

guide for the development of bicycle facilities



American Association
of State Highway and
Transportation Officials

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Bicycles at Modern Roundabouts

Generally there are three ways to accommodate bicyclists in roundabouts: 1) in mixed flow with vehicular traffic, 2) along separate bicycle paths, and 3) on bicycle lanes along the outside diameter of roundabouts (not currently recommended).

The following safety issues should be considered when contemplating bicycles in roundabouts:

- Bicyclists are vulnerable users of roundabouts and consideration should be given for their accommodation.
- In low-speed [approximately 20 km/hr (12 mph)], single-lane roundabouts, few negative safety impacts have been observed when bicycles are mixed in the traffic stream. Because of the small speed differential, bicyclists are expected to circulate in the traffic lane at approximately the same speed as vehicles. When bike lanes lead to this type of roundabout, it is preferable to discontinue them 10 to 20 m (35 to 65 feet) before reaching the roundabout, rather than continuing the lane through the roundabout.
- Bicycle safety tends to deteriorate at higher speed, multi-lane roundabouts and at flared entries. At these roundabouts, special solutions should be sought when warranted by bicycle volumes. Among the possible solutions are separate bikeways, shared use of the pedestrian facility, separate bike routing through other intersections, or grade separation for the vulnerable modes.

A majority of bike crashes at roundabouts involve entering vehicles and circulating bicycles, reinforcing the need to reduce entering speeds by providing ample deflection, to maintain good visibility for entering traffic and to enforce yield conditions for entering traffic.

Traffic Signals

At signalized intersections where bicycle traffic exists or is anticipated, the timing of the traffic signal cycle, as well as the method of detecting the presence of the bicyclists, should be considered. In mixed traffic flow the bicyclist normally can cross the intersection under the same signal phase as motor vehicles. The greatest risk to bicyclists is during the clearance interval and during the actuated phases during periods of low traffic flow. Signals should be designed to provide an adequate clearance interval for bicyclists who enter at the end of the green and a total crossing time (minimum green plus clearance interval) long enough to accommodate bicyclists starting up on a new green.

The length of the yellow change interval is dependent upon the speed of approaching traffic. Yellow change intervals adequate for motorists (generally 3.0 s to 6.0 s) are usually adequate for bicyclists. Generally, an all-red clearance interval is not required, but can be used to allow the cyclist who entered the intersection during the yellow interval to clear the



intersection before the conflicting movement receives the green signal. The all-red clearance interval normally ranges from 1.0 s to 2.0 s. The total clearance interval (yellow change interval plus red clearance interval) can be calculated from:¹²

For Metric Units:

$$y + r_{\text{clear}} \geq t_r + \frac{v}{2b} + \frac{w+l}{v}$$

where:

- y = yellow interval(s)
- r_{clear} = red clearance interval(s)
- t_r = reaction time (1.0 s)
- v = bicyclist speed (m/s)
- b = bicyclist braking deceleration (1.2 to 2.5 m/s²)
- w = width of crossing (m)
- l = bicycle length (1.8 m)

For English Units:

$$y + r_{\text{clear}} \geq t_r + \frac{v}{2b} + \frac{w+l}{v}$$

- y = yellow interval(s)
- r_{clear} = red clearance interval(s)
- t_r = reaction time (1.0 s)
- v = bicyclist speed (mph)
- b = bicyclist braking deceleration (4 to 8 ft/s²)
- w = width of crossing (ft)
- l = bicycle length (6 ft)

If field observations are not available, approximately 98 percent of cyclists should be able to clear signals timed for the following speeds: 19 km/h (5.3 m/s) [12 mph (17.6 ft/sec)] for Group A cyclists, 13 km/h (3.6 m/s) [8 mph (12.0 ft/sec)] for Group B cyclists, and 10 km/h (2.8 m/s) [6 mph (9.1 ft/sec)] for Group C cyclists. Approximately 85 percent of cyclists can clear signals timed for speeds 20 percent higher. If local practice does not permit this long a red clearance interval (as given by the equation), the longest red clearance interval consistent with local practice should be used.

When an approach receives a green signal, the bicyclist needs enough time to react, accelerate and cross the intersection. The general equation to determine the minimum green time is:¹²

For Metric Units:

$$g + y + r_{\text{clear}} \geq t_{\text{cross}} = t_r + \frac{v}{2a} + \frac{w+l}{v}$$

where;

- g = minimum green
- y, r_{clear} = yellow and red clearance intervals actually used
- t_{cross} = Time to cross the intersection
- t_r = Reaction time (2.5 s)
- v = Bicycle speed (m/s)
- a = Bicycle acceleration (0.5 - 1.0 m/s²)
- w = Width of crossing (m)
- l = Bicycle length (1.8 m)

For English Units:

$$g + y + r_{\text{clear}} \geq t_{\text{cross}} = t_r + \frac{v}{2a} + \frac{w+l}{v}$$

- g = minimum green
- y, r_{clear} = yellow and red clearance intervals actually used
- t_{cross} = Time to cross the intersection
- t_r = Reaction time (2.5 s)
- v = Bicycle speed (ft/s)
- a = Bicycle acceleration (1.5 - 3 ft/s²)
- w = Width of crossing (ft)
- l = Bicycle length (6 ft)

However, as with all calculated signal timing, actual field observations should be undertaken prior to making any adjustments to the minimum green or clearance intervals. Acute angle intersections require longer crossing times for bicyclists.

Detection of bicycles at traffic-actuated signals is crucial for bicyclists' safety and for compliance with traffic laws. Detectors that have been placed for vehicular traffic can usually detect the presence of bicycles. Quadrupole and diagonal-type loop detectors are examples of induction



loops that provide bicycle detection. Dipole and rectangular loops can also detect bicycles if the detector sensitivity is adjusted. Efforts should be made to ensure that signal detection devices are capable of detecting a bicycle and that the total green plus clearance time (yellow plus all-red) is sufficient for the bicyclist to cross the intersection safely.

Detectors for traffic-actuated signals should be located in the bicyclist's expected path, including left-turn lanes and shoulders. It may also be helpful to the bicyclist if the road surface is marked to indicate the optimum location for bicycle detection. Figure 29 shows the standard pavement symbol which should be placed at the location of a bicycle loop detector to notify the cyclist where to stop.

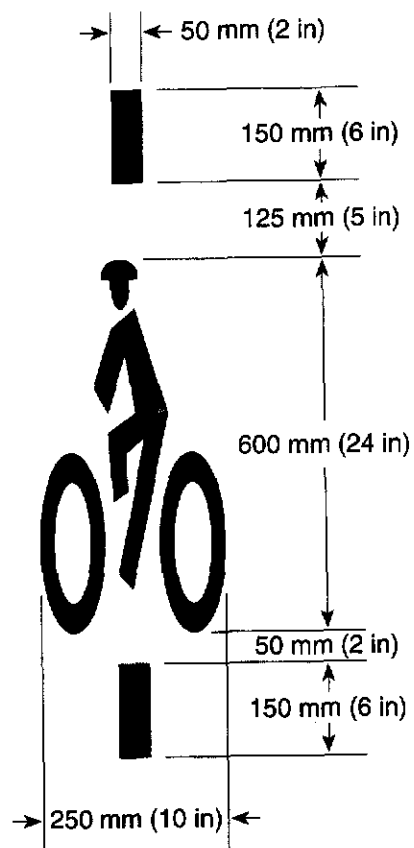


Figure 29. Bicycle detector pavement marking

In some situations, the use of pedestrian- or bicyclist-actuated buttons may be an acceptable alternative to the use of detectors provided they do not require bicyclists to dismount or make unsafe leaning movements. However, actuated buttons should not be considered a substitute for detectors.



Signal Clearance Timing for Bicyclists

BY ALAN WACHTEL, JOHN FORESTER AND DAVID PELZ

Bicycle clearance-time conflicts, in which a motor vehicle hits a bicyclist who has entered a signalized intersection lawfully but has been unable to clear it before the signal changes, are a significant cause of bicycle-motor vehicle collisions. It has been estimated that these accidents constitute 6 percent of urban car/bike collisions, the largest facility-associated cause.¹

These conflicts typically occur when a bicyclist traveling on a minor street that carries slow and infrequent traffic and has a short signal phase, crosses a wide, usually multilane major street or arterial that carries high-speed traffic. (We refer to these as the minor and major streets, but in some cases the "minor street" may also be a major street.) Most often, the conflict occurs at the far side of the intersection, in the outside lane of the major street. A motorist on the cyclist's right starts up or speeds up in this lane as the light turns green, while traffic still clearing the intersection is hidden by vehicles waiting in the inside lanes.

In most cases the motorist has disobeyed the law by entering an intersection without ensuring that traffic already there has cleared. It is important to understand why these accidents do occur, and to devise an appropriate countermeasure.

Clearance timing for automobiles is an important safety issue that is intensely controversial among engineers.² It is even more important for bicyclists, who are exposed to greater risk of clearance-time accidents (as well as injury) than

motorists, for the following reasons:

■ Motor vehicles are larger than bicycles and more easily seen. Moreover, the bicycle and rider are low and easily shielded from view by the hoods of motor vehicles. To a motorist whose view is blocked by traffic in the inside lanes, sometimes only the bicyclist's head is visible.

■ Motor vehicles typically travel farther from the right-hand side of the road than bicyclists, affording motorists on the cross street a better angle of view and a greater distance to correct a mistake.

■ Motor vehicles move into view and clear the intersection more quickly than most bicyclists.

Bicycling is becoming more popular for both transportation and recreation, and traffic law everywhere in the United States requires bicyclists to obey vehicular rules of the road, including signal indications. Many traffic engineers are being asked by local bicycle advocates to modify timing at traffic-actuated signals. There are currently no standards for signal timing to accommodate bicycle traffic, although Forester,¹ and more recently Taylor,³ Abbaszadeh⁴ and Gärder⁵ have considered certain aspects of the question. The *Manual on*

Uniform Traffic Control Devices (MUTCD) contains two sentences on this subject: "Bicycles generally can cross intersections under the same signal timing arrangement as motor vehicles. Where bicycle use is expected, extremely short change intervals should not be used and an all-red clearance interval may be necessary."⁶ While this advice is probably correct as far as it goes, it does not go very far.

In October 1992, the California Bicycle Advisory Committee, a citizens' committee that advises the California Department of Transportation, appointed a subcommittee to propose such standards. This article is based on the subcommittee's report, and provides the tools needed to respond to requests for signal retiming, or to adjust timing at intersections where bicycle clearance-time accidents are likely. Although the emphasis is on bicycles, the ideas offered should apply equally well to automobiles—in particular the calculation of risk, the importance of the minimum green interval as well as the red clearance interval in preventing clearance-time accidents, and the approach to reconciling safety considerations with traffic flow.

There are two distinct cases to consider: bicyclists who enter at full speed late in the green or during the yellow phase ("rolling start"), and those who have stopped on red and start from a new green ("standing start"). The rolling start governs the length of the yellow and red clearance intervals; the standing start governs the length of

Conversion Factors

To convert from	to	multiply by
mi	km	1.6
ft	m	0.30
mph	ft/sec	1.5
ft/sec	mph	0.68

Table 1. Bicyclist Crossing Times at Six Palo Alto Intersections

Major street	Width (ft)	Minor street	Entering on old green or yellow (rolling start)			Starting up from red on new green (standing start)		
			Number of cyclists	Mean time(s) (s/mean)	Mean speed (mph)	Number of cyclists	Mean time(s) (s/mean)	Mean speed (mph)
El Camino Real	130	Embarcadero Road	39	5.4	16.5	131	10.2 (0.22)	8.7
El Camino Real	120	Los Robles Avenue	25	5.1 (0.24)	16.2	61	11.2 (0.22)	7.3
El Camino Real	120	Park Boulevard	21	6.4	12.8	113	11.7 (0.19)	7.0
Oregon Expwy	70	Bryant Street	23	5.4 (0.35)	8.9	123	9.1 (0.36)	5.2
Oregon Expwy	90	Cowper Street	18	5.1	12.1	83	9.9 (0.24)	6.3
Oregon Expwy	110	Greer Road	13	5.9 (0.26)	12.8	39	10.5 (0.27)	7.2

the minimum green interval.

In practice there is a third category: bicyclists who approach a red signal slowly in the hope that it will change before they come to a complete stop ("semirolling start"). These bicyclists enter the intersection at some time after the signal has changed, yet at less than full speed. This article will show that this case does not need to be treated separately.

Yellow Interval

California, like most states, operates under the "permissive yellow rule," which allows vehicles to enter the intersection on yellow (called amber in some states) and to be in the intersection when the signal turns red. Our discussion of yellow and red intervals (but not of green) assumes this rule.

The *Traffic Engineering Handbook*,⁷ following an ITE Proposed Recommended Practice,⁸ gives the length of the yellow warning interval (neglecting grades) as

$$y \geq t_r + v/2b \quad (1)$$

where

t_r = reaction time

v = approach speed

b = magnitude of the vehicle's braking deceleration

For an automobile, t_r is normally taken as 1 second (sec), v as the posted speed limit or 85th percentile speed, and b as 10 feet per second² (although the California *Traffic Manual*⁹ recommends 12 ft/sec²). This is well within the braking ability of passenger cars, which almost always exceeds 20 ft/sec² and sometimes 30 ft/sec². The deceleration value therefore allows for variations in road conditions (including wet pavement) and in braking ability of vehicles

and drivers; for driver inattention, hesitation or misjudgment; and for driver and passenger comfort. The resultant yellow times should lie between approximately 3 and 6 sec, according to MUTCD¹⁰; the *Traffic Control Devices Handbook* suggests a maximum of 5 sec.¹¹

The speed of bicyclists ranges from less than 10 miles per hour (mph) for schoolchildren to 25 mph for fit adults. In June 1985, the Palo Alto (Calif.) Transportation Division timed bicyclists at six intersections where clearance-time

accidents had occurred or were considered likely to occur, based on physical characteristics and bicyclist volume. Table 1 summarizes the data collected. Bicyclists crossing El Camino Real at these intersections are predominantly high school and college students and adults; those crossing Oregon Expressway also include elementary school students. These measurements, although the best currently available, should be considered preliminary, and results derived from them are subject to confirmation, revision and local variation.

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OR CONTACT

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The Palo Alto observations show rolling-start speeds ranging from about 12 mph to 17 mph (except on Bryant crossing Oregon, where the cyclists for the most part are elementary school students). The crossing times on red (standing start) were distributed more or less normally, with the standard deviation σ averaging 0.25 of the mean (this ratio is shown in brackets). A time 1σ (about 25 percent) above mean (speed 0.8 of mean) corresponds to the 84th percentile in time (16th percentile in speed); a time 2σ (about 50 percent) above mean (speed 0.67 of mean) corresponds to the 98th percentile in time (second percentile in speed). Unfortunately, the original measurements have not been preserved, and enough information remains to determine σ for only three of the six rolling starts; in these cases the ratio of σ to mean closely matches the ratio for a standing start.

Taylor³ measured the speed of 28 university students, finding a mean of 14.1 mph, a comparable figure. He does not report standard deviation, but his 85th and 15th percentiles (approximately 1σ) are 2.5 mph (0.18 of mean) above the mean and 3.6 mph (0.26 of mean) below the mean respectively, comparable to the Palo Alto standard deviations.

According to Forester,⁴ reasonable (not maximum) braking deceleration ranges from about 8 ft/sec² for slower bicyclists using one-wheel caliper or coaster brakes to 15 ft/sec² for fast bicyclists using two-wheel caliper brakes. Taylor measured mean braking deceleration among college students as 7.5 ft/sec² and the 15th percentile as 4.2 ft/sec².

Again taking $t_r = 1$ sec, and conservatively assuming braking deceleration of 4 and 8 ft/sec² for slow and fast bicyclists respectively, yields yellow times on level roads of 2.5 sec ($v = 8$ mph, $b = 4$ ft/sec²) and 2.8 sec ($v = 20$ mph, $b = 8$ ft/sec²). For the fastest bicyclists, who can presumably brake more effectively, the value would be 2.5 sec ($v = 25$ mph, $b = 12$ ft/sec²). For comparison, the AASHTO *Guide for the Development of Bicycle Facilities*² recommends that a speed of 10 mph and an undefined "perception/reaction/braking time" of 2.5 sec be used to check clearance intervals.

Notice that the fastest bicyclists normally travel no faster than motor vehi-

cles, and the braking deceleration of the two types of vehicles is comparable; bicycle stopping time is therefore equal to or less than motor vehicle stopping time. Slower, less-experienced bicyclists can be expected to brake less effectively, but they also travel at slower speeds. Thus, in all cases, yellow intervals that are adequate for motorists should also be adequate for bicyclists. This conclusion is not sensitive to the precise values of speed and braking deceleration chosen.

Red Clearance Interval

A sufficiently long yellow interval guarantees that a reasonable driver is never forced to enter an intersection involuntarily on the red light. In the extreme case, the light turns red just as the vehicle reaches the intersection. If cross traffic immediately receives a



Alan Wachtel is vice chair of the California Bicycle Advisory Committee and chairman of the Signal Timing

Subcommittee. As a consultant, he has helped develop bicycle plans for Santa Clara and Marin counties, and the cities of Berkeley and San Francisco. He is an Associate Member of ITE.



John Forester, P.E., is a cycling transportation engineer, expert witness and educator who lives in Sunnyvale, Calif.

He is the author of Effective Cycling and Bicycle Transportation.



David Pelz, P.E., is public works director of the City of Davis, Calif., and chairman of the California Bicycle

Advisory Committee. He is a registered traffic engineer and an Associate Member of ITE.

green light, conflict occurs and a collision is possible. Traffic law resolves this conflict by requiring traffic facing a circular green signal to yield the right of way to other traffic lawfully within the intersection, but this requirement is difficult to observe, and it is clear that it is overlooked frequently. Hence it may be desirable to delay the green in order to let the intersection clear.

This clearance time can be provided by extending the yellow interval, but since entering the intersection on the yellow is not forbidden, some drivers and bicyclists can always be expected to enter from farther away on the last of the yellow, no matter what its length. This method is therefore ineffective. A better solution is to provide a red clearance interval (often called an all-red interval) long enough for the intersection to clear. This interval is determined by

$$r_{clear} \geq (w + l)/v \quad (2)$$

where

w = width of the intersection, measured from the near-side stop line to the far edge of the conflicting traffic lane

l = length of the vehicle⁷

(Alternatively, width can be measured to the farthest conflicting pedestrian crosswalk or, as for pedestrians, to the center of the farthest traffic lane, and l can be neglected, but these refinements do not materially affect the discussion.) From the standpoint of clearance-time safety, long red clearance intervals are justified at any traffic signal controlling a wide intersection. The length of the interval can be calculated from intersection width and prevailing speeds, both motor vehicle and bicycle, preferably on the basis of direct local observations. In the absence of such observations, reasonable mean bicycle speeds might be 18 mph (26 ft/sec) for fast cyclists, 12 mph (18 ft/sec) for casual adult cyclists, and 9 mph (13 ft/sec) for children. Since this is a matter of safety, the 98th percentile crossing time is proposed as a suitable cutoff, rather than the 85th (and certainly not the 85th percentile speed). If, as appears plausible from the Palo Alto data, σ is taken as 0.25 of mean crossing time, then the second percentile (2σ) speed is 0.67 of the mean. The 98th percentile time is thus only 50 percent greater than the mean and only 20 percent greater than the 85th percentile time. The fol-

lowing speeds would then accommodate approximately 98 percent of each population group: 12 mph (18 ft/sec) for fast cyclists, 8 mph (12 ft/sec) for casual adult cyclists, and 6 mph (9 ft/sec) for children.

For an automobile, $l \cong 20$ ft. Taking as an example $w = 130$ ft (Embarcadero crossing El Camino Real) and $v = 25$ mph gives a clearance time r_{clear} of 4.1 sec; at 30 mph, 3.4 sec. For a bicycle, $l \cong 6$ ft, but v may be 8 mph or less, giving a clearance time of 11.6 sec. In fact, a bicyclist who travels at 8 mph requires 4.6 sec just to clear a 48-ft intersection. Moreover, slow bicyclists are likely to keep farther to the right, making them less conspicuous and closer to cross traffic approaching from the right. Even at $v = 25$ mph, the time to cross a 130-ft intersection would still be 3.7 sec. As a rule it is not enough merely to permit cyclists to reach a median refuge, since the median may be too narrow to accommodate bicycles.

Red clearance intervals this long have a number of disadvantages:

- They seem to delay traffic on the major street. Increasing cycle length to counteract longer red times causes delay to all traffic. It is shown below, though, that a shorter red clearance must be compensated for by a longer green interval. Thus the minimum signal time devoted to the minor street remains fixed—only the proportions of green and red clearance vary. These proportions affect the capacity only of the minor street, not the major street.

- They may encourage motorists on the minor street to enter on the red, believing that they are protected. However, since this behavior, unlike entering on an old yellow, is unlawful, it might reasonably be expected to be less common.

- When no traffic is present clearing the intersection, a long red clearance interval may confuse waiting drivers, who do not understand why the signal fails to change. Such intervals are occasionally used for pedestrian clearance, but they are normally activated only when pedestrians are present.

As a result, red clearance intervals are not used everywhere, and where they are used they are usually much shorter than demanded by Equation 2. The California *Traffic Manual*, for instance, generally limits them to 2 sec, which is clearly not long enough to

eliminate all potential conflicts, even among motor vehicles. As a reasonable step toward reducing the risk of rolling-start bicycle clearance-time accidents, it makes sense to use as much red clearance interval as local practice permits.

Notice that since a bicyclist requires a yellow time of 2.5 sec to 2.8 sec, and the yellow interval at all intersections should be at least 3 sec, a bicyclist who must enter the intersection does obtain the benefit of 0.2 sec to 0.5 sec or more of yellow interval as additional clearance time.

Green Interval

The length of the minimum green interval is governed by the standing and semirolling cases, since in the worst case rolling-start bicyclists may enter the intersection on the last of the yellow and miss the green entirely. Given only the reasonable assumption that the magnitude of braking deceleration exceeds the magnitude of starting acceleration, it can be shown that a semirolling-start bicyclist is always able to overtake a standing-start bicyclist waiting at the intersection (supporting research has been omitted here for brevity). Thus semirolling starts do not need to be considered separately.

Consider a bicyclist who has stopped on red and starts from a new green (standing start). The signal phase is always longer than in the previous case, since it now includes a green interval in addition to the yellow and red clearance. The bicyclist, however, initially travels more slowly and needs more time to cross the intersection.

Suppose the bicyclist's forward acceleration is a and the maximum speed attained is v . If the maximum speed is not reached within the intersection, then the acceleration time is given by

$$w + l = at_{acc}^2/2 \quad (3)$$

$$t_{acc} = \sqrt{2(w + l)/a} \quad (4)$$

and the crossing time is

$$t_{cross} = t_r + \sqrt{2(w + l)/a} \quad (5)$$

If maximum speed is instead reached within the intersection, then the acceleration time is v/a , over the distance $v^2/2a$. The remaining $w + l - v^2/2a$ is covered at speed v , for a total time of

$$t_{cross} = t_r + v/a + (w + l - v^2/2a)/v = t_r + v/2a + (w + l)/v \quad (6)$$

Note that this expression is formally identical to the one for yellow time plus red clearance time, although the value of the acceleration is different (most likely $a \ll b$).

From our own observations we believe that a varies widely even among cyclists capable of attaining the same final speed, and depends on gearing and technique as well as strength. To obtain some empirical values, one of the authors made rough measurements of his own standing acceleration times. He found that he could accelerate from zero to 17 mph (25 ft/sec) in 7 sec, corresponding to $a = 3.6$ ft/sec² over distance $v/2 = 87$ ft. Starting in high gear and reducing the effort in order to simulate a slower bicyclist, he accelerated from zero to 10 mph (15 ft/sec) in 10 sec, corresponding to $a = 1.5$ ft/sec² over 73 ft. Since the green time must be governed by the slowest bicyclist, it seems reasonable to assume that, for wide intersections where clearance time is an issue, maximum speed is reached within the intersection.

Taylor measured mean rolling (not standing) acceleration over 150 ft as 1.4 ft/sec² (15th percentile = 0.7 ft/sec²) and over 60 ft as 3.8 ft/sec² (range 1.8–6.4 ft/sec²). Given the greater frictional resistance at low speed and greater air resistance at high speed, these numbers can be considered roughly comparable to ours.

In general, to avoid clearance-time conflicts on a new green, the sum of minimum green, yellow and red clearance must equal or exceed the crossing time from a standing start:

$$g + y + r_{clear} \geq t_{cross} \quad (7)$$

The value of t_{cross} (on a new green) can be found by direct observation. If y and r_{clear} have been set, then g can be found by subtraction. This is true whether or not y and r_{clear} conform to the values given in (1) and (2). On the plausible assumption that maximum speed is reached within the intersection, t_{cross} can alternatively be calculated from (6).

Notice, however, that an insufficient red clearance interval—that is, one shorter than given by (2)—entails a longer green interval and therefore does not shorten the total signal phase, which

is determined by t_{cross} . The longer green does increase the minor street's capacity and reduce the delay.

If maximum speed is reached within the intersection, we can draw two further related conclusions:

- For given v and a , the time needed to cross the intersection on a new green is given by (6), and the time to cross at full speed on an old green by $(w + l)/v$. The difference is fixed at $t_r + v/2a$, regardless of intersection width. This difference represents the time lost in reacting to the green light and then accelerating to full speed.

- If yellow and red clearance are given by (1) and (2) and crossing time by (6), then the minimum green is fixed at $v/2a - v/2b$.

The prediction that the difference between standing and rolling crossing times should be fixed at $t_r + v/2a$ can be tested by looking at the Palo Alto data in Table 1. The difference in average crossing times on new green and old green at the six intersections is (in seconds) 4.8, 6.1, 5.3, 3.7, 4.8 and 4.6, which is roughly constant and hence consistent with the prediction. There is no way to compare crossing times for individual bicyclists, whose speeds and acceleration times might vary. In the author's measurements described above, the acceleration time v/a varied only from about 7 sec to 10 sec, corresponding to $t_r + v/2a$ between 4.5 sec and 6 sec; these numbers correspond closely to the Palo Alto observations. (In Table 1, however, greater differences, implying longer acceleration times, are not necessarily associated with lower crossing speeds, as they were in these tests.)

Take the difference conservatively as 6 sec; 1 sec of this is reaction time, so $v/2a \cong 5$ sec (acceleration time $v/a \cong 10$ s). It was estimated earlier that yellow time is 2.5–2.8 sec; 1 sec of this is also reaction time, so $v/2b \cong 1.5$ –1.8 sec. Subtracting, the green needs to last only about 3.2 sec to 3.5 sec. Because of the uncertainty in $v/2a$ and $v/2b$, the error in this figure may be fairly large.

More accurately, rather than comparing $t_r + v/2a$ to $t_r + v/2b$, we should compare $t_r + v/2a$ (about 6 s) to the yellow interval actually provided (excluding any portion of yellow that has been assigned to reduce the succeeding red clearance). Since a yellow interval is at least 3-sec long, even 3 sec of green should be sufficient.

This calculation, of course, depends on the signal providing sufficient red clearance time for bicyclists to clear the intersection on an old green. In other words, signal phasing intended solely to promote safety, if there were no other considerations, would provide a relatively short green interval and a relatively long red clearance interval, similar to WALK and DON'T WALK indications for pedestrians. If the red-clearance time falls short of this value, which is almost certain in practice, the green time must be increased accordingly to provide clearance on the new green.

For example, consider an intersection (such as those in Palo Alto) where the slowest bicyclists need 10 sec to cross on an old green and 16 sec on a new green. For safety alone, the timing for this intersection should be 3 sec of green, 3 sec of yellow, and 10 sec of red clearance. If the red clearance interval is reduced, then the green should be increased accordingly. The shorter red and longer green reduce the intersection delay on the minor street, but provide less than optimal protection against rolling clearance-time accidents.

If the red clearance interval is inadequate, clearance-time conflict on a new green is greatest when a traffic-actuated phase shows only its minimum green interval, with no overtaking traffic to call extensions. Extending the minimum green to reduce this conflict, however, may unnecessarily delay traffic on the major street. One solution is to define a minimum green and an extension time, but to automatically incorporate one extension time when the signal phase is actuated. This method lengthens the green time for bicyclists when no other vehicles are also waiting to cross; otherwise the extensions are provided by the waiting vehicles and signal timing is unaffected.

The effect of this longer green time on traffic flow on the major street is normally minimal, except where congestion is severe or timing is tightly constrained. At peak hours the side streets are full and call a long signal phase regardless of the presence of bicyclists; at other times the major street does not need its full capacity and can tolerate longer delays (the signal is undersaturated). If necessary, the major street's green interval can also be lengthened to preserve its proportion of the signal cycle.

Risk Assessment

Since retiming a signal entails effort and affects traffic flow, it is helpful to quantify the risk of clearance-time conflicts.

Consider a steady stream of bicyclists traveling through an intersection. As the light turns yellow, a certain number are forced to enter the intersection; from equations (1) and (2) above, these bicyclists require a minimum clearance time of $t_r + v/2b + (w + l)/v$ to reach the far side safely. Suppose that at a particular intersection the yellow plus red clearance time actually provided is less than this minimum by an amount Δi_{roll} (i for interval). Then the fraction of bicyclists caught in the intersection as the light turns green for cross traffic (or the probability that an individual bicyclist will be caught in the intersection) is

$$P_{roll} = \Delta i_{roll}/C \quad (8)$$

where C is the period of the signal cycle. (Taylor derives an equivalent result by a different method, calculating the time the cyclist spends in the dilem-

ma zone where it is possible to neither stop nor clear.)

Greater values of the clearance deficit Δi_{roll} trap more bicyclists in the intersection, but they also have an additional effect: they trap each bicyclist for a longer time. Assuming as a reasonable approximation that risk is proportional both to the probability of being trapped and to the length of time trapped (on average, in this case, $\Delta i_{roll}/2$), then the risk per cyclist R is given by

$$R_{roll} = P_{roll} \Delta i_{roll}/2 = \Delta i_{roll}^2/2C \quad (9)$$

Finally, total exposure E is proportional to the volume of bicyclists crossing (V_{cyc}), measured in cyclists/h or cyclists/d:

$$E_{roll} = R_{roll} V_{cyc} = V_{cyc} \Delta i_{roll}^2/2C \quad (10)$$

where E is then measured in cyclist-s/h or cyclist-s/d.

In principle, E also depends on the volume of motor vehicle traffic per lane on the major street and on the time this traffic spends in the intersection. That traffic, however, is not flowing freely, but starting up on a new green when the

conflict occurs; the dependence is therefore likely to be weak (as long as there is some traffic waiting in the far lane) and will be neglected here. A more elaborate model would also sum over bicyclists of varying speed and braking ability, but this much detail seems superfluous; it should generally be enough to look at the worst case.

We can find a similar expression for bicyclists who enter from a standing start and are caught in the intersection. In this case we define Δi_{stand} as the difference between the crossing time t_{cross} required from a standing start and the total $g + y + r_{clear}$ time provided, if less. In fact, the probability of being caught in this situation does not depend directly on Δi_{stand} (so long as Δi_{stand} exceeds zero); rather, all bicyclists starting up on the new green are caught. To a first approximation, this is just the fraction who arrive on a red light:

$$P_{stand} = r/C \quad (11)$$

where the red interval r includes the red clearance interval r_{clear} , and cycle length $C = g + y + r$.

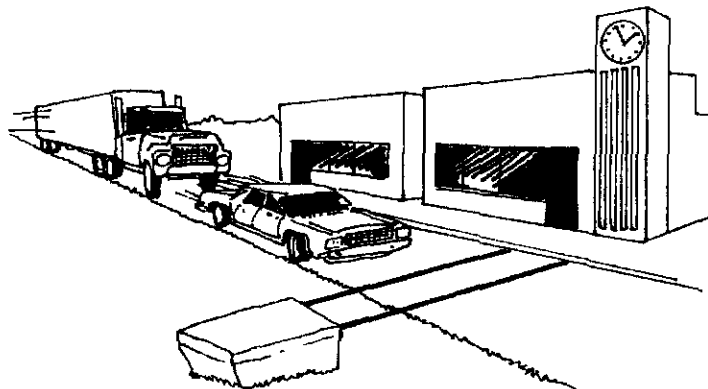
Again, there are several corrections to this expression. Consider a line drawn at the stopping distance away from the intersection. The flow of bicycle traffic is uniform approaching this line, but nonuniform beyond it if braking occurs. Then:

- Bicycle traffic reaching this line during the yellow interval y —or at least during the minimum yellow time $t_r + v/2b$ given in equation (1), about 3 s—stops at the intersection.
- Traffic reaching this line during the red interval r brakes, and most of it eventually stops at the intersection. However, bicyclists who reach this line during the last $t_r + v/b$ of the red interval (the stopping time) do not reach the intersection before the light turns green, and therefore do not stop completely. In fact, as stated earlier, they overtake bicyclists stopped at the intersection (semirolling start), and hence suffer shorter exposure to clearance-time conflicts.
- An unknown number of bicyclists intentionally achieve a semirolling start and also reduce their exposure to clearance-time conflicts.

Because the intervals involved in these corrections are small compared to r , their effects are minor, and the second and third tend to cancel the first. In

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the interest of simplicity we therefore neglect them.

The risk per cyclist is then

$$R_{stand} = P_{stand} \Delta i_{stand} = r \Delta i_{stand} / C \quad (12)$$

and the exposure is

$$E_{stand} = R_{stand} V_{cyc} = V_{cyc} r \Delta i_{stand} / C \quad (13)$$

The total exposure for both rolling and standing starts then becomes

$$E_{total} = E_{roll} + E_{stand} = (V_{cyc} / 2C) (\Delta i_{roll}^2 + 2r \Delta i_{stand}) \quad (14)$$

where the first term in the sum is due to the rolling start and the second to the standing start.

This expression for E_{total} can be applied in three ways:

- To prioritize intersections that are already candidates for retiming.
- To identify intersections that would benefit from retiming, by comparing E_{total} with some threshold value. The appropriate threshold should be determined by further study and measurements.
- To determine the measures that most effectively reduce risk.

In particular, equation (14) reveals how to obtain the greatest benefit from retiming a signal. The clearance deficits Δi_{roll} and Δi_{stand} are never greater than approximately 10 sec, and often are much less. At an intersection with a major street, the red time r on the minor street is never less than about 30 sec, and often is much greater. The second term in equation (14)—especially given its factor of 2—therefore dominates. In other words, the most likely victims of clearance-time accidents are the large number of bicyclists waiting at a red light who start up on a new green (reflected in the numbers of cyclists observed in Table 1), rather than the relatively small number who are unlucky enough to be caught as the yellow light turns red.

Fortunately this conflict is also the easiest to resolve. The standing clearance deficit Δi_{stand} can be reduced to zero (at least for a reasonable range of bicyclists) by providing a long-enough green interval, as calculated earlier, either as minimum green alone or by incorporating a mandatory extension. If necessary, in order to preserve traffic flow on the major street, its green

interval can be lengthened in proportion (although, as also explained earlier, this can often be avoided); the greater red interval on the minor street is harmless as long as Δi_{stand} is close to zero.

No green interval, no matter how long, can directly prevent rolling-start accidents. Dealing with these accidents requires setting Δi_{roll} to zero, which means providing a long-enough red clearance interval. Since the intervals needed are so large, this will usually not be done. Nonetheless, providing some red clearance interval reduces the risk, particularly because Δi_{roll} appears as a square in equation (14).

Conclusion

Again, the numbers given here are based on preliminary data, which should be verified by further measurements in different locations, and the analysis itself should be tested to see whether it produces satisfactory results.

A practical means of reducing clearance-time accidents is to provide as long a red clearance interval as local policy permits, in order to reduce the hazard on rolling starts, and a total crossing time (minimum green plus yellow plus red clearance) long enough to eliminate the hazard on standing starts.

Individual intervals are determined according to the rules discussed in this article. In principle, these rules apply at all traffic signals where bicycles are permitted. In practice, they will be of greatest benefit at intersections where one or more of the following is true:

- Bicycle clearance-time accidents have occurred.
- Physical characteristics (such as width) and bicyclist volume make such accidents likely, as evaluated either by the risk assessment method proposed above or simply by inspection.
- A bike-laned street or a signed bicycle route crosses a major street.

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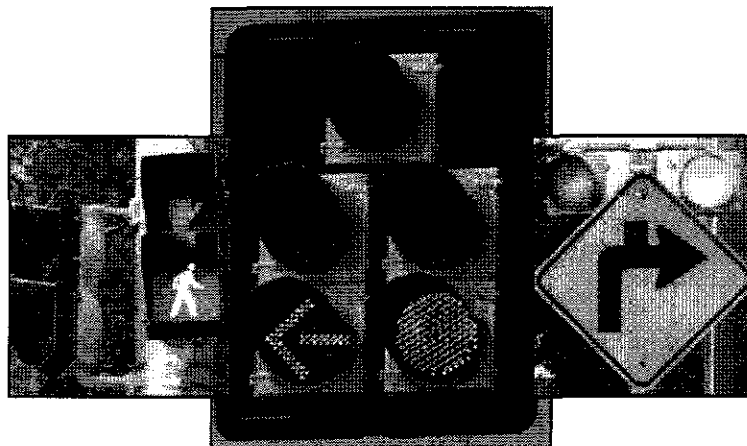
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Manual on Uniform Traffic Control Devices

for Streets and Highways

2003 EDITION

Part 4
Highway Traffic Signals



U.S. Department of Transportation
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Administration



MUTCD-1

22. **Highway Traffic Signal**—a power-operated traffic control device by which traffic is warned or directed to take some specific action. These devices do not include signals at toll plazas, power-operated signs, illuminated pavement markers, warning lights (see Section 6F.78), or steady-burning electric lamps.
23. **In-Roadway Lights**—a special type of highway traffic signal installed in the roadway surface to warn road users that they are approaching a condition on or adjacent to the roadway that might not be readily apparent and might require the road users to slow down and/or come to a stop.
24. **Intersection**—(a) the area embraced within the prolongation or connection of the lateral curb lines, or if none, the lateral boundary lines of the roadways of two highways that join one another at, or approximately at, right angles, or the area within which vehicles traveling on different highways that join at any other angle might come into conflict; (b) the junction of an alley or driveway with a roadway or highway shall not constitute an intersection.
25. **Intersection Control Beacon**—a beacon used only at an intersection to control two or more directions of travel.
26. **Interval**—the part of a signal cycle during which signal indications do not change.
27. **Interval Sequence**—the order of appearance of signal indications during successive intervals of a signal cycle.
28. **Lane-Use Control Signal**—a signal face displaying signal indications to permit or prohibit the use of specific lanes of a roadway or to indicate the impending prohibition of such use.
29. **Lens**—see Signal Lens.
30. **Louver**—see Signal Louver.
31. **Major Street**—the street normally carrying the higher volume of vehicular traffic.
32. **Malfunction Management Unit**—same as Conflict Monitor.
33. **Minor Street**—the street normally carrying the lower volume of vehicular traffic.
34. **Movable Bridge Resistance Gate**—a type of traffic gate, which is located downstream of the movable bridge warning gate, that provides a physical deterrent to vehicle and/or pedestrian traffic when placed in the appropriate position.
35. **Movable Bridge Signal**—a highway traffic signal installed at a movable bridge to notify traffic to stop during periods when the roadway is closed to allow the bridge to open.
36. **Movable Bridge Warning Gate**—a type of traffic gate designed to warn, but not primarily to block, vehicle and/or pedestrian traffic when placed in the appropriate position.
37. **Pedestrian Change Interval**—an interval during which the flashing UPRAISED HAND (symbolizing DONT WALK) signal indication is displayed. When a verbal message is provided at an accessible pedestrian signal, the verbal message is “wait.”
38. **Pedestrian Clearance Time**—the time provided for a pedestrian crossing in a crosswalk, after leaving the curb or shoulder, to travel to the far side of the traveled way or to a median.
39. **Pedestrian Signal Head**—a signal head, which contains the symbols WALKING PERSON (symbolizing WALK) and UPRAISED HAND (symbolizing DONT WALK), that is installed to direct pedestrian traffic at a traffic control signal.
40. **Permissive Mode**—a mode of traffic control signal operation in which, when a CIRCULAR GREEN signal indication is displayed, left or right turns are permitted to be made after yielding to pedestrians and/or oncoming traffic.
41. **Platoon**—a group of vehicles or pedestrians traveling together as a group, either voluntarily or involuntarily, because of traffic signal controls, geometrics, or other factors.
42. **Preemption Control**—the transfer of normal operation of a traffic control signal to a special control mode of operation.
43. **Pretimed Operation**—a type of traffic control signal operation in which none of the signal phases function on the basis of actuation.
44. **Priority Control**—a means by which the assignment of right-of-way is obtained or modified.
45. **Protected Mode**—a mode of traffic control signal operation in which left or right turns are permitted to be made when a left or right GREEN ARROW signal indication is displayed.
46. **Pushbutton**—a button to activate pedestrian timing.
47. **Pushbutton Locator Tone**—a repeating sound that informs approaching pedestrians that they are required to push a button to actuate pedestrian timing and that enables pedestrians who have visual disabilities to locate the pushbutton.
48. **Ramp Control Signal**—a highway traffic signal installed to control the flow of traffic onto a freeway at an entrance ramp or at a freeway-to-freeway ramp connection.
49. **Ramp Meter**—see Ramp Control Signal.
50. **Red Clearance Interval**—an optional interval that follows a yellow change interval and precedes the next conflicting green interval.

- F. Provide spare equipment to minimize the interruption of traffic control signal operation as a result of equipment failure;
- G. Provide for the availability of properly skilled maintenance personnel for the repair of all components; and
- H. Maintain the appearance of the signal displays and equipment.

Section 4D.03 Provisions for Pedestrians

Support:

Chapter 4E contains additional information regarding pedestrian signals.

Standard:

The design and operation of traffic control signals shall take into consideration the needs of pedestrian as well as vehicular traffic.

If engineering judgment indicates the need for provisions for a given pedestrian movement, signal faces conveniently visible to pedestrians shall be provided by pedestrian signal heads or a signal face for an adjacent vehicular movement.

Guidance:

Safety considerations should include the installation, where appropriate, of accessible pedestrian signals (see Sections 4E.06 and 4E.09) that provide information in nonvisual format (such as audible tones, verbal messages, and/or vibrating surfaces).

Where pedestrian movements regularly occur, pedestrians should be provided with sufficient time to cross the roadway by adjusting the traffic control signal operation and timing to provide sufficient crossing time every cycle or by providing pedestrian detectors.

Option:

If it is desirable to prohibit certain pedestrian movements at a traffic control signal, a PEDESTRIANS PROHIBITED (R9-3) or No Pedestrian Crossing (R9-3a) sign may be used (see Section 2B.44).

Section 4D.04 Meaning of Vehicular Signal Indications

Support:

The "Uniform Vehicle Code" (see Section 1A.11) is the primary source for the standards for the meaning of vehicular signal indications to both vehicle operators and pedestrians as set forth below, and the standards for the meaning of separate pedestrian signal indications as set forth in Section 4E.02.

Standard:

The following meanings shall be given to highway traffic signal indications for vehicles and pedestrians:

A. Steady green signal indications shall have the following meanings:

1. Traffic, except pedestrians, facing a CIRCULAR GREEN signal indication is permitted to proceed straight through or turn right or left except as such movement is modified by lane-use signs, turn prohibition signs, lane markings, or roadway design. But vehicular traffic, including vehicles turning right or left, shall yield the right-of-way to other vehicles, and to pedestrians lawfully within the intersection or an adjacent crosswalk, at the time such signal indication is exhibited.
2. Traffic, except pedestrians, facing a GREEN ARROW signal indication, shown alone or in combination with another signal indication, is permitted to cautiously enter the intersection only to make the movement indicated by such arrow, or such other movement as is permitted by other signal indications shown at the same time. Such vehicular traffic shall yield the right-of-way to pedestrians lawfully within an adjacent crosswalk and to other traffic lawfully using the intersection.
3. Unless otherwise directed by a pedestrian signal head, pedestrians facing any green signal indication, except when the sole green signal indication is a turn arrow, are permitted to proceed across the roadway within any marked or unmarked crosswalk. The pedestrian shall yield the right-of-way to vehicles lawfully within the intersection at the time that the green signal indication is first shown.

B. Steady yellow signal indications shall have the following meanings:

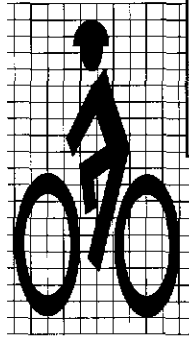
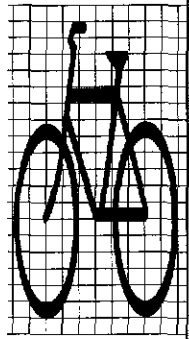
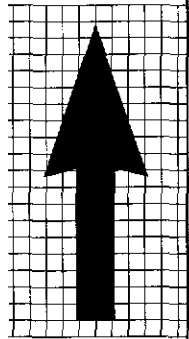
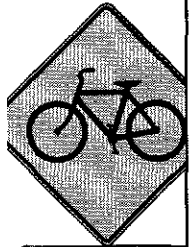
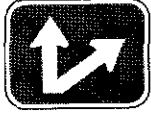
1. Traffic, except pedestrians, facing a steady CIRCULAR YELLOW or YELLOW ARROW signal indication is thereby warned that the related green movement is being terminated or that a red signal indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.

BEGIN
RIGHT TURN LANE



LANE

YIELD TO



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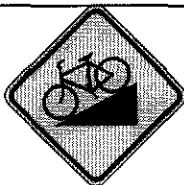
Part 9 Traffic Controls for Bicycle Facilities



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MUT CD-4

CHAPTER 9D. SIGNALS

Section 9D.01 Application

Support:

Part 4 contains information regarding signal warrants and other requirements relating to signal installations.

Option:

For purposes of signal warrant evaluation, bicyclists may be counted as either vehicles or pedestrians.

Section 9D.02 Signal Operations for Bicycles

Standard:

At installations where visibility-limited signal faces 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.

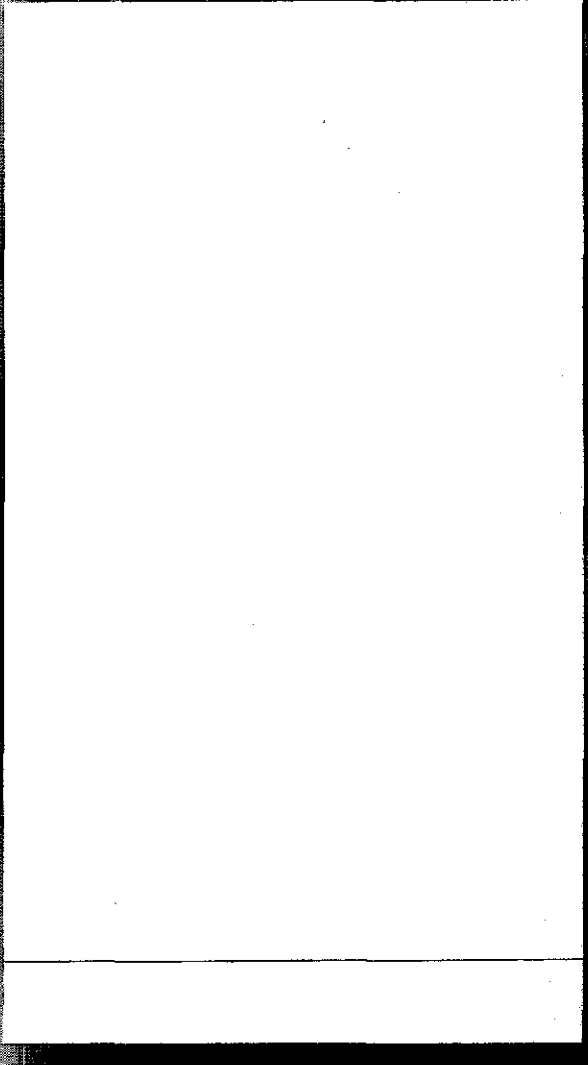
On bikeways, signal timing and actuation shall be reviewed and adjusted to consider the needs of bicyclists.



STATUS REPORT

INSURANCE INSTITUTE
FOR HIGHWAY SAFETY

Vol. 36, No. 4, April 28, 1971



YELLOW LIGHTS: Small changes in the timing of signal lights could reduce crashes at urban intersections

More than one million crashes occur annually at U.S. intersections with traffic signals. To reduce these, officials in many cities are using red light cameras to reduce deliberate signal violations (see p.1). New research indicates that retiming yellow signal lights also would reduce crashes.

The yellow light phase plus the very short all-red phase that follows the yellow light at many intersections is known as a change interval. Research has established that the duration of this interval can affect the chance of inadvertent red light running. Based in part on research conducted by the Institute during the 1980s (see *Status Report*, July 14, 1984), the Institute of Transportation Engineers (ITE) adopted a proposal for establishing the duration of traffic signal change intervals. A recent Institute study shows the recommendations are effective.

In particular, modifying change intervals in accordance with ITE's proposed recommendations can reduce the risk of crashes involving pedestrians and bicyclists. Such modifications also may reduce the overall risk of multiple-vehicle crashes, particularly crashes involving injuries.

Working with state and local transportation officials in New York, Institute researchers identified 122 standard four-leg intersections on Long Island. For the study, roughly half of these intersections were designated as controls and half were considered for signal retiming. Application of the ITE formulas indicated that the duration of the change intervals should be modified at 40 of the 51 experimental sites.

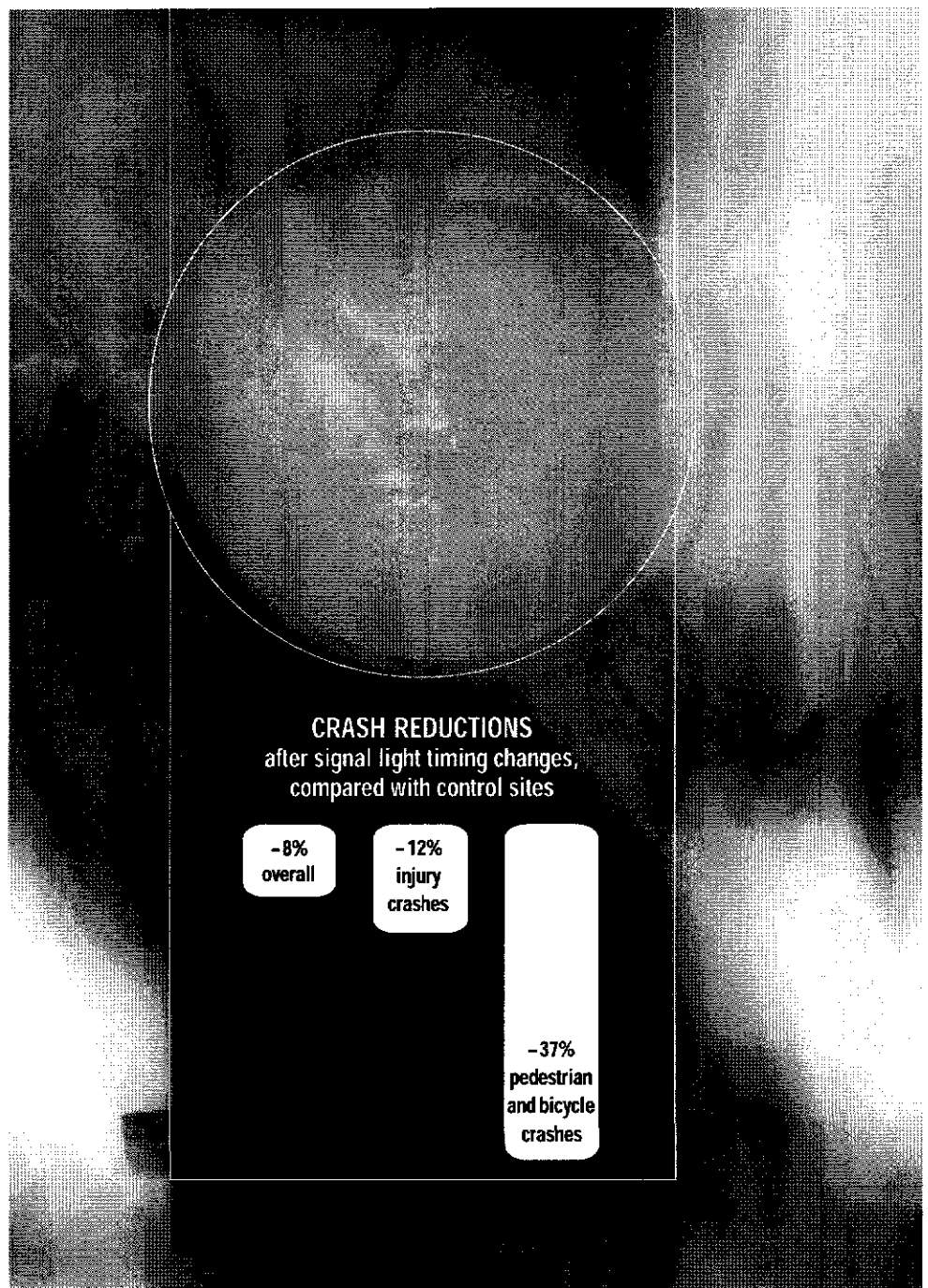
Eight percent fewer reportable crashes — that is, crashes with injuries or \$1,000+ damage — were recorded during the 36 months after the signal lights were retimed, relative to the control sites. Crashes involv-

ing pedestrians and bicyclists dropped 37 percent relative to the control group of intersections. The researchers found a 12 percent reduction in injury crashes. The experimental sites were 9 percent less likely than the controls to report multiple-vehicle injury crashes.

"Such benefits suggest that many urban intersections could benefit from similar modifications," says Richard Retting, the Institute's senior transportation engineer.

The ITE formula computes the yellow interval timing as a function of approach speed and grade, along with assumed values for perception-reaction time, deceleration rate, and acceleration due to gravity.

For a copy of "Changes in crash risk following the retiming of traffic signal change intervals" by R.A. Retting et al., write: Publications, Insurance Institute for Highway Safety, 1005 North Glebe Road, Arlington, VA 22201.



HSS-2

SURVEYS & RESULTS

January 2003 Survey

- 20 valid responses
- 60% knew of MUTCD Standard 9d.02 & used it in developing signal timing
- WHY USE MUTCD? Avoid liability, there are many bicyclists, it's a good idea, it's a MUTCD standard ...
- Of these 60%, almost 2/3 had few complaints and 10% had tolerable delays – none cited serious problems that required rollback of newly installed bike friendly signal timing ...
- Of the 40% who were not familiar with MUTCD standard – did not implement bike signal timing because ... not enough bicyclists, not enough staff, high costs, no need, no existing accepted methodology ...

August 2006 Survey

- Sent to ITE Traffic, ITE Ped/Bike, EBTE, and APBP listserves
- 28 valid responses
- Number of signals in agency ranged from 38 to 2030; up to 75% pre-timed; 60% of those who answered question about installing bike detection said they did and type ranged from video to loops to PPB;
- 21% had policy – and 3 of 4 of these had few/no complaints with bike timing changes they had implemented; 1 of 4 had tolerable delays; no one reverted back to previous signal timing ...
- 79% with no policy – several issues were listed as the top 4 reasons why not ... 21% said would be negative impact to existing traffic ... 26% said too few bikes ... 32% said staff feels is NOT a problem ... 21% said too few staff ... 16% said signal hardware can't accommodate additional bike timing ... 16% said signal software can't accommodate bike timing ... separate comments provided – several updating bike master plans and will include MUTCD standard; several times, signal tech upgrades done without regard or consideration to bike issues;

Adaptive Signal Timing for Bicycles

Masoud Akbarzadeh, PE, County Traffic Engineer ^[a]
Ananth Prasad, PE, Associate Civil Engineer ^[a]
Nora Chung, PE, Associate Civil Engineer ^[a]
Thien Pham, Assistant Civil Engineer ^[a]

Abstract

Bicycles are considered vehicles and share the roads. However, when it comes to crossing at signalized intersections, bicycles are usually treated as pedestrians by requiring them to use pedestrian/bicycle push buttons. This safe and appropriate solution works well for novice bicyclists although it is not a feasible solution for professional and commuter type bicyclists. This method may also result in inefficient signal operation if all bicyclists use pedestrian timings to cross at intersections. On the other hand, if bicyclists use vehicle loops at intersections they get motor-vehicle-based minimum green and clearance times which may be inadequate to fully clear an intersection. Bicyclists, like pedestrians and motorists, need adequate crossing time to clear the intersection. Their relative slower speeds compared to motor vehicles require longer green and clearance times. If bicycle timing parameters are used at signalized intersections as minimum values, then motorist delay will increase and other safety issues such as red light violations may occur. Somewhere between the pedestrian timing and motor vehicle timing is the optimal bicycle timing and providing this only when bicycles are present will promote safe and efficient multi-modal operation of traffic signals. This research project presents one possible solution to provide bicycle-related signal timing when bicycles are detected at signalized intersections.

Introduction

The County of Santa Clara, also referred to as "Silicon Valley," is located at the southern end of the San Francisco Bay and encompasses approximately 1,400 square miles. Santa Clara County is a major employment center for the region. The County's population of nearly 1.7 million is one of the largest in the state. The County of Santa Clara Roads and Airports Department maintains approximately 700 miles of roadway, including 62 miles of multi-lane expressway system which was designed as a sub-regional network to relieve local streets and supplement the freeway system. The Average Daily Traffic (ADT) on these expressways varies from 45,000 to 80,000 vehicles, and the system is used by approximately 1.5 million motorists per day.

The expressway system includes wider paved shoulders and limited on/off access points which are desirable and frequently used by professional and commuter type bicyclists. In an effort to improve bicycle safety and operations at signalized expressway intersections, two County projects were funded by the Bicycle Transportation Account (BTA) Program to install bicycle detection devices at 20 higher demand locations.

Due to the unique characteristics of bicycles, bicycle specific signal timing is required to better accommodate bicycles at signalized intersections. Our solution provides bicycle specific signal timing only when bicycles are detected at the intersection. Motor vehicle specific signal timing is provided at other times thereby balancing bicycle operational needs and motor vehicle delay at intersections. This solution accommodates both standing start and rolling start bicyclists for all three arrival types.

Background

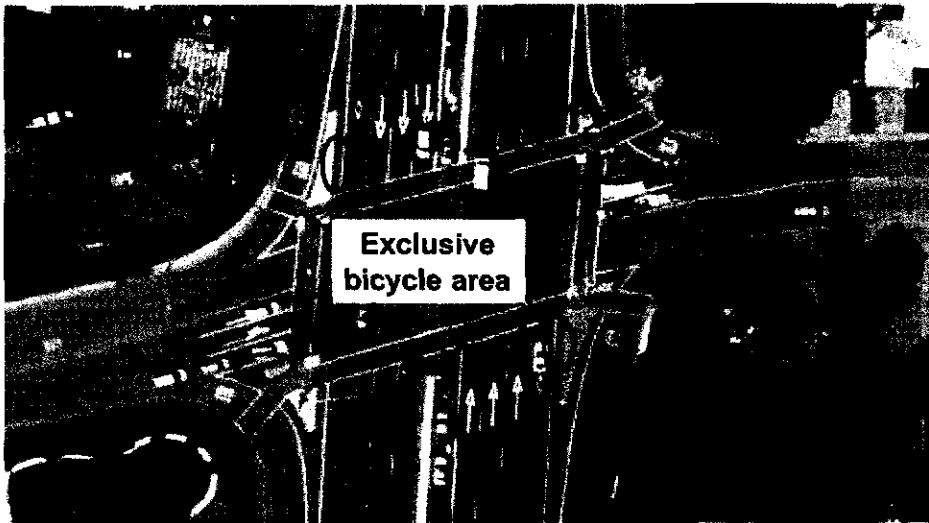
In 1991, the County Board of Supervisors adopted a policy which allowed bicycles on the County's limited access expressways. Since then, the County has been proactive in improving expressways to better accommodate bicycles. Some of the implemented improvements include; shoulder widening, lane realignment, minimum of 16 ft wide right-most shared lane, bicycle signing, striping and pavement

^[a] Roads and Airports Department, County of Santa Clara, 1505 Schallenberger Road, San Jose, CA 95131. Tel (408) 494-2700

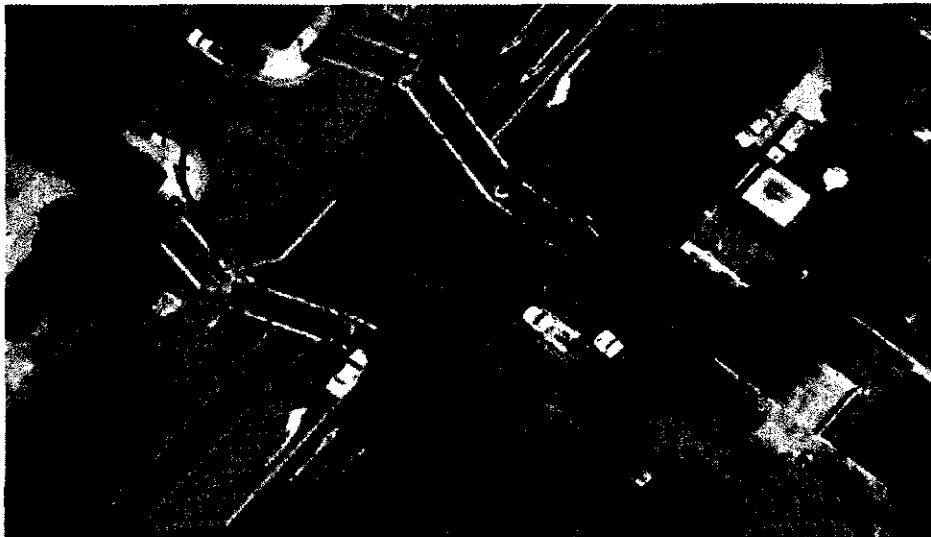
markings, bicycle slots and legends at intersections, sensitive loops to detect bicycles, marking detector loops, development of bicycle accommodation guidelines (BAG), and increasing the minimum green time. Adaptive Signal Timing for Bicycles is the latest idea which further improves the bicycle operation at targeted intersections.

Project Goals

The primary goal of the project was to develop and implement a way to detect bicycles and provide special signal timing to cross an intersection. This included detecting moving bicycles to provide appropriate green extension time. Also, to explore ideas and develop consistent strategies for improving the bicycle operation without increasing motorist delay. Target locations included expressway intersections with a designated bicycle lane/route on cross streets. The candidate intersections had to have adequate bicycle exclusive areas such as bicycle slots or gore areas.



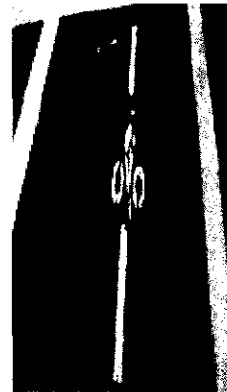
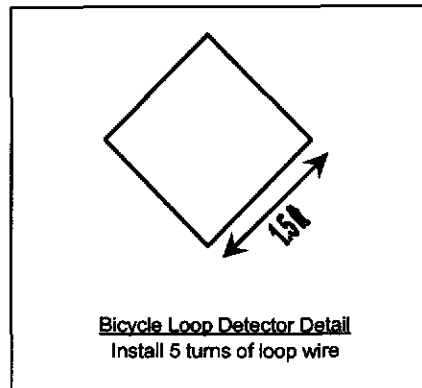
Candidate intersection with exclusive bicycle areas as shown



Intersection without bicycle exclusive areas (not suitable for this project)

Bicycle Detection Methods

Video camera, microwave and detector loop technologies were evaluated for accuracy of detection and reliability. After four months of field testing we concluded that the video detection process had difficulties in detecting bicycles in darkness and resulted in occasional false calls due to vehicle shadows appearing on the bicycle lane. The newer technology cameras may have corrected these problems. We also considered microwave as an option but because the bicycle travel area is too close to the pedestrian area we opted to skip this and decided to test detection loops. We selected a induction loop that is smaller in size to fit in a 4 ft wide typical bicycle slot. We found that a diamond loop with 1.5 ft sides and a minimum of 5 turns of loop wire provided good results.



Bicycle legend is installed in order to optimize the effectiveness of the detector's.

Signal Timing Factors

1. Bicycle Speed

It is important to choose an appropriate bicycle speed in order to calculate minimum green, yellow and all red intervals for bicycles. Our research in this area did not reveal sufficient solid information; hence, we conducted a study by observing bicyclists at key locations on several expressway intersections during both AM and PM peak periods as well as during school start and finish times. The speed was calculated by using the time it takes to cross two marked points on either side of the intersection. Based on our observations at 10 project intersections, bicyclist speeds traveling on the expressways were greater than the bicyclist speeds traveling on the cross streets. Also, bicyclists traveling on the expressway were comfortable entering the intersection in mid-to-late green due to the long green phase on expressways. However, bicyclists on a stale green on the cross streets anticipated stopping and in fact slowed down on their approach to the intersection. The following table shows the Mean, Median, and 85th percentile on the bicycle speed data collected at 10 of the project intersections.

Bicycle Speed Study On 10 Project Intersections (ft/sec)				
Speed Category	Expressway		Cross Street	
	Rolling	Standing	Rolling	Standing
85th Percentile	33	16	28	15
Mean	26	14	21	14
Median	24	13	20	12

Based on our collected bicycle speed data, the standing start condition was lower in all three categories (85th, mean, and median). Bicyclists traveling on expressways were typically more

advanced riders and faster than bicyclists on the cross streets. Our speed study was comparable to other similar studies found in our research:

- a. ITE study by John Forester, et al.
In 1995, Forester's study summarized the speed of bicyclists in three categories: fast, typical, and school children bicyclists. His observations included 26 ft/sec for fast, 18 ft/sec for typical, and 13 ft/sec for school children.^[2]
- b. UC Davis
In 2004, UC Davis' study on bicyclists showed speeds of 33 ft/sec for the fastest bicyclists, 13.5 ft/sec mean speed, and 18.57 ft/sec 85th percentile speed.^[3]

In addition, AASHTO recommends when field studies of bicycle speeds are not available to use 17.6 ft/sec for advanced, 12 ft/sec for basic, and 9.1 ft/sec for children and senior bicyclists.^[4]

Due to the small sample size and big variation in speed data as well as non-conclusive data available elsewhere, for the purposes of this project we used 12 ft/sec as recommended by AASHTO for basic bicyclist.

2. Bicyclist Characteristics

Understanding the bicyclist's behavior is another important factor in developing bicycle-specific signal timing. Our study concluded that bicyclists felt comfortable starting from a fresh green to cross a wide intersection as opposed to entering the intersection on a stale green. We also observed that most bicyclists stopped on a yellow while motor vehicles tend to accelerate to clear the intersection. Finally, we observed that most school children and senior bicycle riders used crosswalks to cross, employing the pedestrian push buttons.

3. Intersection Geometry

Intersection geometry features such as, approach grade, road width, and road alignment play an important role in determining the appropriate signal timing for bicycles. Adequate space is needed for each approach to create a minimum 4 ft wide bicycle slot or a minimum of 16 ft wide shared lane in order to implement the adaptive timing methodology.

Bicycle Signal Timing Calculations

Based on the aforementioned factors, the bicycle minimum green and clearance times are calculated for each intersection. The bicycle minimum green is calculated as follows:

1. Bicycle Crossing Time (BCT)

- a. For Rolling Bicyclist

$$BCT \text{ (in sec)} = (W+L) / V \quad \text{Where,}$$

W = Intersection Width (in ft),

L = Bicycle Length (6 ft),

V = Bicycle Speed (12 ft/s).

- b. For Standing Bicyclist

$$BCT \text{ (in sec)} = C + (W+L) / V \quad \text{Where,}$$

C = t + V/2a,

t = Reaction Time (1 sec)

a = bicycle acceleration (1.5 ft/s²)^[2]

2. Bicycle Minimum Green Time (BMG)

Bicycle Crossing Time is longer for standing start bicyclists and therefore it is used to calculate the minimum green time. To maximize the minimum green time, motor vehicle yellow and all red are used in this equation.

$$BMG = BCT \text{ (standing)} - \text{yellow interval} - \text{all red interval}$$

3. Bicycle Green Extension, Yellow and All Red Intervals

Rolling bicyclists approaching and entering the intersection during the green interval will govern the clearance time. Bicycle Clearance Time is calculated as follows:

$$\text{Bicycle Clearance Interval (yellow + all red)} = BCT \text{ (Rolling)} - \text{Green Extension}$$

Since our detectors can detect moving bicyclists and are capable of providing green extension, it is better to provide longer green extension than it is to increase the all red interval to a higher value, potentially resulting in increased red light violations. In addition, MUTCD suggests a red clearance interval not to exceed 6 seconds^[1]. Hence, by keeping a constant of 3 seconds for bicycle all red and a typical motor vehicle yellow time for the intersection, we can calculate the green extension time interval as follows:

$$\text{Green Extension Time} = BCT \text{ (Rolling)} - \text{yellow} - \text{all red (maximum of 3 seconds as constant)}$$

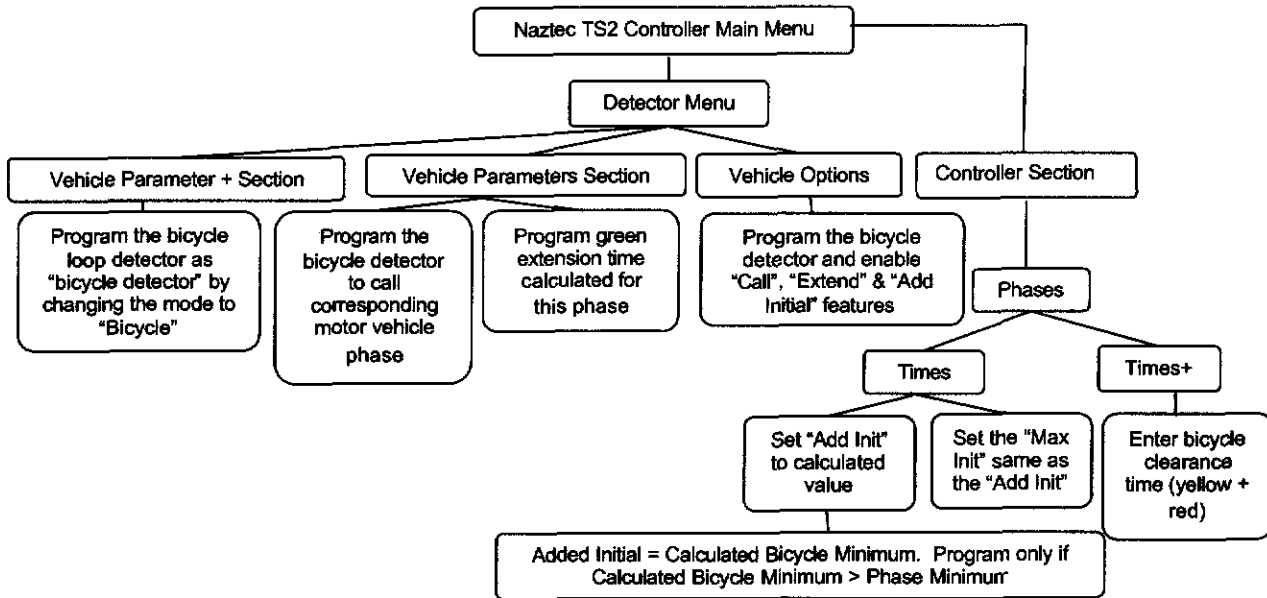
(If Bicycle green extension is less than vehicle green extension then use vehicle green extension as minimum value).

The table below shows bicycle signal timing calculations for the 20 project intersections.

	Expressway	Cross Street	Expwy Crossing Distance (in ft)		Existing Motor Vehicle Timing (in sec)						Bicycle Crossing Time (Standing) (in sec)		Bicycle Min. Green (in sec)		Bicycle Crossing Time (Rolling) (in sec)		Existing Motor Vehicle Green Extension (in sec)		Bicycle Green Extension (in sec)		Bicycle Clearance (y+r) (in sec)		
			SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	SB/WB	NB/EB	
1	Almaden	Branham	149	142	8	8	3	3	1.6	1.6	18	18	14	13	13	13	4	4	7	7	6	6	
2	Capitol	Santer	108	98	8	8	4	4	1	1	15	14	10	9	10	9	4	4	4	4	4	6	5
3	Lawrence	Bollinger	138	145	8	8	3.6	3.6	1	1	17	18	13	13	12	13	4	4	6	6	7	7	
4	Lawrence	Prospect	146	158	8	8	4	4	1	1	18	19	13	14	13	14	4	4	6	7	7	7	
5	Lawrence	Hornstead	164	166	8	8	4	4	1	1	19	20	14	15	14	15	4	4	7	8	7	7	
6	Central	Castro	134	132	5	8	3.2	3.6	1	1	17	17	13	12	12	12	4	4	6	5	6	7	
7	San Tomas	Hamilton	127	128	8	8	4	4	1	1	16	16	11	11	11	11	3.6	3.6	4	4	4	7	7
8	San Tomas	Payne	126	127	8	8	4	4	1	1	16	16	11	11	11	11	3.6	3.6	4	4	4	7	7
9	Foothill	Grant	108	110	8	8	3.5	3.5	2	2	15	15	9	9	10	10	4	4	4	4	6	6	
10	Foothill	San Antonio	167	-	8	-	3.5	-	1.5	-	20	-	15	-	15	-	4	-	4	-	7	-	
11	Almaden	Redmond	154	162	8	8	3	3	1.6	1.6	18	19	14	14	14	14	4	4	8	8	6	6	
12	Almaden	Coleman	132	140	8	8	4	4	1	1	17	17	12	12	12	12	4	4	5	5	7	7	
13	Capitol	Ocala	98	115	8	8	3.6	3.6	1	1	14	15	9	11	9	10	4	4	4	4	4	5	6
14	Montague	Zanker	139	146	8	8	4.3	4.3	1	1	17	18	12	13	12	13	4	4	5	6	7	7	
15	Lawrence	Araques	167	170	8	8	4	4	1	1	20	20	15	15	15	15	4	4	8	8	7	7	
16	Lawrence	Elko	144	144	8	8	3.5	3.5	1	1	18	18	13	13	13	13	4	4	6	6	7	7	
17	Lawrence	Cabrillo	143	151	8	8	3.5	3.5	1	1	18	18	13	14	13	13	4	4	6	7	7	7	
18	Lawrence	Reed	154	147	8	8	4	4	1.5	1.5	19	18	13	13	14	13	4	4	7	6	7	7	
19	San Tomas	Cabrillo	141	143	8	8	3.2	3.2	1.5	1.5	17	18	13	13	13	13	4	4	6	7	6	6	
20	San Tomas	Williams	142	135	8	8	3.6	3.6	1	1	18	17	13	12	13	12	4	4	6	5	7	7	

Implementation of Bicycle Timing in Naztec TS2 Controller

In order for the controller to provide sufficient time for bicycles without causing undue delay for motorists, it was necessary to provide the bicycle timing only when bicycles are detected. The following chart shows how to program a Naztec TS2 controller for this application. Note, most controllers have similar features but some are not capable of the programming shown on the following page.



Dynamic Signal Timing Process

For this study, bicyclists are grouped into three arrival types; bicyclists arriving on green, yellow, or red.

Similarly, bicyclists are also grouped based on how they start to cross the intersection

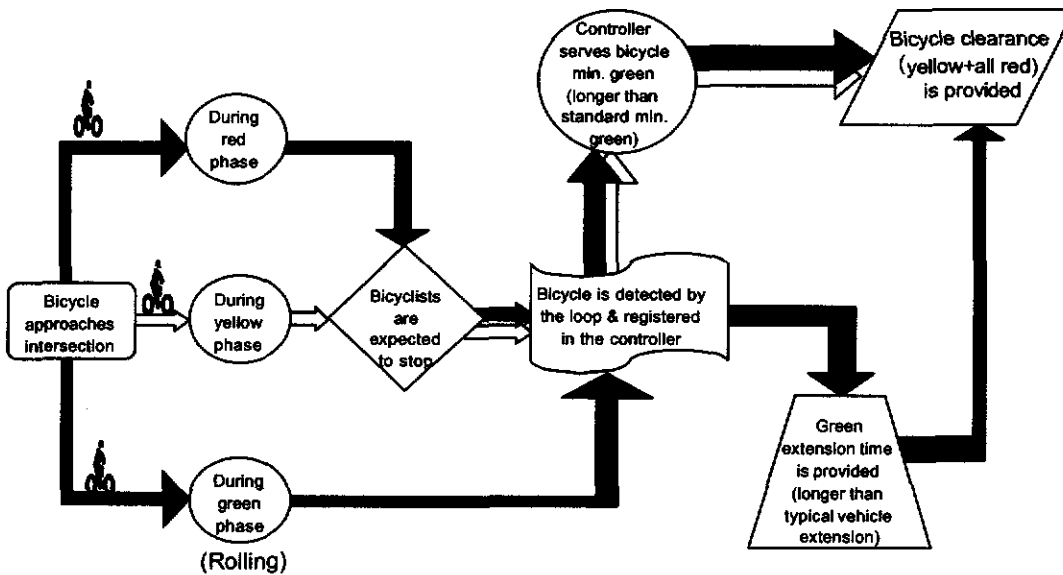
1. Standing Bicyclists:

Arrive during the yellow or red phase and wait at the intersection for a green signal indication.

2. Rolling Bicyclists:

Arrive during the green phase and are moving through the intersection.

The following flowchart summarizes the controller decision making process in determining bicycle signal timing for the project's signalized intersections:



Project Cost

Based on the project's total cost for 40 approaches at 20 intersections, the average bicycle detection cost was \$8,000 per approach. This cost included design, construction, minor civil work, striping, loop installation, and associated electrical work. Our existing controllers were capable of supporting this programming and thus no additional equipment was necessary.

Conclusion

Bicyclists, like motorists and pedestrians, need adequate signal timing to cross an intersection completely. With properly installed bicycle detection, it is possible to provide adequate bicycle signal timing that engages only when bicycles are present. In-pavement loop detectors similar to vehicle loop detectors work well for bicycles too. The advantage of using the detector loops is that moving bicycles can also be detected and bicycle specific green extension can be provided when bicycles are detected during the green phase. In the absence of bicycles, normal motor vehicle timings are provided to minimize intersection delay. Bicycle timing capabilities are not available in some controllers and we hope to see this feature become a standard on all controllers in the near future. Only intersections that have exclusive bicycle areas such as a bicycle slot or a minimum of 16 ft wide shared lanes can accommodate this detection methodology. This application particularly benefits the professional and commuter type of bicyclists at large intersections. The average cost for installation of bicycle detection was \$8,000 per approach.

Acknowledgements

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