higher speeds than average when climbing 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 uphill roadways (17).

3. THE ACCELERATION AND SPEED DETERMINATION PROBLEM

The determination of field bicyclists’ acceleration and speed is recommended by the guidance documents (4-6) as well as the utilization of 15th percentile speeds. However, no methodology to determine field speeds or acceleration is provided. It should be noted that automated methods to extract object trajectories from video data are possible (e.g. 18), though not widely available.

Even if 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, starting from a standing position initial speed is zero and it takes a time \( t_c \) to reach cruising speed. The change of speed is in turn a function the acceleration \( a \) from time zero \( t_0 \) (the time when bicyclists’ movement is imminent) to the 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). Hence, many potential acceleration values can be observed in a second by second trajectory analysis. To compare against guidance acceleration and speed values, it is necessary to have a consistent methodology, derived from fundamental physics equations of motion, to obtain representative average acceleration and speed values.

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 \( v_c \), assuming constant acceleration, the time to reach cruising speed is \( t_c = v_c / a \) and the distance traveled is equal to \( d_c = 1/2a(t_c)^2 = (v_c)^2 / 2a \).

The time elapsed up to the first observations is equal to:

\[
t_f = t_c + (t_f - t_c) = t_c + (d_i - d_c) / v_c \quad (1)
\]

Replacing \( v_c = t_c a \) and \( d_c = (v_c)^2 / 2a \) into (1):

\[
t_f = \frac{v_c}{a} + \frac{d_i - (v_c)^2 / 2a}{v_c}
\]
In equation (2) there are two values that are known from measurement \((t_1, d_1)\) and two unknowns, \(v_c\) and \(a\). Hence, the problem is indeterminate. It is not possible to estimate both values simultaneously. This indetermination can be broken by taking another observation. 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 starting at time/distance \((t_0, d_0)\).

Without loss of generality let’s assume that \(t_1 < t_2\) and \(d_1 < d_2\). Using the observations \((t_1, d_1)\) and \((t_2, d_2)\) it is possible to have four different acceleration profiles based on the point at which each bicycle rider has finished accelerating (i.e., the cyclist has reached a cruising speed). These cases are described as follows:

- **Case 1:** The cyclist reaches cruising speed within at or before reaching the time/distance \((t_1, d_1)\).
- **Case 2:** The cyclist reaches cruising speed after \((t_1, d_1)\) but before reaching \((t_2, d_2)\).
- **Case 3:** The cyclist reaches cruising speed after \((t_2, d_2)\).
- **Case 4:** The cyclist does not have a non-decreasing speed profile.

To simplify the notation and expressions, the prime symbol is introduced to denote the differences, for example, the partial time/distance between observation 1 and 2 are denoted:

\[
t_{2'} = t_2 - t_1
\]
\[
d_{2'} = d_2 - d_1
\]

Similarly, the partial time/distance between observation 0 and 1 are denoted:

\[
t_{1'} = t_1 - t_0
\]
\[
d_{1'} = d_1 - d_0
\]

### Determining Case 1

The cyclist reaches cruising speed within at or before reaching the time/distance \((t_1, d_1)\), hence, it is possible to solve the indeterminacy because the second period is travelled at a cruising speed:

\[
v_c = (d_2 - d_1) / (t_2 - t_1) = d_2' / t_2'
\]

Replacing (3) into (2) we obtain the value of \(a\):

\[
t_j = \frac{d_2'}{2at_2'} + \frac{d_jt_2'}{d_2'},
\]
Given that accelerations cannot be negative, Case 1 holds when this obvious inequality is valid:

\[
\frac{d_z}{d_j} > \frac{t_y}{t_j}
\]

**Determining Case 2**

The cyclist reaches cruising speed after \((t_1, d_1)\) but before reaching \((t_2, d_2)\), hence, in case 2 we can estimate the acceleration in the first period:

\[
a = \frac{d_z}{2t_y(t_1 - \frac{d_1}{d_z}t_y)} \quad (4)
\]

\[
t_c = \frac{v_c}{a}
\]

However, \(t_c\) and \(v_c\) are still unknown. In this case, \(v_c\) is reached in the time interval \([t_j, t_2]\) and equation (2) must be written as:

\[
t_2 = \frac{v_c}{2a} + \frac{d_z}{v_c} \quad (6)
\]

Expressing equation (6) as a 2\(^{nd}\) order equation:

\[
\frac{(v_c)^2}{2a} - t_2v_c + d_z = 0
\]

Replacing, we obtain:

\[
v_c = at_z \pm \sqrt{(at_z)^2 - 2ad_z} \quad (7)
\]

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

\[
(at_z)^2 - 2ad_z > 0
\]

\[
t_2^2 > 2d_z/a
\]

From the analysis of equation (7) only one root may be feasible. This root is infeasible:

\[
v_c = at_z + \sqrt{(at_z)^2 - 2ad_z} \quad (8)
\]

This is proved because the cruising speed must satisfy \(v_c \leq at_z\) (i.e., in Case 2 the cruising speed is assumed to be reached in the time interval \([t_j, t_2]\)).
For the only potentially feasible root, see 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).

\[ v_c = at_2 - \sqrt{(at_2)^2 - 2ad_2} \quad (9) \]

\[ t_1a \leq v_c \leq t_2a \quad (10) \]

**Determining Case 3**

For Case 3, the cyclist reaches cruising speed after \((t_2, d_2)\). Hence, we may have two average accelerations in each period, \(a_1\) and \(a_2\):

\[ d_i = \frac{1}{2}a(t_i)^2 \quad (11) \]

\[ d_2' = v_1t_2' + \frac{a_2(t_2')^2}{2} \quad (12) \]

From (11) we know that:

\[ a_1 = \frac{2d_1}{(t_1)^2} \quad (13) \]

From (12) we obtain:

\[ a_2 = \frac{2(d_2' - a_1t_1t_2')}{(t_2')^2} \quad (14) \]

Since \(a_2 > 0\), a feasibility constraint is that:

\[ d_2' > 2a_1t_1t_2', \quad d_2' > v_1t_2' \quad (14) \]

The distance traveled in the interval \([t_1, t_2]\) must be larger than the distance that would be traveled if the speed at time \(t_1\) is maintained, i.e. if \(a_2 = 0\). If this condition does not hold, the bicyclists is decreasing its speed, i.e. \(a_2 < 0\), and the speed profile is no longer a non-decreasing function of time. This is not what is usually expected from a cyclists crossing an intersection from a standing position; it would be the intuitive behavior is the bicyclists is breaking to reach a standing position. This latter case naturally brings up the final case 4.

**Determining Case 4**

From a standing position Cases 1 to 3 have assumed a positive acceleration until the cyclists eventually reaches the cruising speed, (i.e, the speed profile is non-decreasing). However, in Case 4 the cyclist does not have a non-decreasing 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.
Determining Acceleration and Speed Distributions

Utilizing two time/distance measurements and the formulas presented in this section, it is possible to classify a bicyclists’ performance case, acceleration, and cruising speed value. This framework is applied to two intersections in Portland, Oregon utilizing data previously collected (11). Each bicycle crossing time is allocated to an acceleration case and then average acceleration and cruising speed values are calculated for each bicycle rider. Aggregating individual bicycle rider performance values it is possible to put together distribution functions of average acceleration and cruising speeds. These distributions can be used to calculate average and 15th percentile values. Field data description, results and insights are provided in the following sections.

4. CASE STUDY DESCRIPTION

Two intersections are included in this case study. Data have been collected both during the winter and summer periods and these particular intersections were chosen because they are located along popular commute routes and they had good pavement conditions at the time of data collection.

The first investigation, referred hereafter as the “flat” intersection study, is the intersection of SE Madison Street and SE Grand Avenue in Portland, Oregon. Crossing time data were collected for cyclists traveling on SE Madison Street westbound and crossing SE Grand Avenue. Because the intersection of SE Madison Street and SE Grand Avenue is located along a popular morning commute route, data collection took place during the expected morning peak hour between 7:00 AM and 10:30 AM.

The second investigation, referred hereafter as the “grade” intersection study, was the intersection of NE Weidler Street and N Vancouver Avenue in Portland, Oregon. Crossing time data were collected for cyclists traveling uphill on NE Weidler Street eastbound and crossing N Vancouver Avenue. This intersection is located along a popular commute route leaving downtown Portland, so the collection period coincided with the expected afternoon peak period between 3:00 PM and 6:30 PM.

Crossing time data were obtained using video footage of the data collection. For each intersection, 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 provided a view of the cyclists approaching the intersection, stopping at the near-side of the intersection on a red light, and traveling 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; in Figure 1, clockwise from top left: video camera perspective for the level intersection study on SE Madison, field setup diagram with intersection distance measurements, summary of cyclists by group, and video camera perspective for the grade intersection on NE Weidler facing west. For consistency, researchers collected data only from the cyclists that: 1) came to a complete stop at the intersection, 2) stopped at the first crosswalk line and were the first cyclists in a queue, and 3) who had at least one foot on the ground. This allowed researchers to capture the reaction and startup time required for a cyclist from the same reference point, and eliminated cyclists that were balancing on their bike before receiving a green. Perception and reaction time is not included in the following measurements.
FIGURE 1. Data collection setup and summary.

Each intersection was divided into two sections; a line midway through the intersection was painted on the pavement to separate distance 1 and distance 2 ($d_1'$ and $d_2'$ using the notation in the previous section); distance $3 = d_1' + d_2'$ refers to the entire intersection and it is the sum of the previous two. During each data collection, two data collectors were present to film and to collect rider and bicycle characteristics.

Figure 2 and Figure 3 present the total crossing time ($d_1' + d_2'$) distributions using the same scale to facilitate comparisons. As shown in the figures, the crossing times are skewed towards the left. Both the flat and grade intersections show a long “tail” of cyclists falling to the right, who had longer than average crossing times. It can be easily observed that the flat intersection has shorter crossing times and less spread/standard deviation than the grade intersection.

5. STATISTICAL ANALYSIS OF ACCELERATION AND RIDERS’ PERFORMANCE

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Female Winter</th>
<th>Female Summer</th>
<th>Male Winter</th>
<th>Male Summer</th>
<th>Total Winter</th>
<th>Total Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE Madison St/SE Grand Ave</td>
<td>50</td>
<td>52</td>
<td>50</td>
<td>97</td>
<td>100</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE Weidler St/N Vancouver Ave</td>
<td>42</td>
<td>29</td>
<td>47</td>
<td>55</td>
<td>89</td>
<td>84</td>
</tr>
</tbody>
</table>
Table 1 and Table 2 show the results from the statistical analysis of crossing times at the flat and grade intersections, respectively. Comparisons were made using the unpaired T-test and non-central T-test and studied the female and male demographics. The comparison of gender groups at the flat intersection (see
Table 1) shows that the mean and 85th percentile crossing times were statistically significantly different, with females having a longer crossing time at a significance level greater than 99% only in the second interval. Red italic values indicate > 99% significance.

**FIGURE 2** Histogram of total crossing time, flat intersection, n=249

**FIGURE 3** Histogram of total crossing time, grade intersection, n=173
TABLE 1 T-test between mean crossing times, and Noncentral T-test between 85th percentile crossing times, flat Intersection

<table>
<thead>
<tr>
<th>Crossing Time</th>
<th>T-test between Mean Crossing Times (sec)</th>
<th>T-test between 85th Percentile Crossing Times (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μfemale</td>
<td>μmale</td>
</tr>
<tr>
<td>t₁</td>
<td>3.71</td>
<td>3.61</td>
</tr>
<tr>
<td>t₂</td>
<td>2.22</td>
<td>2.05</td>
</tr>
<tr>
<td>t₁ + t₂</td>
<td>5.93</td>
<td>5.65</td>
</tr>
</tbody>
</table>

* Indicates > 95% significance, ** Indicates > 99% significance, *** Indicates > 99.9% significance

The comparison of gender groups at the grade intersection (shown in Table 2) shows that the mean and 85th percentile crossing times t₁, t₂ and t₁ + t₂ were found to be statistically significantly different, with females having a longer crossing time at significance level greater than 99.9%. These results suggest that males tend to achieve higher acceleration/speeds on grades; a result that is consistent with previous results in the literature.

TABLE 2 T-test between mean crossing times, and Noncentral T-test between 85th percentile crossing times, grade Intersection

<table>
<thead>
<tr>
<th>Crossing Time</th>
<th>T-test between Mean Crossing Times (sec)</th>
<th>T-test between 85th Percentile Crossing Times (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μfemale</td>
<td>μmale</td>
</tr>
<tr>
<td>t₁</td>
<td>4.84</td>
<td>4.39</td>
</tr>
<tr>
<td>t₂</td>
<td>2.49</td>
<td>2.14</td>
</tr>
<tr>
<td>t₁ + t₂</td>
<td>7.34</td>
<td>6.53</td>
</tr>
</tbody>
</table>

* Indicates > 95% significance, ** Indicates > 99% significance, *** Indicates > 99.9% significance

Results seem to indicate that males tend 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 is facilitated when the acceleration cases developed in Section 3 are applied; the results are shown in Table 3. At the flat intersection, males have a higher tendency to keep increasing their speed in the second half of the intersection (more case 2 and 3 cases). As expected, both groups at the grade intersection require more time to reach cruising speeds. At the flat intersection both groups tend to achieve a cruising speed in the second part or even after the intersection. The chi-square tests indicate that there is a significant difference (>99%) between the distribution of acceleration cases at the flat and grade intersection (case 4 observations are zero and were not included in the chi-square test).

At the flat intersection, the majority of cyclists reach cruising speed in the first half of the intersection (Case 1), with few cyclists in Case 2, and even fewer in Case 3. However, at the grade intersection, most the cyclists are identified as Case 1, but in comparison to the flat intersection, a greater percentage of cyclists are still accelerating through the second half of the intersection. This means that the grade must impact riders in such a way that cyclists continue to accelerate over a longer distance on a grade.
TABLE 3  Acceleration Case by Gender (%)

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Group</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>Female</td>
<td>98</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>82</td>
<td>12</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Grade</td>
<td>Female</td>
<td>45</td>
<td>51</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>46</td>
<td>44</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4 and 5 present histograms of accelerations for the flat and grade intersection studies. It is clear that the values of the acceleration at the flat intersection are significantly higher than those at the flat intersection. Table 4 and 5 show that at the flat intersection, there is no statistically significant difference between male and female cyclist mean and 15th percentile acceleration for both study periods. However, the mean cruising velocities show a statistically significant difference (with 99.9% significance) in both study periods; male cyclists achieve greater speed in comparison to female cyclists. As indicated previously, this suggests that although the rate of acceleration is not significantly different, male cyclists continue to accelerate for a longer period of time than female cyclists, reaching a greater cruising speed. This is consistent with the finding of acceleration case distributions discussed previously, where a greater percentage of male cyclists were identified as Case 2 and 3 at the flat intersection reaching cruising speed in the second half of the intersection or beyond. At the grade intersection there are statistically significant differences, with male cyclists achieving greater acceleration. This seems to verify that there is a physical impact of the hill on acceleration and cruising speed, which is evident when looking at performance by gender.
FIGURE 4  Histogram of accelerations, flat intersection, n=249

FIGURE 5  Histogram of accelerations, grade intersection, n=172
6. COMPARISON WITH EXISTING GUIDELINES

Current AASHTO (4) and CALTRANS (5) guidelines recommend field measurements or an acceleration of 1.5 ft/sec² and a bicycle cruising speeds of 14.7 (feet/sec). The application of the AASHTO and CALTRANS guidelines result in 10.6 seconds and 11.2 seconds for the flat and grade intersection respectively; the flat intersection has a W = 61 feet and the grade intersection a W = 70 feet. The field measurement of the 85th percentile of crossing times indicate these values are 6.4 seconds and 7.8 seconds respectively for the flat and grade intersection. If one second for perception and reaction time is added (as suggested by AASHTO), then the crossing time is estimated as 7.4 and 8.8 seconds respectively (see Figures 2 and 3).

The existing guidelines are adding 3.2 seconds and 2.4 seconds of green time for the flat and grade intersection respectively. These additional times can have a significant accumulated impact on vehicle delays, fuel consumption, and emissions if the green time is provided on a minor crossing (with no pedestrian crossing request) and the red is extended for the main congested arterial. Percentage-wise, the existing guidelines are adding 30% and 21% of crossing times when compared to the 85th percentile for flat and grade intersections respectively. The AASHTO recommended values are closer to the 98th percentile but they are still higher than the observed 98th percentile.

A comparison of the acceleration and speed values from Table 5 and the existing guidelines indicates that the biggest difference is found in the value of acceleration (higher in the field) and that speeds in the field are actually less than 14.7 ft/sec. The data suggests that a value of 1.5 ft/sec² is too low and should be adjusted for Portland riders to no less than 2.0 ft/sec² for a
grade intersection and 3.0 ft/sec$^2$ for a flat intersection. The field observed acceleration for the grade intersection is closer to the AASHTO and Caltrans values; hence, the lower percentage-wise difference in green crossing times between calculated (guidelines) and field measurements or the grade intersection. The application of an assumed speed of 14.7 ft/sec (higher than the field observed 15$^{th}$ percentile of 13 ft/sec) over a wider intersection also helps to reduce the difference between calculated and field minimum green crossing times.

Finally, according to Table 3, the population of riders fit within Case 1, Case 2, or Case 3 of the acceleration profiles was described in Section 3. However, conceptually, the formula proposed in the AASHTO guidelines does not fit exactly within any of the acceleration profile cases. The lack of direct connection between the physical equations of motion and guidelines formulas may lead to inefficiencies. Although it is always good practice to include room for additional safety terms, it may be better if the additional safety term is explicit in the calculation so that the traffic engineers are aware of its existence and value.

7. CONCLUSIONS

This paper demonstrated how field-collected observations from a basic video setup can be successfully used to estimate design acceleration and speed values using equations of motion. This analytical procedure allows for further statistical analysis of cyclist acceleration and cruising speed performance by demographic groups and intersection grade (if these data are collected). Findings from the statistical analysis are intuitive and consistent with the expected performance of bicycle riders by gender and intersection grade.

The existing policy guidelines (AASHTO, Caltrans, NACTO) require that an adequate clearance interval be provided and that in determining this minimum interval, field investigation of bicyclists’ speeds is recommended. The guides suggest intervals sufficient for 15$^{th}$ percentile speeds should be used. Field data observations indicate that the suggested values provided by the formula and guidelines default values tend to overestimate minimum crossing times for Portland’s, Oregon, bicycle riders. In particular, default acceleration values seem to be lower than observed field values; default cruising speed values seem to be slightly higher than observed field values. Clearly, as other work has shown, the performance values derived for a particular intersection crossing location depend on the location of the intersection, the type of cyclist, and the time of the data collection. Engineers should be cognizant of this issue when deploying data collection equipment and reducing data for analysis.

It is recommended that additional research efforts focus on the estimation of field acceleration and speed values and the derivation of a minimum green crossing time formula that more closely resemble physical equations of movement and explicitly considers a safety factor. Guidance should be provided to adjust default values based on geometric and demographic parameters if feasible. A more accurate determination of minimum green times will allow for safer and more comfortable bicycle traffic signal design without generating unnecessary costs in terms of delays, fuel consumption, and emissions.

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