Capacity Analysis of Pedestrian and Bicycle Facilities

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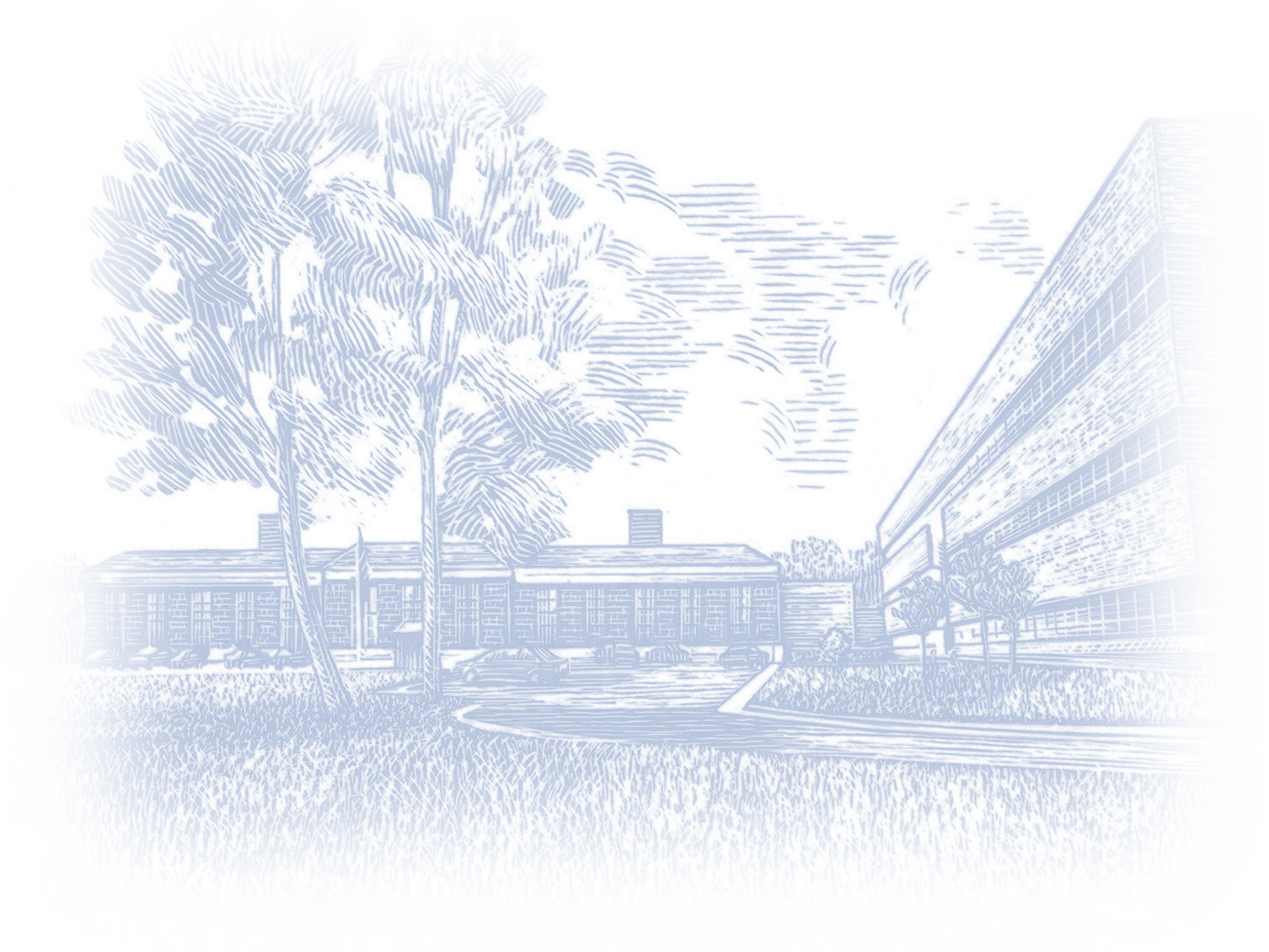

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16. Abstract
The objective of this project was to develop revised operational analysis procedures for transportation facilities with pedestrian and bicyclist users. This document contains both new and revised procedures for analyzing various types of exclusive and mixed–use bicycle facilities. These procedures are recommended to determine the level of service for bicycle facilities on the basis of previous domestic and international bicycle operations research conducted to date. This document only addresses procedures for streets, roads, and intersections with designated bicycle facilities. In addition to this report, there were two additional reports produced as part of this effort on Capacity Analysis of Pedestrian and Bicycle Facilities. These reports are subtitled as:

1. Recommended Procedures for the "Pedestrian" Chapter of the Highway Capacity Manual (FHWA–RD–98–107)
2. Recommended Procedures for the "Signalized Intersection" Chapter of the Highway Capacity Manual (FHWA–RD–98–106)

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INTRODUCTION

The following are the procedures recommended by the research team for future versions of Chapter 14, "Bicycles," of the Highway Capacity Manual(TRB, 1994). These procedures are recommended to determine the Level of Service (LOS) for bicycle facilities based on previous domestic and international bicycle operations research conducted to date as presented in the Bicycle Literature Review Section of the Research Reportfor this project (Rouphail et al., 1997). This document only addresses procedures for streets, roads, and intersections with designated bicycle facilities. Those without designated bicycle facilities will not be addressed here because they normally do not attract enough bicycle users to warrant operational analyses from the bicycle perspective. For an analysis of the characteristics of bicycle facilities that attract/deter cyclists, the reader is referred to a recent study by Harkey et al. (1998).

UNINTERRUPTED BICYCLE FACILITIES

This section focuses on the operational analyses of uninterrupted bicycle facilities, including exclusive off–street bicycle paths, mixed–use off–street paths, and designated bicycle lanes (or paved shoulders). The concept of "frequency of events" is proposed as the service measure of effectiveness for all three types of uninterrupted bicycle facilities. Events, for these procedures, are bicycle maneuvers required by a bicyclist on a path, including passings (same direction encounters) and meetings (opposite direction encounters) as presented by Botma (1995).

The total frequency of events on a facility for these procedures is related to the service volumes of bicycles using or projected to be using the facility, and does not have to be observed directly. Botma has determined the relationship between service volumes of bicycles and the frequencies of passings and meetings under a variety of conditions with the use of field studies and simulation. These relationships are based on certain assumptions regarding the mean speeds and speed distributions of bicycles and pedestrians, which are listed with the various procedures. The speeds of pedestrians and bicycles and their variability affect the number of passings and meetings that occur. If an analyst has detailed information available regarding local pedestrian and bicycle speeds, alternate volume/frequency relationships can be developed (Botma, 1995). However, the development of alternate equations will not be covered here.

A "lane" for bicycles throughout the recommended procedures is considered to be approximately 1.0 m (3.3 ft). However, the actual width of a bicycle facility is much less important than the number of effective bicycle lanes the facility operates with for these analyses. Each additional effective lane being used by bicyclists dramatically increases capacity irrespective of the width of the facility. While this report assumes that 2.1– to 2.4–m (7– to 8–ft) paths and 3–m (10–ft) paths will typically operate with two and three effective lanes, respectively, a particular facility may operate with a different number of effective lanes. Therefore, it is imperative that the number of effective bicycle lanes be observed in the field where possible prior to conducting these analyses.

Pending the development of metric standards for bicycle facilities, it is expected that most of the existing 2.4–m– (8–ft–) wide bicycle facilities conforming to current American Association of State and Highway Transportation Officials (AASHTO) English unit standards (AASHTO, 1991) will operate as two–lane facilities. However, due to the additional width, one should keep in mind that the LOS derived using the two–lane procedures may be on the conservative side. Unfortunately, until further research is conducted regarding these procedures in the United States, it is impossible to quantify the effect of minor differences in path width for a given number of effective bicycle lanes. However, it is the opinion of the research team that the procedures contained in this document will apply to most of the current existing 2.4–m (8–ft) bicycle facilities in the United States.

When using the following procedures, the analyst should note that bicycle flows have different peaking characteristics than motor vehicles. Bicycle volumes peak more abruptly, especially in the vicinity of college and university campuses. Daily volumes, or even hourly volumes, may not appear to be very substantial until this peaking is considered. One study in Madison, Wisconsin (Hunter and Huang, 1995), measured peak hour volumes as 10 to 15 percent of total daily volume at various locations. Another study in the state of Washington (Niemeier, 1996), conducted primarily in the Seattle area, measured peak hour factors between 0.52 and 0.82 at various locations. The applicability of these particular observations to other areas is unknown, but it is obvious from these numbers that failure to account for peaking characteristics when determining flow rates will often result in overly optimistic estimates of LOS.

The two–lane path procedures have also been extended to three–lane paths using the three–lane volumes reported by Botma (1995) and the same weights between passings and meetings as for two–lane paths. Botma only reported frequencies for two–lane paths in his article because he was unsure of the extension to three lanes. Therefore, the three–lane facility analyses presented here should be used with caution. While it is expected that a two–way path with 3–m (10–ft) lanes will operate with more than two effective lanes, the exact relationship between number of lanes and lane width is not yet known for U.S. conditions, and may depend on local bicyclist behavior.

Perhaps the most important thing to note when using the uninterrupted bicycle facility procedures is that LOS "F" is not equivalent to capacityfor the facility. An unacceptable number of events is always reached prior to capacity, and, in some cases, capacity can be almost twice the volume at which LOS F is reached. The procedures in this document are based on frequencies of events and perceived LOS, not on the carrying capacity of the facility.

2.1 Exclusive Off–Street Bicycle Paths

Exclusive off–street bicycle paths are separated from motor vehicle traffic and do not allow pedestrians. These facilities are often constructed to serve areas not served by city streets or to provide recreational opportunities for the public, as illustrated in Figure 1. These bicycle facilities accommodate the highest volumes of bicycles among the three types of uninterrupted facilities addressed in this document, and provide the best LOS because the bicycles are not forced to share the facility with other modes traveling at much higher or lower speeds.

The following equations, which were originally presented by Botma (1995), are proposed for computing the total frequency of events on exclusive bicycle paths. The equations are set up for two–way bicycle paths. For one–way exclusive bicycle paths, a value of zero would be used for the bicycle volume traveling in the opposite direction of that being evaluated.

$$F_{pass} = 0.188\,(V_{bike\text{-}sm}) \qquad [1]$$

$$F_{meet} = 2\,(V_{bike\text{-}op}) \qquad [2]$$

$$F_{total} = 0.5(F_{meet}) + F_{pass} \qquad [3]$$

where:

F_{pass} = frequency of passing in events/h;

F_{meet} = frequency of meeting in events/h;

F_{total} = total weighted frequency of events in events/h;

$V_{bike\text{-}sm}$ = bike volume in the same direction being analyzed in bikes/h; and

$V_{bike\text{-}op}$ = bike volume in the opposite direction being analyzed in bikes/h.

The frequencies of meetings and passings resulting from these equations are based on the assumption that bicycle speeds on paths are normally distributed with a mean of 18 km/h (11.2 mi/h) and a standard deviation of 3 km/h (1.9 mi/h). These values are reasonable, based on the information reported in the Bicycle Literature Review Section of the Research Reportfor this project (Rouphail et al., 1997). If the observed mean speed or standard deviation of speed differs from these values, equations 1, 2, and 3 cannot be used. Consult Table 5 and Example 3 (described later) for such situations.

Tables 1 and 2, which are based on Botma's work, are then proposed to convert the total frequency of events to LOS. Service volumes for a 50:50 directional split are provided in the tables for reference. If a 50:50 directional split for the facility an be assumed, the LOS can be obtained directly by using the service volumes in the tables. For splits other than 50:50, Equations 1 through 3 can be used in combination with Tables 1 and 2.

FIGURE 1: Exclusive bicycle path

TABLE 1 Level of Service (LOS) for two-lane, two-way exclusive bicycle paths (2.1- to 2.4-m paths)

LOS	Total frequency of events (events/h)	Two-lane service volume (bikes/h) in both directions (50:50 split)
A	< 40	65
B	< 60	105
C	< 100	170
D	< 150	250
E	< 195	325
F	≥ 195	------

SOURCE: Adapted from Botma, 1995.

TABLE 2 Level of Service (LOS) for three-lane, two-way exclusive bicycle paths (3–m paths)

LOS	Total frequency of events (events/h)	Three-lane service volume (bikes/h) in both directions (50:50 split)
A	< 90	150
B	< 140	230
C	< 210	350
D	< 300	500
E	< 375	630
F	≥ 375	------

SOURCE: Adapted from Botma, 1995.

All the service volumes given in this section for exclusive paths assume "ideal" conditions. Lateral obstructions, extended sections with appreciable grades, and other local factors may reduce the LOS for a facility. Unfortunately, such factors have not been sufficiently documented to date to make a quantitative assessment of their effects.

2.2 Mixed–Use, Off-Street Paths

Mixed-use, off-street paths, like exclusive bicycle paths, are separated from motor vehicle traffic. However, mixed-use paths allow others to use the path, including pedestrians, rollerbladers, rollerskaters, skateboarders, and those in wheelchairs and any other imaginable mode of non-motorized transportation, as illustrated in Figure 2. Mixed-use paths are often constructed for the same reasons as exclusive bicycle paths: to serve areas not served by city streets or to provide recreational opportunities for the public. Mixed-use paths are also very common on university campuses in the United States because motor vehicle traffic and parking are often heavily restricted. In the United States, there are very few paths limited exclusively to bicycles. Most off-street paths in this country fall into the mixed-use path category.

FIGURE 2: Mixed–use off–street bicycle path

On mixed–use facilities, the presence of pedestrians can be detrimental to bicycle capacity because they move at much lower speeds. However, it is very difficult to establish a single bicycle/pedestrian equivalent value because the relationship between the two modes differs depending on their respective volumes, directional splits, and other conditions.

Note that the LOS on a mixed–use facility is not necessarily the same from the viewpoint of pedestrians and bicycles. Pedestrian LOS on mixed–use paths is discussed separately in the pedestrian chapter of the Research Reportfor this project (Rouphail et al., 1997).

The following equations, which were originally presented by Botma (1995), are proposed for computing the total frequency of events on mixed–use bicycle paths. The equations are set up for two–way bicycle paths. For the rare case of one–way mixed–use bicycle paths (i.e., a 100/0 directional split), the analyst would enter a value of zero for both the bicycle and pedestrian volumes traveling in the opposite direction of that being evaluated.

$$F_{pass} = 3 (V_{ped–sm}) + 0.188 (V_{bike–sm}) \qquad [4]$$

$$F_{meet} = 5 (V_{ped–op}) + 2 (V_{bike–op}) \qquad [5]$$

$$F_{total} = 0.5(F_{meet}) + F_{pass} \qquad [6]$$

where:

F_{pass} = frequency of passing in events/h;

F_{meet} = frequency of meeting in events/h;

F_{total} = total weighted frequency of events in events/h;

$V_{ped\text{-}sm}$ = pedestrian volume in the same direction being analyzed in ped/h;

$V_{ped\text{-}op}$ = bike volume in the opposite direction being analyzed in ped/h;

$V_{bike\text{-}sm}$ = bike volume in the same direction being analyzed in bikes/h; and

$V_{bike\text{-}op}$ = bike volume in the opposite direction being analyzed in bikes/h.

As in the previous section, the frequencies of meetings and passings resulting from these equations are also based on the assumption that bicycle speeds are normally distributed with a mean of 18 km/h (11.2 mi/h), and that pedestrian speeds are normally distributed with a mean of 4.5 km/h (2.8 mi/h). Slower average pedestrian speeds would cause an increase in the frequency of both passings and meetings.

The frequency of events for mixed-use paths for several different bicycle volumes and directional splits has been computed at selected pedestrian volumes for the convenience of the user. These are presented in Table 3. Alternatively, the user may utilize Equations 4 through 6 to compute the total frequency of events. Once computed, the number of events is entered in Table 4 to estimate the prevailing LOS.

TABLE 3 Total frequency of events for mixed-use paths

Bike vol both dir (bikes/h)	**Directional split of bikes (same:opp)**	Total frequency of events (events/h)			
		Two-way pedestrian volumes of			
		0 (ped/h)*	**20 (ped/h)***	**40 (ped/h)***	**80 (ped/h)***
100	30:70	76	131	186	296
100	40:60	68	123	178	288
100	50:50	59	114	169	279

100	60:40	51	106	161	271
100	70:30	43	98	153	263
200	30:70	151	206	261	371
200	40:60	135	190	245	355
200	50:50	119	174	229	339
200	60:40	103	158	213	323
200	70:30	86	141	196	306
400	30:70	303	358	413	523
400	40:60	270	325	380	490
400	50:50	238	293	348	458
400	60:40	205	260	315	425
400	70:30	173	228	283	393
800	30:70	605	660	715	825
800	40:60	540	595	650	760
800	50:50	475	530	585	695
800	60:40	410	465	520	630
800	70:30	345	400	455	565
* 50:50 directional split assumed for pedestrians					

SOURCE: Adapted from Botma, 1995.

It is important to note that all the service volumes given in this section for mixed-use paths assume "ideal" geometric and traffic conditions. Lateral obstructions, extended sections with appreciable grades, and other local factors may reduce the LOS for a facility. Unfortunately, such factors have not been sufficiently documented to date to make a quantitative assessment of their effects.

TABLE 4 Bicycle Level of Service (LOS) for mixed-use paths

LOS	Total frequency of events (events/h) for two-lane paths (2.1- to 2.4-m paths)	Total frequency of events (events/h) for three-lane paths (3-m paths)
A	< 40	< 90
B	< 60	< 140
C	< 100	< 210
D	< 150	< 300
E	< 195	< 375
F	≥ 195	≥ 375

SOURCE: Adapted from Botma, 1995.

2.3 On-Street Bicycle Facilities

Bicycle lanes are lanes on a street designated exclusively for the use of bicycles. These lanes are separated from motor vehicle traffic by pavement markings, as illustrated in Figure 3. Bicycle lanes are normally placed on streets where bicycle use is fairly high and the separation of bicycles from motor vehicle traffic is warranted. For additional information about the planning for on-street bicycle facilities, the user is referred to a study by Harkey et al. (1998).

Paved shoulders are part of the cross section of the street, but not part of the traveled way for motor vehicles. Bicycles using paved shoulders are separated from motor vehicles by the right edge line (shoulder stripe). Paved shoulders are often constructed on new roadway facilities when allowed by right-of-way requirements.

Bicycles generally use paved shoulders as one-way facilities in the same direction as motor vehicle traffic, much like bicycle lanes. For the purpose of analysis, designated bicycle lanes and paved shoulders will be treated the same. The procedures in this section are appropriate for on-street facilities where there are significant distances between interruptions, such as traffic signals or STOP signs. See the Combined Bicycle Facility section of this document for a discussion of on-street bicycle lanes or paved shoulders with frequent interruptions.

The widths of on-street bicycle facilities vary greatly in the United States, ranging from 1.2-m (4-ft) designated bicycle lanes to 3-m- (10-ft-) wide paved shoulders. However, due to the fact that bicycles using on-street facilities can "borrow" space from the adjacent lane under low to moderate motor vehicle volumes, there are very few on-street facilities that do not operate with at least two effective lanes (allowing passing). Due to this and the fact that on-street bicycle facilities are normally provided for the exclusive use of bicycles, it is recommended that the procedures for exclusive bicycle paths presented previously in this document also be used here for on-street facilities.

FIGURE 3: Designated on-street bicycle lane

It is expected that on-street bicycle lanes and paved shoulders with widths up to 1.8 m (6 ft) will operate with two effective lanes and that wider paved shoulders will operate as three effective lanes. However, heavy motor vehicle volumes, high speeds, roadway debris, or other local conditions may affect the actual width available to the bicyclists. As mentioned earlier, an observation of facility operation prior to analysis is recommended to determine the actual number of effective lanes.

One important distinction between on-street facilities and exclusive off-street facilities is the multitude of possible factors affecting LOS for on-street facilities, including adjacent motor vehicle traffic (which is often moving much faster than the bicycles), heavy vehicle traffic, commercial and residential driveways, and adjacent on-street parking. The service volumes given in this section for on-street facilities are for "ideal" conditions. The factors mentioned here, in addition to lateral obstructions, extended sections with appreciable grades, and other local factors, may reduce the LOS for a facility. Unfortunately, such factors have not been sufficiently documented to date to make a quantitative assessment of their effects. One possible approach to determining LOS for on-street bicycle facilities is to quantify the impact of prevailing geometric and traffic conditions on the average and standard deviation of bicycle speeds on the facility. Under this framework, the expectation is that friction with vehicular traffic, parked vehicles, and driveway density would result in a lower mean speed and higher standard deviation than on a comparable off-street path. To illustrate this effect, Table 5 gives the number of events and corresponding LOS for a range of bicycle volumes and average and standard deviations of bicycle speeds. As indicated in the table, the number of events

increases (and LOS drops) as speed decreases and standard deviation increases. For example, with a bicycle flow rate of 200 bicycles/h, the LOS may vary from A to E depending on the observed values of mean and standard deviation of bicycle speeds. With proper calibration of these two parameters, the proposed methodology could, therefore, be equally applied to on-street bicycle facilities. The standard deviation of speeds describes the variation in speeds about the average or mean bicycle speed for the facility. The standard deviation will be relatively smaller for those facilities used primarily by commuters, and relatively larger for recreational facilities.

TABLE 5 Effect of bicycle mean and standard deviation of speeds on events and Level of Service (LOS) for one-way, on-street bicycle facilities

Bicycle flow rate (bike/h)	Standard deviation [a] (km/h)	Number of events and LOS								
		Bicycle mean speed (km/h)								
		12	13	14	15	16	17	18	19	20
100	1.5	28(A)	26(A)	24(A)	---	21(A)	20(A)	19(A)	18(A)	17(A)
100	3.0	56(B)	52(B)	48(B)	23(A)	42(B)	40(B)	38(A)	36(A)	34(A)
100	4.5	85(C)	78(C)	73(C)	68(C)	63(C)	60(C)	56(B)	53(B)	51(B)
200	1.5	56(B)	52(B)	48(B)	45(B)	42(B)	40(B)	38(A)	36(A)	34(A)
200	3.0	113(D)	104(D)	97(C)	90(C)	85(C)	80(C)	75(C)	71(C)	68(C)
200	4.5	169(E)	156(E)	145(D)	135(D)	127(D)	119(D)	113(D)	107(D)	102(D)
300	1.5	85(C)	78(C)	73(C)	68(C)	63(C)	60(C)	56(B)	53(B)	51(B)
300	3.0	169(E)	156(E)	145(D)	135(D)	127(D)	119(D)	113(D)	107(D)	102(D)
300	4.5	254(F)	234(F)	218(F)	203(F)	190(E)	179(E)	179(E)	160(E)	152(E)

[a] Standard deviation of bicycle speeds. If standard deviation data are unavailable, use the following default values:
1.5 km/h for facilities used primarily by commuters
2.0 km/h for facilities used by various user types
4.5 km/h for facilities used primary by recreational users

SOURCE: Adapted from Botma, 1995.

INTERRUPTED BICYCLE FACILITIES

This section focuses on operational analyses of interrupted bicycle facilities, including signalized and unsignalized on-street designated bicycle facilities with and without exclusive right-turn lanes for motor vehicle traffic. An example of a bicycle lane treatment at a signalized intersection having an exclusive right-turn lane is shown in Figure 4.

The concept of "control delay" is proposed as the service measure of effectiveness for interrupted bicycle facilities. Control delay is the portion of the total delay incurred by bicyclists passing through an intersection that is caused by the intersection traffic control, and includes initial deceleration, queue move-up time, stopped delay (i.e., the actual time stopped) and final acceleration delay. Control delay differs from total delay in that control delay does not include the delay caused by factors other than the intersection traffic control.

Delay is very important to bicyclists because bicyclists are completely exposed to the elements. Also, excessive delays to bicyclists on designated bicycle facilities may cause them to disregard traffic control devices or use alternate routes that are not intended for bicycle use. Once bicycle delay is determined, it can also be incorporated with vehicle and pedestrian delays to get a multimodal LOS for the intersection.

FIGURE 4: Bicycle lane treatment at a signilized intersection

Only intersections with on-street bicycle facilities will be addressed in this document. It is acknowledged that interruptions exist between off-street facilities and crossing streets or other off-street facilities, but these types of intersections are not common in the United States and have not been extensively researched.

3.1 Signalized Intersections

A signalized intersection covered by these procedures is one where there is a designated on-street bicycle lane on at least one approach.

It is proposed that control delays be estimated from the uniform delay portion of the delay model in the Highway Capacity Manual (HCM)(TRB, 1994) as currently applied to motor vehicles for signalized intersections. The HCMcurrently uses stopped delay instead of control delay for signalized intersections, but that is likely to be changed to control delay (signal delay) in future editions.

The typical width of an on-street bicycle lane for which this recommended analysis applies is between 1.2 and 1.8 m (4 and 6 ft). A wide range of capacities and saturation flow rates have been reported around the world for these types of facilities. The ideal saturation flow rate may be as high as 2,600 bicycles/h of green, based on our observations of signalized intersections with significant bicycle traffic as described in the Research Reportfor this project (Rouphail et al., 1997). However, very few intersections provide ideal conditions for bicycles. Adjustment factors for less than ideal conditions have not been sufficiently documented to date to make any meaningful recommendations at this time. Until adjustment factors are developed, it is recommended that a saturation flow rate of 2,000 bicycles/h of green be used as an average value for most intersections.

Using a saturation flow rate of 2,000 bicycles/h of green assumes that right-turning motor vehicles yield the right of way to through-bicyclists as required by law. Aggressive right-turning traffic could reduce this value.

It is then recommended that the capacity of an on-street bicycle facility at a signalized intersection be computed as follows:

$$c_{bike}=s_{bike}(g/C) \qquad [7]$$

where:

c_{bike}= capacity of the designated on-street bicycle facility in bicycles/h;
s_{bike}= saturation flow of the designated on-street bicycle facility in bicycles/h of green;
g = effective green time in s; and
C = cycle length in s.

Control delay is then computed as follows:

$$d= 0.5C\,[1 - (g/C)]^2 / \{1 - (g/C)[\mathrm{Min}\,(V_{bike}/ c_{bike}, 1.0)]\} \qquad [8]$$

where:

d= average signal delay in s/bicycle;
g = effective green time in s;
C = cycle length in s;
Min = minimum (smaller) of V_{bike}/c_{bike} and 1.0;
V_{bike}= flow rate of bicycles in bicycles/h; and
c_{bike}= capacity of the designated on-street bicycle facility in bicycles/h.

The delay equation shown here differs slightly from the delay equation contained in Chapter 9 of the 1994 Update to the 1985 HCMbecause it computes control delay as opposed to stopped delay. This equation applies to both through and right-turning bicycles. It also applies to those left-turning bicycles making a "pedestrian style" left turn (i.e., in two stages, with bicycles traveling adjacent to the pedestrian crosswalks of the two intersecting streets). Advanced bicyclists who leave the bicycle lane and make left turns with motor vehicles are not covered by this procedure. Users of this procedure should also note that right-turning bicycles at intersections with heavy pedestrian flows will often experience additional delay depending on the configuration of the approach.

It is then recommended that the LOS be determined based on control delay, as shown in Table 6. These values are taken from the unsignalized chapter of the HCM. These are lower than the values in the signalized chapter for motor vehicles. However, lower delays are justified because bicycles are exposed to the elements.

TABLE 6 Level of Service (LOS) for interrupted bicycle facilities

LOS	Control delay (s)
A	< 5
B	< 10
C	< 20
D	< 30
E	< 45
F	> 45

SOURCE: Adapted from TRB, 1994.

At most signalized intersections, the only delay to through bicycles is caused by the signal itself because bicycles have the right of way over turning vehicles during the green phase. One possible exception is at signalized intersections, which force bicycles to weave with right-turning motor vehicle traffic on the intersection approach. This could cause additional delay to bicycle traffic at high motor vehicle volumes, although there is a lack of prior research in this area to confirm this effect. The research team was unable to effectively study the potential for a weaving effect due to a lack of suitable locations in the United States, as reported in the Research Reportfor this project (Rouphail et al., 1997). Therefore, at this time, it is impossible to make any recommendations as to the additional delay that may be caused by weaving-type configurations.

3.2 Unsignalized Intersections

An unsignalized intersection covered by these procedures is one where there is a designated on-street bicycle lane on at least one of the minor approaches.

The analysis procedures recommended for unsignalized intersections are for the minor approaches that are controlled by STOP signs. Bicycles on the major approaches are not delayed at most unsignalized intersections because they have the right of way over turning vehicles. One possible exception is at unsignalized intersections, which force bicycles to weave with right-turning motor vehicle traffic on the intersection approach. This could cause additional delay. However, at this time, it is impossible to make any recommendations as to the additional delay that may be caused by weaving-type configurations because of a lack of prior research in this area.

It is also assumed that bicycles on a minor approach turning right from one designated bicycle lane to another are not delayed because they do not have to wait for gaps in motor vehicle traffic. Experienced bicyclists making left turns from either the minor or major approach often leave the bicycle lane and queue with motor vehicles. It is impossible to make any recommendations as to the analysis of these types of left turns due to a lack of prior research in this area. Many bicyclists make "pedestrian style" left turns, which involve crossing the street twice. These bicycles are then effectively through-traveling-bicycles and should not be counted as left turns.

Very little research has been conducted regarding the evaluation of bicycle "critical gaps," and no research regarding "follow-up times" could be located for bicycles as used in the HCMfor computing control delay for motor vehicles at unsignalized intersections. Gap distributions have been reported by both Ferrara (1975) and Opiela et al. (1980) for bicycles crossing two-lane major streets. However, the research team is uncomfortable recommending the 3.2-s critical gap reported by Opiela et al. or a critical gap based on Ferrara's data because either would be much lower than the current critical gap used in the HCMfor motor vehicles in the same situation.

It is felt that the methodology currently used in the HCMfor motor vehicles at unsignalized intersections is also applicable to bicycles. Once critical gaps and follow-up times for bicycles are determined, it is recommended that the average control delay for bicycles be computed using the delay equation in Chapter 10 of the HCM. One caution deserves mention here. Bicycles differ from motor vehicles in that they normally do not queue linearly at a STOP sign. As a result, multiple bicycles often accept a single available gap. This fact will probably impact the determinations of bicycle follow-up times. Unfortunately, no prior research documenting and quantifying this behavior could be located.

It is then recommended that users determine the LOS based on control delay, as shown in Table 5, which is based on the values currently given in the HCMfor motor vehicles at unsignalized intersections. Due to a lack of prior research in this area, the research team cannot make any recommendations regarding delay and LOS for bicycles at all-way stop intersections at this time.

COMBINED BICYCLE FACILITIES

This section focuses on operational analyses of combined designated on-street bicycle facilities with uninterrupted and interrupted elements (e.g., arterials).

The research team proposes to use average bicycle travel speed, including stops, as the service measure of effectiveness for combined bicycle facilities. The average travel speed is based simply on the travel distance between two points and the average amount of time required to traverse that distance, including stops at intersections.

For these procedures, combined bicycle facilities are on-street arterials made up of both segments and intersections with designated bicycle facilities. The first step in analyzing an arterial is to define its limits. Once the limits are defined, the arterial must be broken into individual segments and intersections for analysis. Average travel speed is then computed as follows:

$$ats_{bike} = \frac{l_{total}}{[\{\Sigma\, l_i/(as_i)\} + \{(\Sigma\, d_j)\,/\,3600\}]} \qquad [9]$$

where:

ats_{bike}= average travel speed of bicycles in km/h;

l_{total}= total length of arterial in km over which bicycles travel;

l_i= length of segment (i) in km; as $_i$= bicycle running speed over segment (i) in km/h; and

d_j= average bicycle delay at intersection (j) in s.

Similar to motor vehicle traffic, bicycle speeds on uninterrupted facilities are not affected by volume over a large initial range. It is recommended that 25 km/h (15.5 mi/h) be used as the average bicycle running speed for the combined bicycle facility procedure. This speed falls within the range of speeds from previous studies as reported in the Bicycle Literature Review Section of the *Research Report*for this project (*Rouphail et al., 1997*).

The research team acknowledges that there are many other possible factors affecting speed, including adjacent motor vehicle traffic, which is often moving much faster than the bicycles; commercial and residential driveways; adjacent on-street parking; lateral obstructions; extended sections with appreciable grades; and other local factors. Unfortunately, factors such as these have not been sufficiently researched to date to make any quantitative assessment of their effects. Intersection delay is computed as described in the Interrupted Facilities section.

It is then recommended that the LOS be determined as shown in Table 7. This table is based on roughly the same ratios of average travel speeds to the ideal average speed currently given in Chapter 11 of the *HCM*for motor vehicles on arterials.

TABLE 7 Bicycle arterial Level of Service (LOS)

Bicycle running speed	**25 km/h**
LOS	Average travel speed* (km/h)
A	≥ 22
B	≥ 15
C	≥ 11
D	≥ 8
E	≥ 7
F	< 7

*computed from Equation [9]; includes stops

SOURCE: Adapted from *TRB*, 1994.

EXAMPLE PROBLEMS

Example 1 - Uninterrupted, Exclusive Bicycle Path

For this example, the following is assumed:

- the bicycle path operates with two effective lanes;
- the path runs approximately north-south;
- peak-hour volume of 90 bicycles/h;
- peak-hour factor of 0.60; and
- a 70:30 directional split northbound:southbound.

The first step is to convert the peak-hour volume to a peak flow rate as follows:

1. Adjusted Peak-Hour Flow Rate = Peak-hour volume/peak-hour factor = 90/0.60 = 150 bikes/h
2. The total frequency of events and LOS for each direction is then computed using Equation [3] (which incorporates Equations [1] and [2]) and the computed peak flow rate of 150 bikes/h:

$F_{total} = 0.5\ [F_{meet}] + [F_{pass}]$

$= 0.5\ [2\{V_{bike\text{-}op}\}] + [0.188\{V_{bike\text{-}sm}\}]$

$= 0.5\ [2\{(\text{opp. dir. split})(\text{peak flow rate})\}] + [0.188\{(\text{same dir. split})(\text{peak flow rate})\}]$

NORTHBOUND: $F_{total} = 0.5\ [\ 2\{(0.30)(150)\}] + [0.188\{(0.70)(150)\}] =$ **65 events/h**

Using Table 1, this represents **LOS C**for the northbound direction.

SOUTHBOUND: $F_{total} = 0.5\ [\ 2\{(0.70)(150)\}] + [0.188\{(0.30)(150)\}] =$ **113 events/h**

Using Table 1, this represents **LOS D**for the southbound direction.

Example 2 - Uninterrupted, Mixed-Use Path

For this example, the following is assumed:

- the bicycle path operates with three effective lanes;
- the path runs approximately east-west;
- adjusted peak-hour flow rate of 150 bicycles/h;
- adjusted peak-hour flow rate of 80 pedestrians/h;
- a 60:40 directional split of bicycles eastbound:westbound; and
- a 50:50 directional split of pedestrians eastbound:westbound.

The total frequency of events and LOS for each direction is then computed using Equation [6] which incorporates Equations [4] and [5]):

$F_{total} = 0.5 [F_{meet}] + [F_{pass}]$

$= 0.5 [5\{V_{ped-op}\} + 2\{V_{bike-op}\}] + [3\{V_{ped-sm}\} + 0.188\{V_{bike-sm}\}]$

= 0.5 [5{(opp. dir. ped split)(ped peak flow rate)} + 2{(opp. dir. bike split)(bike peak flow rate)}] + [3{(same dir. ped split)(ped peak flow rate)}

+ 0.188{(same dir bike split)(bike peak flow rate)}]

EB: $F_{total} = 0.5 [5\{(0.5)(80)\} + 2\{(0.4)(150)\}] + [3\{(0.5)(80)\} + 0.188\{(0.6)(150)\}]$

= **297 events/h**

Interpolation between 100 and 200 bikes/h on Table 3 produces the same results. Using Table 4, this represents **LOS D**for the eastbound direction.

WB: $F_{total} = 0.5 [5\{(0.5)(80)\} + 2\{(0.6)(150)\}] + [3\{(0.5)(80)\} + 0.188\{(0.4)(150)\}]$

= **321 events/h**

Interpolation between 100 and 200 bikes/h on Table 3 produces the same results. Using Table 4, this represents **LOS E**for the westbound direction.

Example 3 - On-Street Bicycle Lane

For this example, the following is assumed:

- a bicycle lane with allowance for passing;
- hourly bicycle volume of 150 bicycles/h, and a PHF of 0.75;
- heavy side friction characterized by large vehicle volume and high driveway density; and
- observed mean speed of 18 km/h and standard deviation of 4.5 km/h.

Since the standard deviation of speeds of 4.5 km/h is different from the default value of 3 km/h, equations [1] to [3] cannot be used. Table 5 must be used to predict the number of passing events and LOS.

First, the bicycle volume is converted to a peak flow rate as follows:

Bicycle flow rate = Hourly Volume/ PHF = 150/0.75= 200 bikes/h

Referring to Table 5, for 200 bikes/h, a mean speed of 18 km/h and standard deviation of 4.5 km/h, the predicted number of passing events is 113/h. This represents a **LOS D**on the facility.

For comparison purposes, if the default values were used (18 km/h, 3 km/h standard deviation), the predicted number of events would drop to 75 events/h. This would incorrectly represent **LOS C**on the facility.

Example 4 - Interrupted, Signalized Intersection For this example, the following is assumed:

- effective green time for movement in question = 20 s, cycle length = 50 s; and
- adjusted peak-hour flow rate is 120 bicycles/h for approach in question.

First, the capacity is computed using Equation [7], with an assumed bicycle saturation flow rate (s_{bike}) of 2000 bikes/h of green:

$c_{\text{bike}} = s_{\text{bike}}(g/C) = 2000(20/50) =$ **800 bikes/h**

The average signal delay is then computed using Equation [8]:

$d = 0.5C\,[1 - (g/C)]^2 / \{1 - (g/C)[\text{Min}\,(V_{\text{bike}} / c_{\text{bike}}, 1.0)]\}$

$= 0.5(50)\,[\,1 - (20/50)\,]^2 / \{\,1 - (20/50)[\text{Min}\,(120/800, 1.0)]\,\} =$ **9.6 s**

Using Table 6, this represents **LOS B.**

Example 5 - Combined Bicycle Facility

For this example, the following is assumed:

- the 2-km (1.2-mi) arterial contains four links and three signalized intersection nodes;
- the peak direction for this link during the peak hour is westbound;
- the four links are 0.5, 0.2, 1.0, and 0.3 km (0.31, 0.12, 0.62, and 0.19 mi) in length, respectively;
- the signalized intersections all have cycle lengths (C) of 100 s with g/C ratios of 0.3, 0.5 and 0.4 on the westbound approaches; and
- the adjusted peak-hour flow rate in the westbound direction is 600 bicycles/h.

The average delays for each of the intersections are computed using Equation [8] (which incorporates Equation [7]) and an assumed bicycle saturation flow rate (s_{bike}) of 2000 bikes/h of green:

$d_i = 0.5C\,[1 - (g/C)]^2 / \{1 - (g/C)[\text{Min}\,(V_{\text{bike}} / \{c_{\text{bike}}\}, 1.0)]\}$

$= 0.5C\,[1 - (g/C)]^2 / \{1 - (g/C)[\text{Min}\,(V_{\text{bike}} / \{(s_{\text{bike}})(g/C)\}, 1.0)]\}$

$d_1 = 0.5\,(100)\,[1 - (0.3)\,]^2 / \{\,1 - (0.3)\,[\text{Min}\,(600/\{(2000)(0.3)\}, 1.0\,]\,\} = 35.0$ s

$d_2 = 0.5\,(100)\,[1 - (0.5)\,]^2 / \{\,1 - (0.5)\,[\text{Min}\,(600/\{(2000)(0.5)\}, 1.0\,]\,\} = 17.9$ s

$d_3 = 0.5\,(100)\,[1 - (0.4)\,]^2 / \{\,1 - (0.4)\,[\text{Min}\,(600/\{(2000)(0.4)\}, 1.0\,]\,\} = 25.7$ s

Using an average uninterrupted travel speed (as_i) of 25 km/h (15.5 mi/h) for all links, the average travel speed for the arterial is computed using Equation 9:

$$ats_{\text{bike}} = \frac{l_{\text{total}}}{[\{\Sigma\, l_i/(as_i)\} + \{(\Sigma\, d_j) / 3600\}]}$$

$= 2 / [\,\{\,(0.5 + 0.2 + 1.0 + 0.3) / (25)\} + \{\,(35.0 + 17.9 + 25.7\,) / 3600\,\}] =$ **19.6 km/h**

Using Table 7, this represents **LOS B.**

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