Analysis of Traffic Signal Clearance Interval Requirements for Bicycle-Automobile Mixed Traffic

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Clearance intervals (including both the yellow change and all-red clearance intervals) at signalized intersections that are of inadequate lengths for bicycle/rider units may cause accidents. Steps that can be taken to provide safe clearance intervals for bicycles and automobiles are examined. Data on bicycle/rider unit speed, acceleration, and deceleration were collected and analyzed. Using the results of the analysis and an accepted theory for computing safe clearance intervals, a methodology is obtained for computing safe clearance intervals for traffic containing bicycles and automobiles. The clearance interval required by bicycles will probably be somewhat larger than that for automobiles. Providing a single longer clearance interval for both users may cause undue delay or unsafe conditions for automobiles. Therefore, alternatives that provide different warning signals to each user at the appropriate time are presented, and the question of whether this particular signal should be timed for bicycles is answered. A mathematical expression is derived for computing the probability of a bicyclist's being caught in the intersection when the cross-street traffic receives a green. This probability allows one to compute the number of bicycles per hour that will be caught in the intersection. Since traffic engineers require information of this nature to provide safe intersection clearance for both automobiles and bicycles, it is hoped that this and subsequent work will provide methodologies necessary to incorporate into common design manuals, such as AASHTO's *Guide for the Development of Bicycle Facilities* and various state and city manuals.

There are many characteristic differences between the units of a bicycle and its rider and a car and its driver. These differences can have significant safety and operational implications when bicycles and automobiles operate on the same facilities. Bicycles are smaller, offer a rider less protection in the event of an accident, and have different operating characteristics (such as speeds and acceleration and deceleration rates). Because the bicycle offers little protection for the bicyclist, a car-bicycle accident can be very serious. This study investigates the computation of traffic signal clearance interval durations (defined in this paper to be the combination of the yellow vehicle change interval and the all-red clearance interval) required for the safe operation of bicycle-automobile mixed traffic. Inadequate clearance interval duration is considered by Forester to be the "largest identified facility-associated cause of car-bike collisions" (*1*). In addition, an Oregon study reports that "bicyclists disregarding signals" account for 8 percent of all urban bicycle–motor vehicle accidents in that state. The Oregon Department of Transportation's current policy to help alleviate this problem is to add loop detectors in bike lanes to extend the length of the green phase, if a bicyclist is in position to be caught by a clearance interval of inadequate length (*2*).

In order to study this situation, data on bicyclist speed, acceleration, and deceleration were collected. The data are analyzed herein and should prove useful for other analyses. Combining outputs from this data analysis with theory on computing safe clearance intervals yields one of the major outputs of this study: a methodology for computing safe clearance intervals for signals controlling bicycle-automobile mixed traffic.

Inevitably, it will be asked whether a particular traffic signal should be timed for bicycle-automobile mixed use or just for automobile use, since, as is shown herein, accommodation of bicycles will usually require a longer clearance interval, which may increase delay for automobiles. A mathematical expression is derived (computing the probability of bicyclists' being caught in an intersection through no fault of their own) to help traffic engineers answer this question. In addition, data are collected to verify this formula.

Because a bicycle/rider unit is small and normally travels on the far right side of the road, it is less likely to be seen by a motorist entering an intersection on the cross street than a car would be. Undoubtedly many accidents occur because the bicyclist could and should have stopped before the intersection; others occur simply because the clearance interval is too short for some bicycle/rider units to stop before the intersection, but not long enough for them to clear the intersection before the cross-street traffic receives a green. These bicycle/rider units are those caught in the dilemma zone. If caught in the dilemma zone, a bicyclist cannot physically make a correct decision and will therefore be in the intersection when the cross street receives a green. (It should be noted that there is actually no dilemma for the bicyclist. The bicyclist cannot make a correct decision. The term "impossibility zone" might be more appropriate, but dilemma zone is used for historical reasons.)

The dilemma zone is shown pictorially in Figure 1. If the clearance interval is too short, a dilemma zone exists such that no matter what a rider decides to do (stop or proceed), the rider will be caught in the intersection. If the clearance interval is the minimum allowed for safety purposes, then the bicyclist has the opportunity to make a correct decision and there is no dilemma zone. If the clearance interval is greater than this minimum, an optional zone is introduced, in which either decision is acceptable.

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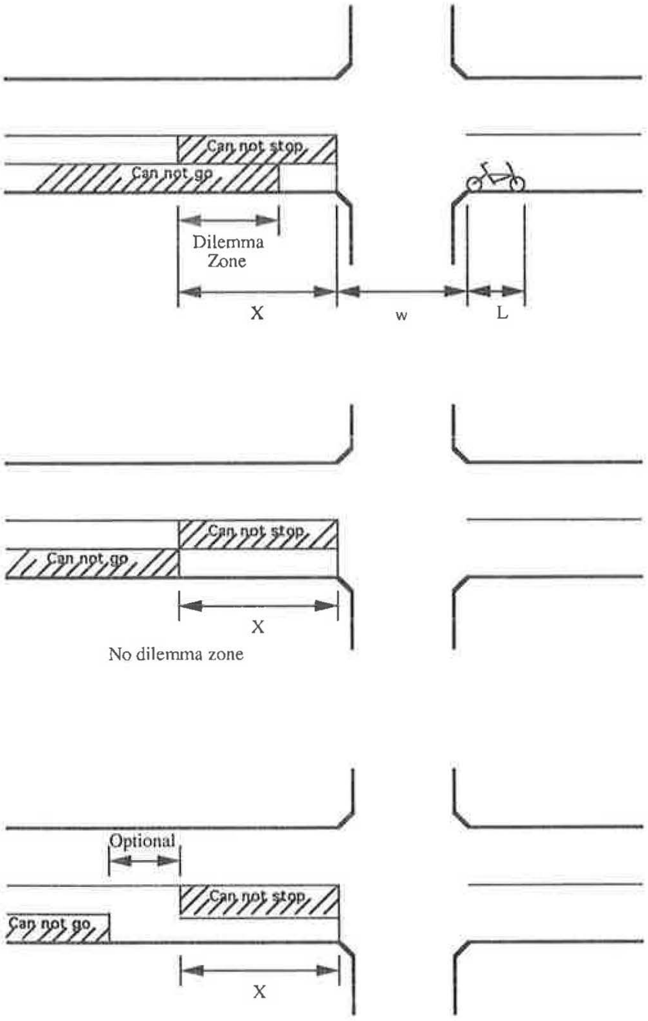


FIGURE 1 Dilemma zone.

Keeping a car from being caught in a dilemma zone has been the object of much study (*3–5*). Some information is also available on preventing bicycles from being caught, though, as will be shown later, this information is inadequate (*1,6*). This paper adds to that body of knowledge on preventing this situation for bicycles.

DATA

To analyze clearance intervals, the required data are the normal cruising speeds for bicycle/rider units in mixed traffic (not their fastest speeds), the rates of acceleration that bicyclists would like to use in order to proceed comfortably through yellow lights (not maximum accelerations in emergencies), and the comfortable rates of deceleration for bicycle/rider units while braking to complete stops (again, not emergency stops). Normal and comfortable rates are appropriate, since one does not wish to design for abnormal or uncomfortable situations.

Data were collected and analyzed to obtain these values. The data collection procedures and subsequent data analysis are discussed in the following two subsections. So that the reader may, if desired, skip these two subsections and return to them after finishing the rest of the paper, the results of the data analysis (for level, dry pavement) applicable to the rest of the paper are as follows, where 1 km/hr equals 0.6214 mph and 1 m/sec^2 equals 3.281 ft/sec^2:

	Normal Cruise Speed (km/hr)
7.5 percentile	16.1
Mean	22.5
92.5 percentile	29.0

	Acceleration (m/sec^2)	*Deceleration (m/sec^2)*
15th percentile	0.30	1.22
Mean		2.29

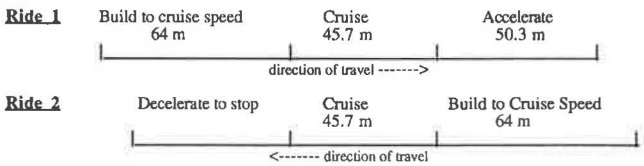
Data Collection Procedure

It is fairly easy to collect speed data without a bicyclist knowing it, but it is not so easy to do for the acceleration and deceleration rates. Since bicycle speed data collected in this manner were available elsewhere, it was deemed more important to collect the latter data, though speed data were also collected.

In the first data collection session, 13 subjects were tested (8 taken voluntarily from city streets, 4 who were friends of the author, and the author). Each subject was asked to make two rides on level pavement (see Figure 2). In Ride 1, subjects were asked to accelerate up to their normal cruise speed (for travel on city streets in Austin, Texas) for about 64 m (210 ft) and remain at that speed for about 46 m (150 ft). When they reached the end of this segment, they were told to accelerate—at a rate that they would use to make it through a yellow light comfortably and safely—for about 50 m (165 ft). Time to traverse the cruising speed segment and times at 18 and 46 m (60 and 150 ft) of acceleration were measured.

A cruising distance of about 46 m (150 ft) was deemed sufficient, because if the human error in timing is off by 2.3 m (7.5 ft), only a 5 percent error in speed is incurred. Acceleration of about 46 m (150 ft) was thought sufficient since it is close to the maximum distance that a bicyclist would have to accelerate to clear a wide intersection.

In Ride 2, the subjects were again asked to accelerate up to normal cruise speed and remain in that speed for 46 m (150 ft). At the end of the segment, they were asked to decelerate comfortably to a stop by braking (never coasting), as if they saw a yellow light and wanted to be sure they stopped before the intersection.



Note: 1 m = 3.281 ft

FIGURE 2 Diagram of rides used to collect data on speed, acceleration, and deceleration.

After these data were collected and analyzed, it was judged necessary to collect more deceleration data because of their importance in the minimum clearance interval computation methodology. In another data collection session, 15 more subjects were tested (taken voluntarily from city streets). They performed Ride 2 only.

All data were taken on pavement that was level to the human eye and when wind effects were judged to be negligible. Though 24 of the subjects were tested on a narrow, somewhat busy street with cars parked along each side, bicyclists were held until the coast was clear before proceeding. Some interference still may have occurred, but it is not considered significant. The other four subjects were tested in head and tail winds of 16 to 32 km/hr (10 to 20 mph) (estimated by the author); their speeds did show significant differences depending on direction of travel, but the average of the two speeds should adjust for this. The accelerations and decelerations of these four subjects were most likely affected, but they fell within the ranges of the other data and were not adjusted in any way to account for wind effects. It is also important to note that all data were taken on dry pavement.

Data Analysis

Of the 28 total subjects, 5 were female and 23 were male. Ages ranged from 19 to 55, with the average being 29. Statistics on normal cruise speed, deceleration, and acceleration are given in Table 1.

It is interesting to compare these data with previously collected data. Data collected in 1972 show speeds of bicycle/rider units to average about 17 km/hr (10 to 11 mph) and range from 11 to 24 km/hr (7 to 15 mph) (*7*). The data collected for this study show higher speeds, but comparisons are difficult since the conditions under which the 1972 data were collected were not reported. Speed data collected in Mountain View, California, are slightly higher than the data collected in Austin; both Austin and Mountain View can be described as areas where bicycling for both transportation and recreation is popular. The Mountain View data were collected on a level street bike lane in the absence of wind during the entire morning commuting period (conditions that are comparable to those in this study's data collection process, except that the riders in this study knew that they were being timed). For Mountain View, the slowest speed was 19.3 km/hr (12 mph), the median speed was 25.7 km/hr (16 mph), and the 85th-percentile speed was 29.8 km/hr (18.5 mph) (*1*).

No previously collected bicycle acceleration data could be found, so direct comparisons cannot be made. However, comparisons to automobiles provide some insight. Acceleration available to cars can be estimated through Gazis' equation (*3*):

$$a = 4.88 - 0.04034 \cdot v \qquad (1)$$

where a equals acceleration in meters per second squared and v equals speed in kilometers per hour.

TABLE 1 Statistics from Data Collection

Statistic	Speed	Deceleration	Acceleration Over 45.7 m	Acceleration Over 18.3 m
Low	13.2 km/hr	1.15 m/s^2	0.03 m/s^2	0.55 m/s^2
15th percentile	16.9 km/hr	1.28 m/s^2	0.21 m/s^2	--
Mean	22.7 km/hr	2.29 m/s^2	0.43 m/s^2	1.15 m/s^2
Median	23.0 km/hr	2.35 m/s^2	0.40 m/s^2	1.10 m/s^2
85th percentile	26.7 km/hr	2.96 m/s^2	0.58 m/s^2	--
High	33.6 km/hr	3.75 m/s^2	0.91 m/s^2	1.95 m/s^2
# of data points	28	27	12	6

Note: Some statistics are missing (--) due to insufficient number of data points for their computation. 1 km/hr = 0.6214 mph and 1 m/s^2 = 3.281 ft/s^2.

At 22.5 km/hr (14 mph) (the speed of an average bicyclist) a car would be able to accelerate at about 4 m/sec^2 (13 ft/sec^2). As expected, this is greater than a bicycle/rider unit can comfortably achieve at this speed. Even at 64.4 km/hr (40 mph), the car has the ability to accelerate at about 2 m/sec^2 (7.5 ft/sec^2), which is still much greater than the bicycle/rider unit, at 22.5 km/hr (14 mph).

No previously collected data on bicycle deceleration rates were found, but some theoretical information proves interesting for comparative purposes. With tire braking, the maximum deceleration possible is 9.8 m/sec^2 (32.2 ft/sec^2), the acceleration due to gravity, g. This is achievable only if the coefficient of friction between tires and road is 1.0. Actually, the coefficient of friction for vehicles with pneumatic tires varies from about 0.8 (dry concrete) to 0.1 (wet ice), with a value of 0.4 to 0.7 for wet concrete or wet asphalt (*8*). Therefore, the maximum bicycle braking deceleration (under ideal conditions) is about 8 m/sec^2 (26 ft/sec^2).

The center of gravity (in relation to the wheelbase) and weight of a car is such that there is no possibility of flipping over the front wheels while decelerating. This is not the case with a bicycle/rider unit, which is lighter and has a high center of gravity in relation to its wheelbase. This center of gravity moves forward as the rider crouches over the handlebars, which a rider usually does to some extent during braking, since the brakes are usually on the handlebars. The higher and more forward the bicycle/rider unit's center of gravity, the greater its chance of being thrown over the handlebars during braking. Whitt and Wilson computed the maximum deceleration rate achievable by a crouched rider (using dropped handlebars) to be about 0.56 g (*8*). With this as a constraint, the maximum attainable deceleration is about 5.5 m/sec^2 (18 ft/sec^2). In actuality, one would expect riders to decelerate at a rate quite a bit less than this to ensure that they are not thrown.

If one considers braking in wet weather, where the coefficient of friction between tire and road falls to about 0.4, the maximum attainable deceleration is about 4 m/sec^2 (13 ft/sec^2). Again, to be on the safe side, riders would probably brake at rates less than this.

These values hold only if an appropriate force is applied to the rim brake. Therefore, on bicycles on which brakes are not adjusted properly, it is possible that the constraint on maximum deceleration is the amount of force with which the brake block can be pressed against the rim. More research into the actual conditions of bicycle braking mechanisms is required to determine if this actually is the defining constraint.

There is also a coefficient of friction between the brake block and the rim. Under dry conditions this value is near 0.95 and as such should not be a deceleration constraint. Under wet conditions it is possible that this could be a constraint. Using typical bicycle brake block material from 1971, this coefficient of friction was found to drop to about 0.05 when wet (*8*).

Research and development efforts since 1971 have probably improved wet brake coefficients into the range of 0.3 to 0.5, though more research is needed to verify this (*8*).

The deceleration rates obtained in this experiment conform to what is suggested by theory. The maximum rate sampled (3.75 m/sec^2) is less than the "over the handlebar" threshold of 5.5 m/sec^2. Also, the mean and 15th-percentile rates (2.29 and 1.28 m/sec^2, respectively) are significantly less, reflecting either that bicyclists prefer a margin of safety and comfort in their stops or that many bicycle brakes are out of adjustment and riders cannot brake to the "over the handlebar" threshold.

Because of human measurement errors and errors associated with the manner in which bicyclist subjects followed directions, the statistics reported in Table 1 are only approximations. Therefore, for simplicity, those given in the earlier tables are used throughout this study.

SAFE CLEARANCE INTERVAL COMPUTATION

An accepted method for ensuring safe clearance is to allow a minimum clearance interval (which may include an all-red indication after the yellow) such that vehicles that cannot comfortably stop before the intersection have enough time to proceed either into or through the intersection. Only the case of proceeding through the intersection is considered here, because of the safety implications of a bicyclist's being caught in the intersection.

This situation was analyzed by Gazis et al. and presented in the *Transportation and Traffic Engineering Handbook* as follows (*3,9*). To come to a safe stop before the intersection,

$$x = v \cdot t_{p-r} + v^2/(2 \cdot d) \tag{2}$$

where

x = distance required for stopping,
t_{p-r} = perception-reaction time,
v = approach speed, and
d = deceleration.

If a vehicle at distance x from the intersection (when the clearance interval begins) can proceed through the intersection before the clearance interval expires, then there is no dilemma zone (Figure 1). A vehicle can do this without accelerating if the clearance interval (ci) is at least

$$ci_{\min} = (x + w + L)/v = t_{p-r} + v/(2 \cdot d) + (w + L)/v \tag{3}$$

where

$ci_{\min}$ = minimum clearance interval without acceleration,
w = intersection width, and
L = vehicle length.

Since cars are likely to be driving at about the speed limit, they would exceed the speed limit by accelerating through the intersection. For bicycles this is not a problem. Therefore, the minimum clearance interval required for a vehicle to pass through the intersection while accelerating may be applicable to bicycles. This is given by solving the following for $ci_{\min-a}$ using the quadratic equation

$$v \cdot ci_{\min-a} + a \cdot (ci_{\min-a} - t_{p-r})^2/2 = x + w + L$$

or

$$v \cdot ci_{\min-a} + a \cdot (ci_{\min-a} - t_{p-r})^2/2 = v \cdot t_{p-r} + v^2/(2 \cdot d) + w + L \tag{4}$$

yielding

$$ci_{\min-a} = (a \cdot t_{p-r} - v + \{v^2 + 2 \cdot a \cdot [v^2/(2 \cdot d) + w + L]\}^{1/2})/a \tag{5}$$

where $ci_{\min-a}$ is the minimum clearance interval with acceleration, and a equals acceleration.

ANALYSIS OF SAFE CLEARANCE INTERVALS FOR BICYCLE-AUTOMOBILE MIXED TRAFFIC

In cases of mixed bicycle-automobile traffic, a conservative design suggests that minimum clearance intervals be computed for both vehicle types and the largest used. The parameters in the minimum clearance interval equations (Equations 3 and 5) have accepted automobile design values (*9*). For bicycles this is not the case, so it is necessary to analyze what values are appropriate.

The AASHTO *Guide for the Development of Bicycle Facilities* recommends using a bicycle speed of 16.1 km/hr (10 mph) and a perception-reaction time of 2.5 sec, but it says nothing of deceleration or acceleration rates (*6*). Forester recommends bicycle speeds of 24.1 to 32.2 km/hr (15 to 20 mph) for adult transportation routes and 16.1 km/hr (10 mph) for recreation and child routes, a perception-reaction time of 1 sec, and deceleration rates of 4.6 m/sec^2 (15 ft/sec^2) for adult transportation routes and 2.4 m/sec^2 (8 ft/sec^2) for recreation and child routes (*1*).

The noncontroversial values are those for bicycle length (L), 1.8 m (6 ft), and intersection width (w), which changes for each intersection analyzed. Herein, three values are used for sensitivity over narrow, medium, and wide intersections. The values chosen are 9.1, 19.8, and 30.5 m (30, 65, and 100 ft). Perception-reaction times for automobile drivers to perceive a yellow light and react to it by pressing on the brake have been measured, and a design value of 1 sec is normally used (*3–5,9*). However, these times range between about 0.5 and 4.0 sec (*10*). In light of the safety implications for bicyclists, the fact that a bicyclist's perception-reaction time could be different from a car driver's, and the absence of any actual bicyclist perception-reaction data, the author believes that a value greater than 1 sec is called for and recommends that AASHTO's value of 2.5 sec be used.

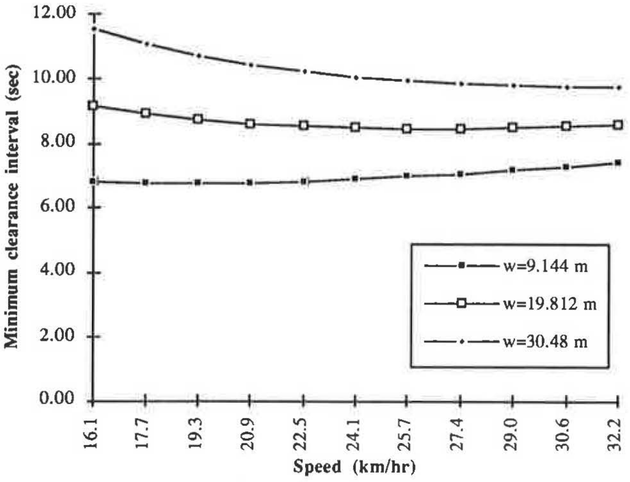
Speeds in the range of 16.1 to 32.2 km/hr (10 to 20 mph) are suggested by the data collected for this study, previously collected data, AASHTO, and Forester.

The higher the design deceleration rate is over the actual requirement for the bicycle/rider population, the smaller the computed minimum clearance interval and the greater a bicyclist's chance of being caught in a dilemma zone. A design value should be chosen to accommodate some percentage of the population of bicycle/rider units on the particular road in question. The author suggests using a value that accommodates about 85 percent of this population. The previous data analysis suggests a value of 1.22 m/sec^2 (4 ft/sec^2). This value is quite a bit less than either of those recommended by Forester (*1*).

Ideally, what is required is the percentage of bicyclists who accelerate through yellow lights. Since it is not known if the percentage of bicyclists who accelerate through intersections is high enough to warrant computing minimum clearance intervals assuming acceleration, the author suggests assuming constant speed. Thus, if one errs it will be on the safe side for bicyclists. Cases with and without acceleration are analyzed herein for comparison. For the former, the previous data analysis concludes that an acceleration of 0.30 m/sec^2 (1.0 ft/sec^2) accommodates 85 percent of the population. Actually, accelerations will probably vary according to intersection width.

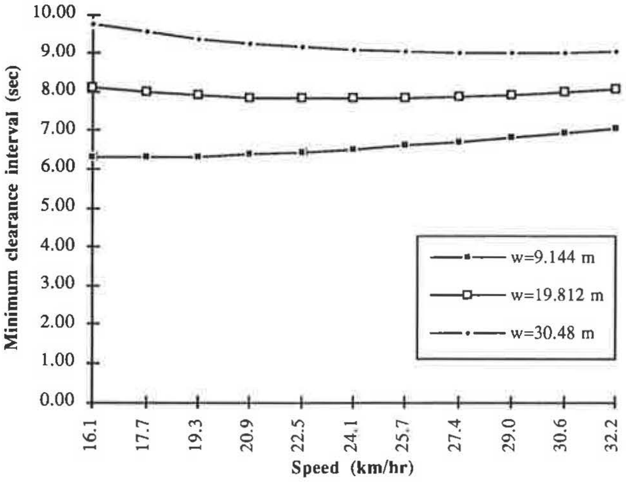
The results of the analysis are shown in Figures 3 and 4. Each figure shows minimum clearance intervals for each of the three intersection widths (w) over the speed (v) range of 16.1 to 32.2 km/hr (10 to 20 mph). Figure 3 is for the case of no acceleration, and Figure 4 assumes acceleration. From these figures one can easily see the magnitudes of the increases in minimum clearance interval required for larger intersection widths and no acceleration versus acceleration. For comparison, the clearance intervals required for automobiles traveling at 56.3 km/hr (35 mph) are 4.5, 5.2, and 5.9 sec for the narrow, medium, and wide intersections, respectively. [These were computed using Equation 3 with the following common automobile design values: d = 3.0 m/sec^2 (10 ft/sec^2), L = 5.8 m (19 ft), t_{p-r} = 1 sec).] These intervals are about 2 to 6 sec less than those required for bicycles, depending on the acceleration assumption and intersection width.

The perception-reaction time used for bicyclists is 2.5 sec. Changes in perception-reaction time result in equal changes to the minimum clearance interval required. For example, assuming a 1-sec perception-reaction time would result in minimum clearance intervals 1.5 sec less than those in Figures 3 and 4. Thus, even for a 1-sec bicyclist perception-reaction time, the minimum clearance intervals required are greater than those for automobiles.



Note: 1 km/hr = 0.6214 mph; 1 m = 3.281 ft.

FIGURE 3 Minimum clearance intervals assuming no acceleration, for three intersection widths (w) and perception-reaction time of 2.5 sec.



Note: 1 km/hr = 0.6214 mph; 1 m = 3.281 ft.

FIGURE 4 Minimum clearance intervals assuming bicycle acceleration of 0.3048 m/sec^2, for three intersection widths (w) and perception-reaction time of 2.5 sec.

The assumptions recommended previously always erred on the conservative side and are reflected in the case of no acceleration and a 2.5-sec perception-reaction time (Figure 3), which leads to the longest minimum clearance intervals. It is interesting to note that with these recommended assumptions, the clearance intervals for wider intersections would need to be more than 7 sec. Clearance intervals of this magnitude are often thought to encourage driver disrespect and possibly increase rear-end collisions (*7*). This problem probably would not occur if the yellow were kept below 5 sec and an all-red used for the rest of the clearance interval, but delay would be added to automobile travel (*9*).

Because the clearance intervals required for bicycle/rider units at the wider intersections (8 to 12 sec) are much larger than those required for automobiles (5 to 6 sec), it may make sense to provide separate warning signals for both users. Pedestrian signals have set a precedent for this. Considering the possible delay costs (if drivers obey a single longer clearance interval) or safety costs (if some do not obey) associated with a single clearance interval warning signal timed for both bicycles and automobiles, the most cost-effective solution may be to provide a separate warning signal for bicyclists. This warning signal could be timed according to the procedures outlined in this paper, while the automobile warning signal would remain timed as before. This separate signal could be an additional light near the current traffic signal (possibly illuminating a yellow bicycle) or a sign upstream from the intersection that lights up a message such as Bicycles Prepare To Stop so that any bicyclist able to view this message should stop before the intersection or risk being caught in the intersection under the red. The principle of the latter signal is the same as that for the Prepare To Stop signs currently used when stopping sight distance is insufficient for a signalized intersection.

It is interesting to note that at different widths, different values of speed yield the highest minimum clearance interval. For example, in the no-acceleration case, a speed of 32.2 km/hr (20 mph) yields the highest minimum clearance interval at the narrow intersection width, while at the two larger intersections, a speed of 16.1 km/hr (10 mph) yields the highest. Since the shapes of these minimum clearance interval-versus-speed curves are convex downward (meaning they have only one minimum), the largest minimum clearance interval is found at either end point of the speed range (16.1 or 32.2 km/hr). By differentiating Equation 3 with respect to v, one obtains the slope of these curves, $1/(2 \cdot d) - (w + L)/v^2$. This slope is negative when v is small and becomes less negative as v increases. The minimum value of $ci_{\min}$ occurs when the slope is 0 or $v = [2 \cdot d \cdot (w + L)]^{0.5}$. For the intersection widths analyzed in Figure 3, these minimums occur at speeds of

- 18.7 km/hr (11.6 mph), narrow;
- 26.1 km/hr (16.2 mph), medium; and
- 32.0 km/hr (19.9 mph), wide.

In this example, computing the minimum clearance intervals for both 16.1 and 32.2 km/hr (10 and 20 mph) and using the highest value would accommodate the bicycle/rider units that would have the most trouble with the intersection width being analyzed. A speed range bounded by the population's lower 7.5 percentile speed and its upper 7.5 percentile speed would accommodate at least the central 85 percent of the population. Obviously, these speed ranges will vary according to intersection location, topography, and the like, but the previous data analysis indicated that this range is about 16.1 to 29.0 km/hr (10 to 18 mph) for relatively flat topography.

METHODOLOGY FOR CLEARANCE INTERVAL COMPUTATION

The following summarizes the previously developed methodology for computing minimum clearance intervals for mixed-use facilities. Compute the automobile minimum clearance interval by an accepted method, such as the one in the *Transportation and Traffic Engineering Handbook*. Compute the bicycle minimum clearance interval as follows, and choose whichever interval is the largest (it or the one computed for automobiles), or use them both and provide separate warning signals for each user. To compute the bicycle minimum clearance interval, the following design values are used in Equation 3: $L = 1.83$ m (6 ft), $t_{p-r} = 2.5$ sec, and $d = 1.22$ m/sec^2 (4 ft/sec^2). Speeds of both 16.1 and 29.0 km/hr (10 and 18 mph) are used, and the largest of the two resulting clearance intervals is chosen. These speeds are valid only for intersections with approximately level grade approaches. If approach grades are significant or any other intersection characteristic affects bicyclists' speeds, different speeds are required.

TIMING SIGNALS FOR BICYCLES

Since bicyclists have the legal right to use almost every roadway, traffic engineers need to time signals for bicyclist safety wherever bicycle volume warrants it. This section deals with how to determine whether bicycle volumes warrant special timing of clearance intervals.

Difficult decisions must be made when considering the tradeoffs between possibly increasing delay to motor vehicle traffic and placing bicyclists in danger by creating dilemma zones for them. Should a signal be timed for mixed traffic if only one bicycle a year crosses the intersection? Probably not. What about one bicycle per day, per hour, per minute, or even more frequently? The problem facing the traffic engineer is easy to identify with. The following relationships are intended to help the with this decision.

$$P = D/(v \cdot C) \tag{6}$$

where

P = probability of a cyclist's being caught in dilemma zone,
D = length of dilemma zone,
v = approach speed, and
C = cycle length.

These values assume random bicycle arrivals.

$$D = v \cdot t_{p-r} + v^2/(2 \cdot d) - v \cdot ci + w + L \tag{7}$$

This formulation assumes no acceleration by the bicyclist. The formulation assuming acceleration would include an additional term, $-a \cdot (ci - t_{p-r})^2/2$.

The length of the dilemma zone is the difference between the distance from the intersection where a bicyclist cannot stop and the distance from the intersection where a bicyclist cannot clear the intersection (Figure 1). The distance from the intersection where a bicyclist cannot stop is given by Equation 2. The distance from the intersection where a bicyclist cannot clear is simply the distance that a bicyclist can travel during the clearance interval ($v \cdot ci$) minus the distance required to clear the intersection ($w + L$), yielding $v \cdot ci - w - L$.

The probability (P) is derived assuming the bicycle/rider unit is equally likely to arrive at the intersection at any point in the traffic signal cycle. In other words, the bicyclist's arrival at the intersection is random with respect to the yellow signal. Since the light turns yellow once in every cycle, and the bicyclist can travel the distance ($v \cdot C$) during the cycle, the bicyclist is equally likely to be at any point on the roadway in the distance ($v \cdot C$) before the intersection when the clearance interval begins. This distance ($v \cdot C$) includes the dilemma zone of length D, so the probability of a bicyclist's being caught in the dilemma zone is simply the ratio of D to the distance that the bicyclist can travel during the signal cycle ($v \cdot C$).

P can be computed for any individual bicyclist or, perhaps more important, for the average bicyclist using any intersection. This probability gives one a feeling for how dangerous the clearance interval of the intersection is for bicyclists. A better measure is obtained by multiplying this probability by hourly bicycle traffic volumes to compute the average number of cyclists caught in the dilemma zone (and presumably in the intersection) per hour. Critical values for this average should be determined through future research.

The probability was derived assuming that bicyclists are equally likely to arrive at the intersection at any point in the signal cycle. This is not a good assumption if something upstream of that intersection systematically influences the timing of bicycle arrivals. An example of this would be a series of traffic signals timed for progression. It is also possible that bicyclists might anticipate the yellow by paying attention to how long the light has been green.

To verify Equations 6 and 7, data were collected at an intersection that has considerable bicycle traffic and no upstream impacts that would systematically affect bicycle arrivals. In computing P, average bicyclist characteristics at this intersection are used instead of the design values. The values assumed are t_{p-r} = 1.5 sec, d = 2.3 m/sec^2 (7.5 ft/sec^2), and v = 19.3 km/hr (12 mph). Though 19.3 km/hr (12 mph) is slower than the 22.5 km/hr (14 mph) average speed suggested by the data analysis, it was chosen because the intersection is fairly congested and has on-street parking. Measured parameters for this intersection are C = 75 sec, w = 20.1 m (66 ft), and ci = 4 sec. This measurement of intersection width is as small as possible. It is measured from curbface to curbface, not stopline to curbface or stopline to stopline. With L = 1.83 m (6 ft), the theoretical dilemma zone size is 14.8 m (48.7 ft) for the average cyclist approaching this intersection, and the theoretical probability that the average cyclist is caught in the dilemma zone is 0.0368 (or 3.68 percent of all cyclists will be caught).

A total of 153 cyclists were observed traveling straight through this intersection. Of these, six (or 3.92 percent) were observed to be in the dilemma zone defined by the average cyclist when the light turned yellow, and four of these six were caught in the intersection when the light turned red (and the cross-street light turned green). One bicyclist, who was traveling very slowly, stopped before the intersection. It is very possible that since his speed was much less than 19.3 km/hr (12 mph), he was not caught in his dilemma zone and could therefore stop. Another cleared the intersection. None of the six cyclists appeared to accelerate in an attempt to clear the intersection. Seven cyclists (including the four already mentioned), or 4.58 percent, were actually caught in the intersection when the light turned red. This indicates that three other cyclists were either caught in their individual dilemma zones, or they made incorrect decisions upon viewing the yellow.

These data appear to agree with the theory (Equations 6 and 7). Both the observed percentage of bicyclists caught in the dilemma zone (3.92) and the observed percentage of bicyclists caught in the intersection (4.58) appear to be very close to the predicted percentage (3.68), but are the differences statistically significant or just the result of chance? The sample is large enough to use the normal approximation to the binomial distribution to test the hypothesis that the true percentage of bicyclists being caught in this intersection (or in this dilemma zone) is 3.68, as predicted by the theory. The two-tailed test of this hypothesis is not even close to being significant for either sample percentage (3.92 or 4.58), so one cannot reject the hypothesis or the theory. It is probable that the small differences between the observed and predicted percentages are due only to chance, so the data do tend to verify the theory.

CONCLUDING COMMENTS

This paper presents (a) a methodology for timing traffic signals for bicycle-automobile mixed traffic, including recommendations on design values for speeds, deceleration and acceleration rates, and perception-reaction times, and (b) a mathematical expression for computing the probability of bicyclists' (through no fault of their own) being caught in the intersection when the cross-street traffic receives a green.

It is recommended that further research be performed to

- More accurately quantify bicyclist perception-reaction times and deceleration and acceleration rates,
- Determine how likely it is that bicyclists will accelerate through yellow signals,
- Better relate bicycle speeds at intersections to various attributes of the intersection environment, and
- Set a standard (in number of bicyclists caught in the dilemma zone per hour) for timing signals for bicycle-automobile mixed use.

In addition, recent accident study results should be examined to determine if conclusions such as Forester's (that inadequate clearance interval duration is the "largest identified facility-associated cause of car-bike collisions") are still valid.

Because of the longer (relative to automobiles) clearance intervals required by bicycles at wide intersections, the most cost-effective solution (considering possible delay and safety costs of longer single clearance intervals to automobile drivers) may be to provide a separate warning signal for bicyclists. This warning signal could be timed according to the procedures outlined in this paper, leaving the automobile warning signal timed as before. This separate signal could be an additional light near the current traffic signal (possibly illuminating a yellow bicycle) or a sign upstream from the intersection that lights up a message such as Bicycles Prepare To Stop so that any bicyclist able to view the message should stop or risk being caught in the dilemma zone. It would be interesting to compare these two options (on a cost/benefit basis) with detector schemes, such as those recommended by the Oregon Department of Transportation, that reduce the probability that bicyclists will be caught in the dilemma zone. The study of these and any other options that enable bicyclists to make correct decisions about their safe clearance of signalized intersections is recommended.

It is further recommended that the results of subsequent studies and the results presented herein be used to form accepted procedures and methods for inclusion in common design manuals, such as the *Transportation and Traffic Engineering Handbook*, AASHTO's *Guide for the Development of Bicycle Facilities*, and city and state design manuals. This will offer the guidance that traffic engineers require to design safe facilities for both automobiles and bicycles.

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