Operational Analysis of Uninterrupted Bicycle Facilities

D. PATRICK ALLEN, NAGUI ROUPHAIL, JOSEPH E. HUMMER, AND JOSEPH S. MILAZZO II

The popularity of bicycles in North America is growing. As the popularity of bicycles has increased, so has the physical network of separate bicycle facilities and designated bicycle lanes in many locations. As a consequence of this growth, there is a demand for more information about bicycle operations on these facilities. Unfortunately, the state of knowledge regarding bicycle operations in the United States currently lags far behind that of motor vehicles and pedestrians. The international research that has been conducted to date regarding bicycle operations on uninterrupted facilities is thoroughly reviewed, and recommended procedures for the operational analysis of uninterrupted bicycle facilities are outlined. The recommended procedures are based on the concept of "frequencies of events" involving a bicyclist and other bicyclists or facility users. Events are defined as bicycle maneuvers required by a bicyclist on a facility, including passings (same-direction encounters) and meetings (opposite-direction encounters). The frequency of events for an uninterrupted bicycle facility is related to the service volumes of bicycles using or projected to be using the facility and does not have to be observed directly. The proposed procedures are, therefore, recommended based not only on their theoretical substance but also on their ease of use by practitioners.

There has been a measurable increase in bicycle use in the United States for both recreational and purposeful trips. As the popularity of bicycles has increased, so has the need to develop methods that can assist transportation engineers and planners in analyzing the performance of bicycle facilities. Unfortunately, the state of knowledge regarding bicycle operations in the United States currently lags far behind that of motor vehicles and pedestrians.

The focus of this article is on "uninterrupted facilities," where bicycle impedance is caused primarily by competition for space with other users (bicycles, pedestrians, joggers, etc.) and by the geometric conditions of the facility. Traffic control effects are, therefore, not relevant to this analysis. The document is organized as follows. In the first section, some basic characteristics of bicycle users are presented followed by a discussion on key bicycle attributes, such as space, bicycle speeds, and facility capacity. The second section describes bicycle facility types. The third section discusses the proposed analysis methodology to be incorporated in a future version of the *Highway Capacity Manual* (*1*) and its application in a numerical setting. The final section provides conclusions and recommendations.

BICYCLE CHARACTERISTICS

Bicycle Use and User Characteristics

There are estimated to be over 100 million bicyclists in the United States, but it is estimated that less than 1 percent of travel trips are made by bicycling in this country (*2*). According to one source (*3*), there are three general categories of bicycle users: the child bicyclist, the casual or inexperienced adult bicyclist, and the experienced adult bicyclist. A report released by the Federal Highway Administration (*4*) divides bicyclists into three similar categories: Group A—advanced bicyclists, Group B—basic bicyclists, and Group C—children. The behavior and attributes of these three groups differ enough to warrant categorization. However, most designated bicycle facilities cater to all three types of bicyclists.

D. P. Allen, California Department of Transportation, 1910 Olympic Boulevard, Suite 151, Walnut Creek, CA 94596. N. Rouphail, J. E. Hummer, and J. S. Milazzo II, Department of Civil Engineering, North Carolina State University, Raleigh, NC 27695-7908.

The child bicyclist (Group C) is defined as a bicyclist who is too young to obtain a driver's license (age 16 in most states). Approximately three-quarters of all children under age 16 ride bicycles, and this group makes up a little less than half of all bicyclists (*3*). A high percentage of children are forced to ride bicycles because they have no other transportation alternatives. This group tends to prefer residential streets with low motor vehicle speed limits and volumes, well-defined bicycle lanes on arterials and collectors, and separate bicycle paths.

The casual or inexperienced adult bicyclist (Group B) is defined as someone who is old enough to possess a driver's license, is moderately skilled, and has a basic, but not extensive, knowledge of bicycling. For this group, bicycling is mostly a recreational activity that is done on residential streets and bicycle paths. However, this group will occasionally make purposeful trips and use major streets. It is estimated that this group makes up approximately 40 percent of the overall bicycling population (*3*).

The experienced or advanced adult bicyclist (Group A) is defined as an experienced, knowledgeable, and skilled bicyclist who is old enough to possess a driver's license. This group tends to use the bicycle for longer trips, and more often for purposeful trips, than the casual adult bicyclist. It is estimated that this group makes up approximately 10 percent of the overall bicycling population (*3*). Cyclists in this group normally prefers the most direct route to their destination, and riders are willing to use a variety of different street types with or without designated bicycle facilities.

A document released by FHWA (*2*) reports that over 50 percent of bicycle trips in the United States are taken for social/recreational purposes. The other trip categories were personal/family business, school/church, work, and other. Bicycle trips will be divided into two categories for the remainder of this article: recreational trips and purposeful trips. Purposeful trips include all categories other than social/recreational. The fact that more than half of all bicycling trips are recreational must be considered when analyzing bicycle traffic because the same is not normally true for motor vehicles.

Hunter and Huang (*5*) conducted a study in several U.S. cities. The study found that bicycle volumes, between the hours of 7:00 a.m. and 7:00 p.m. on weekdays, were fairly constant with peak-hour volumes being approximately one and one-third times the average hourly volumes. They also found that the peak hours on weekdays typically corresponded with local commuter schedules. In one city, they measured peak hour volumes as 10 to 15 percent of total daily volume. The proportion of weekday to weekend traffic varied widely depending on the recreational uses of the bicycle facilities.

A study conducted in the Seattle area by Niemeier (*6*) analyzed bicycle volume data collected over 1 year at five separate locations. The study showed that bicycle volumes were higher during the evening peak than during the morning peak at four of the five locations. Three of the locations had more than double the volume during the evening peak. Bicycle peak-hour factors between 0.52 and 0.82 were observed during the morning peaks at the various locations, and peak-hour factors between 0.58 and 0.80 were observed during the evening peaks. The study showed significant variability in volumes over the year. This variability suggested that a single volume count could be biased by as much as ±15 percent depending on the time of year the count was taken. Volumes were much lower during adverse weather, which one would expect because cyclists are exposed to the elements.

Due to the recreational and social nature of bicycling, bicycle users often ride in pairs. A Dutch study found that, in the Netherlands, the number of paired bicycles was a function of bicycle volume (*7*). However, the relationship differed with location. As expected, the study also found that paired riding was more common during recreational bicycle trips than purposeful trips. The fact that bicyclists often ride in pairs has been noted by others, but no other attempt has been made to quantify this phenomenon.

Bicycle Properties

Space Requirements

A typical bicycle in the United States is 1.75 m (5.75 ft) in length with a handlebar width of 0.6 m (2 ft) (*3*). In the Netherlands, it has been reported that 95 percent of bicycles are less than 1.9 m (6.25 ft) in length and that 100 percent of bicycle handlebar widths are less than 0.75 m (2.5 ft) (*8*).

In addition, a bicyclist needs a certain amount of operating space. No bicyclist, at any speed, can ride a bicycle in a perfectly straight line. One U.S. source reports that a typical bicycle needs between 0.75 m (2.5 ft) and 1.40 m (4.5 ft) of width to operate (*3*). This amount of space can also be referred to as the *effective lane width* for a bicycle. An older study in Davis, California (*9*), recommends a minimum width of 1.28 m (4.2 ft) for bicycles with additional width at higher volumes. In the Netherlands, 1 m (3.3 ft) of clear space is generally recommended for bicycles (*8*). In Germany, 1 m (3.3 ft) is reported as the normal width of one bicycle lane (*10*). In Sweden, 1.2 m (3.95 ft) is reported as a typical bicycle lane width (*11*). A Chinese study reports that the width of a two-lane bicycle path in China is generally 2.5 m (8.2 ft) with an additional 1 m (3.3 ft) added for each additional lane (*12*). The Norwegian Public Roads Administration believes that "one meter is not enough" and recommends a width of 1.6 m (5.3 ft) for single-lane bicycle lanes (*13*).

Overall space requirements for bicycles can also be defined with respect to density. A Canadian study (*14*) found that bicycle operating space greater than 9.3 m^2/bicycle (100.1 ft^2/bicycle) provided for free-flow bicycle conditions. The study also found that, when less than 3.0 m^2/bicycle (32.3 ft^2/bicycle) of operating space is provided, there was no freedom for bicycles to maneuver. A study in China (*12*) found that bicycle operating space greater than 10 m^2/bicycle (107.6 ft^2/bicycle) provided very comfortable operations, and that less than 2.2 m^2/bicycle (23.7 ft^2/bicycle) forced most cyclists to dismount and walk their bicycles. An older study in Davis, California (*15*), found that bicycle operating space greater than 20 m^2/bicycle (200 ft^2/bicycle) provided free-flow conditions, and that less than 3.7 m^2/bicycle (40 ft^2/bicycle) was congested.

Free-Flow Speed

Free-flow speed is also important in the study of bicycle operations. A study conducted in Davis, California (*9*), reported a mean velocity of approximately 19 km/h (11.8 mph) for Class I bicycle facilities and mean bicycle velocities of between of approximately 17.7 km/h (11.0 mph) to 20.1 km/h (12.5 mph) for Class II facilities. Class I facilities are off-street paths, and Class II facilities are designated on-street bicycle lanes.

Another study conducted in Davis, California, reports that the free-flow speed of bicycles is usually above 17.7 km/h (11.0 mph) (*15*). A study conducted primarily in Michigan on university campuses reported average observed speeds of 24.9 km/h (15.5 mph) on bicycle lanes and 20.3 km/h (12.6 mph) on bicycle paths (*16*). A manual released by FHWA (*17*) reported that the 85th percentile speed of bicycles is approximately 24 km/h (15 mph) and that a design speed of 32 km/h (20 mph) on level terrain would allow for nearly all bicyclists to travel at their desired speeds.

In Sweden, the 85th percentile free-flow speed of bicycles is reported to be between 16 km/h (10 mph) and 28 km/h (17.4 mph) (*11*). A Canadian study found a free-flow speed of 25 km/h (15.5 mph) (*14*). One study in China reported observed average bicycle speeds at various locations between 10 km/h (6.2 mph) and 16 km/h (10 mph) with an overall mean of approximately 12 km/h (7.5 mph) (*18*). Another Chinese study reported observed average bicycle speeds between 12 km/h (7.5 mph) and 16.3 km/h (10.1 mph), with an overall mean of approximately 14 km/h (8.7 mph) (*19*). A more recent Chinese study reported peak-hour free-flow speeds of 18.2 km/h (11.3 mph) where bicycle traffic was separated from motor vehicles by a barrier and 13.9 km/h (8.6 mph) at locations without a lane barrier (*20*). A Dutch study reported a mean bicycle speed of 18 km/h (11.2 mph) with a standard deviation of 3 km/h (1.9 mph) (*21*). The Dutch study also reported that the observed average speed appeared to be unaffected by path width.

In summary, free-flow bicycle speed appears to be somewhere between 10 km/h (6.2 mph) and 28 km/h (17.4 mph) with a majority of the observations being between 12 km/h (7.5 mph) and 20 km/h (12.4 mph). The design speed recommended by AASHTO for bicycle facilities in the United States is 32 km/h (20 mph) (*22*), which is the same as that recommended by FHWA in its manual discussed earlier (*17*).

Capacity

Capacity or saturation flow of bicycle facilities is rarely observed in practice, especially in the United States The *Highway Capacity Manual* (*HCM*) (*1*) lists ranges of reported capacities for bicycle facilities between 500 and 2,350 bicycles per hour depending on the type of facility, the number of lanes, and one-way or two-way operation.

A study in Davis, California, reports that bicycle facility capacity is reached at approximately 2,600 bicycles/hour per 1-m (3.3-ft) lane (*15*). Another study in Davis, California, simulated a roadway with bicycle lane widths of 1.2 m (4 ft), 1.8 m (6 ft), and 2.4 m (8 ft) (*23*). The study used the data collected from simulation to develop an equation that predicted bicycle saturation flow from bicycle lane width. Using a 1.2-m (4-ft) lane width in this equation produces a saturation flow of 3,060 bicycles/hr.

The *Swedish Capacity Manual* suggests 1,500 bicycles/hr as the planning capacity of a 1.2-m (4-ft) bicycle lane (*11*). A Canadian study reported the capacity of a 2.5-m (8.2-ft) bicycle path as 10,000 bicycles/hr (*14*). This translates into approximately 5,000 bicycles/hr per 1.25-m (4.1-ft) lane. A Chinese study found bicycle capacities of between 1,800 and 2,100 bicycles/hr per 1-m (3.3-ft) lane (*19*). One Dutch study reports the bicycle capacity of a 2-m (6.6-ft) two-lane path as 6,400 bicycles/hr and the capacity of a 3-m (9.9-ft) three-lane path as 9,600 bicycles/hr (*21*). This translates into 3,200 bicycles/hr per 1-m (3.3-ft) lane. Another Dutch study reported bicycle capacities of 3,000 to 3,500 bicycles/hr per 0.78 m (2.6 ft) of bicycle path (*24*). Based on observations in Beijing, China, a recent study (*20*) reported that "massive bike flows" form when bicycle volumes reach a certain point. According to the report, these massive bike flows act as a unit, and the characteristics of individual bicyclists become unimportant. Based on this massive bike flow theory, a bicycle lane capacity of 2,344 bicycles/hr was reported for uninterrupted facilities separated from motor vehicle traffic. This is slightly lower than the reported theoretical capacity of 2,549 bicycles/hr calculated using the characteristics of individual Chinese bicyclists.

In summary, the saturation flow for a single 1-m (3.3 ft) to 1.2-m (4-ft) bicycle lane appears to be between 1,500 and 5,000 bicycles/hr with a majority of the observations falling between 2,000 and 3,500 bicycles/hr.

UNINTERRUPTED BICYCLE FACILITIES

For the purpose of this article, uninterrupted bicycle facilities are divided into three categories: exclusive off-street bicycle paths, shared off-street paths, and on-street bicycle facilities.

Exclusive 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. These bicycle facilities accommodate the highest volumes of bicycles among the three types and the best levels of service because the bicycles all flow at similar ranges of speed. The capacities of shared off-street and on-street facilities are lower due to the much slower pedestrians and the much faster motor vehicles (among other factors) in the traffic stream. The current definition of a bicycle path in the *HCM* (*1*) is "a bikeway physically separated from motorized traffic by an open space or barrier, either within the highway right-of-way or within an independent right-of-way." In its guide for bicycle facilities (*22*), AASHTO definition of a bicycle lane is almost exactly the same as the *HCM*. In the United States, there are very few paths limited exclusively to bicycles. Most off-street paths fall in the shared-path category.

Shared Off-Street Paths

Shared off-street paths are also separated from motor vehicle traffic. However, shared-use paths allow other modes to use the path, including pedestrians, roller blades, roller skates, skateboards, wheelchairs, and any other imaginable mode of nonmotorized transportation. The primary concern for bicycles on these types of paths from an operational standpoint is the large volumes of slow-moving pedestrians on the paths. Shared-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. Shared-use paths are also very common on university campuses in the United States.

On-Street Facilities

On-street bicycle facilities include designated bicycle lanes, paved shoulders, and undesignated shared curb lanes.

Designated 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. Bicycle lanes are normally placed on streets where bicycle use is fairly high and the separation of bicycles is warranted. Bicycle lanes are usually one-way facilities on which bicycles travel in the same direction as the adjacent motor vehicles. The *HCM*'s current definition of a bicycle lane is "a portion of roadway which has been designated by striping, signing, and/or pavement markings for the preferential or exclusive use of bicycles." In its guide for bicycle facilities (*22*), AASHTO's definition of a bicycle lane is almost exactly the same as the *HCM*'s

Paved shoulders are part of the cross section of the street but not part of the traveled way for motor vehicles. Bicycles are separated from motor vehicles by the right edge line. 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.

Undesignated shared lanes are the outside lanes of street cross sections that bicycles share with motor vehicles. No lane delineation is provided to separate bicycles from motor vehicles for these facilities. These lanes are often, but not always, wider than 3.7 m (12 ft). According to the *HCM*, the recommended minimum width for shared lanes is 4.3 m (14 ft). A study conducted in Maryland (*25*) reported that the optimal width for shared lanes is approximately 4.6 m (15 ft) for roadway sections where a curb is present. Any outside lane on any street can be a shared lane unless bicycle traffic is specifically prohibited. Shared lanes usually have too little bicycle traffic to warrant a bicycle lane. Some urban areas have shared lanes with appreciable bicycle traffic. However, many of these urban facilities do not have designated bicycle lanes due to right-of-way limitations.

PROPOSED ANALYSIS PROCEDURES

Conceptual Approach

Most studies of uninterrupted bicycle operations conducted to date have discounted bicycle speed as a performance measure. It appears that (like motor vehicle speeds) bicycle speeds do not decrease appreciably over a large initial range of bicycle volume. Much of the work to date has concentrated on density or space as a performance measure (*10,12,14,15*). Density is the performance measure currently used in the pedestrian chapter of the *HCM*. However, density has been criticized as a performance measure for bicycles because bicycles do not use space as efficiently as pedestrians.

Some recent work in the Netherlands has presented an alternative to density called *hindrance* (*7,21,26*). Botma (*21*) uses frequencies of events between bicyclists and other facility users to arrive at various levels of service. Due to its conceptual appeal as a "user-experienced" service measure, the "frequency of events" is proposed as the service measure of effectiveness for uninterrupted bicycle facilities. *Events* are defined as bicycle maneuvers required by a bicyclist on a facility, including passings (same-direction encounters) and meetings (opposite-direction encounters) as stated by Botma (*21*). 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 using 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 (*21*). 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 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, regardless of the width of the facility. The number of effective bicycle lanes should always be observed in the field where possible before conducting these analyses.

Procedures for one-way paths are presented in the following sections. However, it should be noted that one-way paths are relatively rare and are often an enforcement problem where they do exist. The one-way path information is presented primarily to build a foundation for the two-way path procedures. Two-way paths are by far the most common type of facility found in the United States.

Pending the development of metric standards for bicycle facilities, it is expected that most of the existing 2.4-m-wide (8-ft-wide) bicycle facilities conforming to current AASHTO (*22*) English unit standards will operate as two-lane facilities. However, due to the additional width, one should keep in mind that the level of service arrived at using the following two-lane procedures may be on the conservative side. On the other hand, if these facilities are being used as three-lane paths, the level of service arrived at using the following three-lane procedures may be too generous. 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, the procedures contained in this article for two-lane paths will apply to most of the currently 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 peaking characteristics different from motor vehicles. Bicycles 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 (*5*), measured peak-hour volumes as 10 to 15 percent of total daily volume at various locations. Another study in the state of Washington (*6*), conducted primarily in the Seattle area, measured peak-hour factors of 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 drastic underestimation of level of service (LOS).

The procedures have been extended to three-lane paths using the three-lane volumes reported by Botma (*21*) and the same weights between passings and meetings as for two-lane paths. Botma reported frequencies only for two-lane paths in his article because he was unsure of the extension to three lanes. Therefore, the three-lane two-way facility analyses presented here should be used with caution.

Perhaps the most important thing to note when using these uninterrupted bicycle facility analysis procedures is that *LOS F is not reached at capacity* for the facility. An unacceptable number of events is always reached before capacity. In some cases, capacity can be twice the volume at which LOS F is reached. These procedures are based on frequencies of events and perceived levels of service, not on the bicycle-carrying capacity of the facility.

The following procedures assume "ideal" facility conditions. Lateral obstructions, extended sections with appreciable grades, and other local factors may reduce the LOS for a given facility. Unfortunately, to date, such factors have not been sufficiently documented to make any recommendations as to their effects.

Methodology for Exclusive Off-Street Bicycle Paths

One-Way Paths

On one-way exclusive bicycle paths, bicycles encounter passing situations but not meetings. The following equation, which was originally proposed by Botma (*21*), is recommended for computing the frequency of passing events on one-way exclusive bicycle paths:

$$F_{\text{pass}} = 0.188(V_{\text{bike}}) \tag{1}$$

where F_{pass} is the frequency of passings in events/hr and V_{bike} is the bike volume in bikes/hr.

The frequencies of passings resulting from this equation are based on the assumption that bicycle speeds on paths are normally distributed with a mean of 18 km/h (11.2 mph) and a standard deviation of 3 km/h (1.9 mph), which is reasonable based on current bicycle literature as reported in the free-flow speed section above.

The use of Table 1, which is based on Botma's work, is recommended to convert the computed frequency of events to level of service. For one-way paths, the level of service can also be obtained directly by using the service volumes reported in the table.

Two-Way Paths

Two-way paths accommodate lower service volumes at each level of service than one-way paths because bicycles experience both passings and meetings, which results in higher frequencies of events.

Determining the level of service for two-way paths is more complex than for one-way paths because the LOS is dependent on the directional split of bicycles, as well as volume. The following equations, which were originally proposed by Botma (*21*), are recommended for computing the total frequency of events on two-way exclusive bicycle paths:

$$F_{\text{pass}} = 0.188(V_{\text{bike-sm}}) \tag{2}$$

$$F_{\text{meet}} = 2(V_{\text{bike-op}}) \tag{3}$$

$$F_{\text{total}} = 0.5(F_{\text{meet}}) + F_{\text{pass}} \tag{4}$$

where

F_{pass} = frequency of passings in events/hr;
F_{meet} = frequency of meetings in events/hr;

TABLE 1 Level of Service for One-Way Exclusive Bicycle Paths

	Two-Lane (2.4 m/8 ft)		Three-Lane (3.0 m/10 ft)	
LOS	frequency passings (event/hr)	two-lane service volume (bike/hr)	frequency passings (event/hr)	three-lane service volume (bike/hr)
A	< 25	130	< 150	780
B	< 50	260	< 300	1560
C	< 100	520	< 590	3120
D	< 170	910	< 1030	5460
E	< 245	1300	< 1470	7800
F	≥ 245	------	≥ 1470	------

F_{total} = total weighted frequency of events in events/hr;
$V_{bike\text{-}sm}$ = bike volume in the same direction being analyzed in bikes/hr; and
$V_{bike\text{-}op}$ = bike volume in the opposite direction being analyzed in bikes/hr.

Once again, the frequencies of events resulting from Equations 4 through 6 are based on the assumption that bicycle speeds are normally distributed with a mean of 18 km/h (11.2 mph) and a standard deviation of 3 km/h (1.9 mph). The total frequency of events will differ in each direction for directional splits other than 50-50, so the frequency of events for each direction must be computed in those cases.

Table 2, which is based on Botma's work, is recommended to convert the total frequency of events to level of service. Service volumes for a 50-50 directional split are provided to illustrate the difference between one- and two-way paths. If a 50-50 directional split for the facility can be assumed, the level of service can be obtained directly by using the service volumes in the table. For splits other than 50-50, Equations 2 through 4 can be used in combination with Table 2.

Methodology for Shared Off-Street Paths

One-Way Paths

On one-way shared-use paths, bicycles encounter passing situations but not meetings. The following equation, which was originally proposed by Botma (*21*), is recommended for computing the frequency of passing events on one-way shared-use paths:

$$F_{pass} = 3(V_{ped}) + 0.188(V_{bike}) \quad (5)$$

where

F_{pass} = frequency of passing in events/hr;
V_{ped} = pedestrian volume in pedestrians/hr; and
V_{bike} = bike volume in bikes/hr.

The frequencies of passings resulting from this equation are based on the assumption that bicycle speeds are normally distributed with a mean of 18 km/h (11.2 mph), and that pedestrian speeds are normally distributed with a mean of 4.5 km/h (2.8 mph). These assumptions are reflected in the higher weight of pedestrian volume ($3V_{ped}$) compared with bicycle volume ($0.188V_{bike}$) in the computation of passing events. Slower average pedestrian speeds would cause an increase in the frequency of passings.

Table 3 is recommended to convert the frequency of events to LOS. Several columns have been included in the table so that the LOS can be determined directly for given pedestrian volumes. The user may interpolate between the tabulated values for intermediate pedestrian flows. It is assumed that one-way shared-use paths are used by all modes in the same direction. If pedestrians are using the path in both directions, the facility should be analyzed as a two-way shared-use path using the pedestrian directional split and a bicycle split of 100 percent.

Two-Way Paths

Two-way paths accommodate lower service volumes at each LOS than one-way paths because bicycles experience both passings and meetings, resulting in higher frequencies of events. The following equations, which were originally proposed by Botma (*21*), are recommended for computing the total frequency of events on two-way shared-use bicycle paths:

$$F_{pass} = 3(V_{ped\text{-}sm}) + 0.188(V_{bike\text{-}sm}) \quad (6)$$

$$F_{meet} = 5(V_{ped\text{-}op}) + 2(V_{bike\text{-}op}) \quad (7)$$

$$F_{total} = 0.5(F_{meet}) + F_{pass} \quad (8)$$

where

F_{pass} = frequency of passing in events/hr;
F_{meet} = frequency of meeting in events/hr;

TABLE 2 Level of Service for Two-Way Exclusive Bicycle Paths

	Two-Lane (2.4 m/8 ft)		Three-Lane (3.0 m/10 ft)	
LOS	total frequency of events (event/hr) per direction	two-lane service volume (bike/hr) for both directions[a]	total frequency of events (event/hr) per direction	three-lane service volume (bike/hr) for both directions[a]
A	< 40	65	< 90	150
B	< 60	105	< 140	230
C	< 100	170	< 210	350
D	< 150	250	< 300	500
E	< 195	325	< 375	630
F	≥ 195	------	≥ 375	------

[a]Assumes a 50:50 directional split

TABLE 3 Bicycle Level of Service for One-Way Shared-Use Paths

Two-Lane (2.4 m/8 ft)				
LOS	frequency passings (event/hr)	two-lane service volume (bike/hr) [given 10 ped/hr]	two-lane service volume (bike/hr) [given 20 ped/hr]	two-lane service volume (bike/hr) [given 40 ped/hr]
A	< 25	U	U	U
B	< 50	105	U	U
C	< 100	370	215	U
D	< 170	745	585	265
E	< 245	1145	985	665
F	≥ 245	-----	-----	-----
Three-Lane (3.0 m/10 ft)				
LOS	frequency passings (event/hr)	three-lane service volume (bike/hr) [given 20 ped/hr]	three-lane service volume (bike/hr) [given 40 ped/hr]	three-lane service volume (bike/hr) [given 80 ped/hr]
A	< 150	480	160	U
B	< 300	1280	960	320
C	< 590	2820	2500	1870
D	< 1030	5160	4840	4200
E	< 1470	7500	7180	6540
F	≥ 1470	-----	-----	-----

U = LOS unattainable due to pedestrian volumes

F_{total} = total weighted frequency of events in events/hr;
$V_{ped\text{-}sm}$ = pedestrian volume in the same direction being analyzed in pedestrians/hr;
$V_{ped\text{-}op}$ = pedestrian volume in the opposite direction being analyzed in pedestrians/hr;
$V_{bike\text{-}sm}$ = bike volume in the same direction being analyzed in bikes/hr; and
$V_{bike\text{-}op}$ = bike volume in the opposite direction being analyzed in bikes/hr.

Once again, the frequencies of events resulting from these equations are based on the assumption that bicycle speeds are normally distributed with a mean of 18 km/h (11.2 mph), and that pedestrian speeds are normally distributed with a mean of 4.5 km/h (2.8 mph). As can be observed from these equations, the total frequency of events will differ in each direction for directional splits other than 50-50 for either pedestrians or bicycles, so the frequency of events for each direction must be computed. The frequency of events for two-way shared-use paths has been computed for several different bicycle volumes and directional splits at selected pedestrian volumes for the convenience of the user. These are presented in Table 4. Alternatively, the user may utilize Equations 6 through 8 to compute total frequency. After using either Table 4 or Equations 6 through 8 to determine the total frequency of events in each direction, Table 4 can also be used to convert the total frequency of events to level of service.

Methodology for On-Street Bicycle Facilities

The procedures in the previous section are also appropriate for on-street facilities where there are significant distances between interruptions, such as traffic signals or stop signs. 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-wide (10-ft-wide) paved shoulders. However, because 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).

An important distinction between on-street facilities and exclusive off-street facilities is the multitude of possible factors affecting level of service for on-street facilities, including adjacent motor vehicle traffic (which is often moving much faster than the bicycles), 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 level of service for a facility. Unfortunately, such factors have not been sufficiently documented to date.

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,* the expectation being 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 (per direction) 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. With proper calibration of these two parameters, the proposed methodology could be equally applied to on-street bicycle facilities.

Numerical Examples

Example 1. One-Way Exclusive Bicycle Path

For the first example, the following is assumed:

- Bicycle path width of 2.4 m (8 ft);
- Peak-hour volume of 150 bicycles/hr; and
- Peak-hour factor of 0.6.

It is assumed that the path has been observed by the analyst and operates with two effective bicycle lanes during the peak hour. The frequency of passings and the LOS are computed by converting the peak volume to a peak flow rate and then using Equation 1.

Adjusted peak-hour flow rate = 150/0.6 = 250 bicycles/hr

F_{pass} = 0.188(250) = **47 events/hr**

Using Table 1, this represents LOS B. The level of service could also have been read directly from Table 1 using the volume of 250 bicycles/hr.

TABLE 4 Total Frequency of Events and Level of Service for Two-Way Shared-Use Paths

Bike Vol Both Dir (bike/hr)	Directional Split of Bikes (same:opp)	Total Frequency of Events (events/hr) Two-way pedestrian volumes of 0 (ped/hr)	20 (ped/hr)[a]	40 (ped/hr)[a]	80 (ped/hr)[a]
100	30:70	76	131	186	296
	40:60	68	123	178	288
	50:50	59	114	169	279
	60:40	51	106	161	271
	70:30	43	98	153	263
200	30:70	151	206	261	371
	40:60	135	190	245	355
	50:50	119	174	229	339
	60:40	103	158	213	323
	70:30	86	141	196	306
400	30:70	303	358	413	523
	40:60	270	325	380	490
	50:50	238	293	348	458
	60:40	205	260	315	425
	70:30	173	228	283	393
800	30:70	605	660	715	825
	40:60	540	595	650	760
	50:50	475	530	585	695
	60:40	410	465	520	630
	70:30	345	400	455	565

Level of Service

LOS	total frequency of events (event/hr) for two-lane (2.4 m/8 ft) paths	total frequency of events (event/hr) for three-lane (3.0 m/10 ft) paths
A	< 40	< 90
B	< 60	< 140
C	< 100	< 210
D	< 150	< 300
E	< 195	< 375
F	≥ 195	≥ 375

[a]50:50 directional split assumed for pedestrians

For the sake of comparison, a similar bicycle volume was observed on an on-street facility with the same width. The observed mean and standard deviation of bicycle speeds were 12 km/h and 4.5 km/h, respectively. It can be shown that the number of passing events in this case is 62 events per hour, yielding LOS C for the facility, as per Table 1.

Example 2. Uninterrupted Two-Way Shared Path

For this example, the following is assumed:

- Bicycle path width of 3 m (10 ft);
- Path direction of approximately east-west;
- Adjusted peak-hour flow rate of 150 bicycles/hr;
- Adjusted peak-hour flow rate of 80 pedestrians/hr;
- 60–40 directional split of bicycles eastbound (EB) versus westbound (WB); and
- 50–50 directional split of pedestrians EB versus WB.

It is also assumed that the path has been observed by the analyst and operates with three effective bicycle lanes during the peak hour. The

TABLE 5 Sensitivity Analysis of Event Frequency and LOS to Mean and Standard Deviation of Bicycle Speeds on Two-Lane Two-Way Exclusive Bicycle Paths

2-Way Bike Volume[a] (bikes/hr)	Standard Deviation (kph)	Mean Speed (kph) 12	13	14	15	16	17	18	19	20
100	1.5	57(B)	57(B)	56(B)	56(B)	55(B)	55(B)	55(B)	54(B)	54(B)
	3.0	64(C)	63(C)	62(C)	61(C)	61(C)	60(B)	59(B)	59(B)	58(B)
	4.5	71(C)	70(C)	68(C)	67(C)	66(C)	65(C)	64(C)	63(C)	63(C)
200	1.5	114(D)	113(D)	112(D)	111(D)	110(D)	110(D)	109(D)	109(D)	108(D)
	3.0	128(D)	126(D)	124(D)	122(D)	121(D)	120(D)	118(D)	118(D)	117(D)
	4.5	142(D)	139(D)	136(D)	134(D)	131(D)	130(D)	127(D)	127(D)	125(D)
300	1.5	171(E)	170(E)	168(E)	167(E)	166(E)	165(E)	164(E)	163(E)	163(E)
	3.0	192(E)	189(E)	186(E)	184(E)	182(E)	180(E)	178(E)	177(E)	175(E)
	4.5	215(F)	209(F)	204(F)	201(F)	198(F)	195(F)	192(E)	190(E)	188(E)

[a]Assumes a 50:50 directional split

total frequency of events and LOS is computed by using Equation 8 for each direction:

$$\text{EB: } F_{\text{total}} = 0.5[5(0.5)(80) + 2(0.4)(150)] + [3(0.5)(80) + 0.188(0.6)(150)] = \textbf{297 events/hr}$$

Interpolation between 100 and 200 bicycles/hr on Table 4 produces the same results. Using Table 4, this represents LOS D in the eastbound direction.

$$\text{WB: } F_{\text{total}} = 0.5[5(0.5)(80) + 2(0.6)(150)] + [3(0.5)(80) + 0.188(0.4)(150)] = \textbf{321 events/hr}$$

Interpolation between 100 and 200 bicycles/hr on Table 4 produces the same results. Using Table 4, this represents LOS E in the westbound direction.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This article presented a comprehensive literature synthesis of bicycle facility analysis, leading to the development of a methodology for operational study of uninterrupted bicycle flow facilities. The synthesis revealed a lack of integrated analysis methods and data that could be used for bicycle facility operational analysis. A methodology based on a Dutch approach was recommended for adoption into future versions of the *Highway Capacity Manual.* The method is very consistent with other *HCM* analyses in that it uses a *user-based* method for LOS assessment, while requiring only planning-based data (in this case service volumes) for use in the procedures.

The procedures have been recommended because it was determined that they are theoretically sound and practically feasible. However, there has been little attempt to validate these procedures here in the United States. Therefore, the authors strongly recommend that these procedures eventually be widely validated in this country due to differences in bicyclist behaviors, levels of experience, bicycle path widths, and bicycles themselves between the United States and Europe. For those interested in validating these procedures, a methodology based on a floating bicycle concept has been developed (*27*).

ACKNOWLEDGMENTS

This work was conducted at North Carolina State University as part of the Pedestrian/Bicyclist Research Program funded by the Federal Highway Administration through the Highway Safety Research Center at the University of North Carolina at Chapel Hill.

REFERENCES

1. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1994.
2. Zeeger, C., et al. *The National Bicycle and Walking Study: Transportation Choices for a Changing America.* Report FHWA-PD-94-023. FHWA, U.S. Department of Transportation, 1994.
3. *Bicycle Planning and Facility Workshop.* Northwestern University Traffic Institute, Evanston, Ill., May 1994.
4. Wilkinson, W. C., A. Clarke, B. Epperson, and R. Knoblauch. *Selecting Roadway Design Treatments to Accommodate Bicycles.* Report FHWA-RD-92-073. FHWA, U.S. Department of Transportation, 1994.
5. Hunter, W. W., and H. F. Huang. User Counts on Bicycle Lanes and Multiuse Trails in the United States. In *Transportation Research Record 1502,* TRB, National Research Council, Washington, D.C., 1995, pp. 45–57.
6. Niemeier, D. A. Longitudinal Analysis of Bicycle Count Variability: Results and Modeling Implications. *Journal of Transportation Engineering,* Vol. 122, No. 3, May–June 1996.
7. Botma, H., and H. Papendrecht. Traffic Operation of Bicycle Traffic. In *Transportation Research Record 1320,* TRB, National Research Council, Washington, D.C., 1991, pp. 65–74.
8. *Sign Up for the Bike: Design Manual for a Cycle-Friendly Infrastructure.* Centre for Research and Contract Standardization in Civil and Traffic Engineering, Netherlands, Sept. 1994.
9. Miller, R. E., and M. R. Ramey. *Width Requirements for Bikeways: A Level of Service Approach.* Report 75-4. Department of Civil Engineering, University of California, Davis, Dec. 1975.
10. Brilon, W. A New German Highway Capacity Manual. *Proc., 2nd International Symposium on Highway Capacity,* Vol. 1, Sydney, Australia, Aug. 1994.
11. Vagverk, S. Chapter 10: Bicycle Traffic Facilities (English translation). In *Swedish Capacity Manual.* National Swedish Road Administration, 1977.
12. Yang, J.-M. Bicycle Traffic in China. *Transportation Quarterly,* Vol. 39, No. 1, Jan. 1985.
13 *City Planning for Cycling.* Directorate of Public Roads, Norwegian Public Roads Administration, Oslo, Dec. 1995.
14. Navin, F. P. D. Bicycle Traffic Flow Characteristics: Experimental Results and Comparisons. *ITE Journal,* Vol. 64, No. 3, March 1994.
15. Homburger, W. S. *Capacity of Bus Routes, and of Pedestrian and Bicycle Facilities.* Institute of Transportation Studies, University of California, Berkeley, Feb. 1976.
16. Opiela, K. S., S. Khasnabis, and T. K. Datta. Determination of the Characteristics of Bicycle Traffic at Urban Intersections. In *Transportation Research Record 743,* TRB, National Research Council, Washington, D.C., 1980, pp. 30–36.
17. *Safety and Locational Criteria for Bicycle Facilities, User Manual Volume II: Design and Safety Criteria.* Report FHWA-RD-75-114. FHWA, U.S. Department of Transportation, 1976.
18. Lui, Y. The Capacity of Highway with a Mixture of Bicycle Traffic. In *Highway Capacity and Level of Service.* Rotterdam, Netherlands, 1991.
19. Liu, X., L. D. Shen, and F. Ren. Operational Analysis of Bicycle Interchanges in Beijing, China. In *Transportation Research Record 1396,* TRB, National Research Council, Washington, D.C., 1993, pp. 18–21.
20. Wei, H., J. Huang, and J. Wang. Models for Estimating Traffic Capacity on Urban Bicycle Lanes. Presented at 76th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1997.
21. Botma, H. Method to Determine Levels of Service for Bicycle Paths and Pedestrian-Bicycle Paths. In *Transportation Research Record 1502,* TRB, National Research Council, Washington, D.C., 1995, pp. 38–44.
22. *Guide for Development of Bicycle Facilities.* American Association of State Highway and Transportation Officials, Washington, D.C., 1991.
23. Ferrara, T. C. *A Study of Two-Lane Intersections and Crossings Under Combined Motor Vehicle and Bicycle Demands.* Report 75-5. Civil Engineering Department, University of California, Davis, Dec. 1975.
24. Stembord, H. Capacity Research and Applications: Country Report of the Netherlands. *Proc., 1991 International Symposium on Highway Capacity,* Rotterdam, Netherlands, 1991.
25. Maryland State Highway Administration. *Evaluation of Wide Curb Lanes as Shared Lane Bicycle Facilities.* Report FHWA/MD-85/06. Maryland Department of Transportation, Baltimore, Aug. 1985.
26. Botma, H., and H. Papendrecht. Operational Quality of Traffic on a Bicycle Path. *ITE 1993 Compendium of Technical Papers,* 1993.
27. Rouphail, N., J. E. Hummer, D. P. Allen, and J. S. Milazzo. *A Floating Bicycle Methodology to Determine Frequencies of Events on Bicycle Paths.* Working paper. North Carolina State University, Raleigh, 1997.

The opinions expressed in this article are those of the authors and not necessarily those of the FHWA or the Highway Safety Research Center.

Publication of this paper sponsored by Committee on Bicycling.