The Highway Capacity Manual's Method for Calculating Bicycle and Pedestrian Levels of Service: the Ultimate White Paper

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1 Executive Summary

This paper concerns the methods for calculating Pedestrian Level of Service and Bicycle Level of Service (PLOS and BLOS hereafter) as they are presented in the 2010 Highway Capacity Manual (HCM). To calculate PLOS or BLOS is to assign a grade, A through F, to a portion of roadway. This grade is meant to correspond to the perceived level of service that that roadway provides to pedestrians or bicyclists, respectively. PLOS and BLOS comprise a portion of the HCM's Multimodal Level of Service methodology (MMLOS).

The HCM MMLOS has been a black box for many practitioners. For various reasons, it can be hard to simply open the HCM and quickly understand how PLOS and BLOS work, what variables they take into account, and how important each of these variables is in determining the final grade. Each of these has consequences for the ways in which PLOS and BLOS make meaning. The technical sensitivity of the final grade to a given variable will influence the extent to which policies employing PLOS and BLOS will be responsive to such variable.

Here we provide a guided tour of the PLOS and BLOS methods. We carefully explain the four formal units of analysis employed by the HCM: the intersection, link, segment, and facility. For each of these and for each of the modes (pedestrian and bicycle), we describe in detail what variables are included and the process, definitions, and formulas that produce the final score. We examine the relative contribution of each variable in determining the final score under a variety of cases. In many cases we also include a sensitivity analysis, setting all inputs to reasonable default values and varying a single variable. We also make note of variables to which PLOS and BLOS are *not* sensitive despite their importance to planners and policymakers. These allow the reader to understand what drives the PLOS and BLOS scores and thus to better interpret the final grade.

1.1 What Determines Pedestrian and Bicycle Level-of-Service

Here is an abbreviated summary that highlights some of the most important variables that determine PLOS and BLOS.

Pedestrian Level of Service

- At an intersection, where the crosswalk is essentially the unit of analysis: the number of lanes crossed typically has the greatest contribution, while high speeds and volumes can also play a large role in determining the final grade.

- On a link: this is co-determined by a calculation of pedestrian space (a measure of crowding) and a pedestrian quality-of-service score. The worser predominates. The score is heavily influenced by the width of the walking area and its separation from vehicles. High traffic volumes can also play a large role.
- On a segment: a polynomial function of intersection PLOS and link PLOS, which also incorporates a roadway crossing delay factor
- On a facility: co-determined by 1) a weighted sum of segment PLOS scores and 2) pedestrian space. The worser predominates.

Bicycle Level of Service

- At an intersection, where the approach is the unit of analysis: primarily a function of the width of the street being crossed and the bicyclists' operating space (wide outside lane, shoulder, or bike lane). High traffic volumes also influence the score.
- On a link: depending on their values, all three can heavily influence the score: 1) vehicle volumes (esp. heavy vehicles) 2) vehicle speeds, and 3) bicyclists' operating space.
- On a segment: a function of intersection BLOS and link BLOS, with a large constant that makes it very difficult to achieve a grade above C.
- On a facility: a length-weighted sum of segment BLOS scores.

1.2 Problems with the HCM PLOS and BLOS Models

We also observe a number of problems and errors, as well as model behavior that is of questionable validity. Here is an abbreviated summary:

Pedestrian Level of Service
Intersection:

- Very insensitive to increases in delay; adding a minute of delay only decreases the score by 5% of one grade
- In the presence of right-turn channelization islands, increases in traffic volumes result in improved PLOS grades. This appears to be a mathematical error.

- Not sensitive to curb ramps, crosswalk markings, median refuge islands, and other common treatments

Link:

- Greater score improvement for 100% on-street parking occupancy than for paving a sidewalk
- No score improvement for widening sidewalks past 10 feet
- No sensitivity to sidewalk quality or smoothness
- No sensitivity to trees or lighting
- No sensitivity to improvements in crosswalks at 'non-boundary' intersections, or unsignalized intersections on minor streets perpendicular to the link

Segment:

- Not sensitive to crossing delays greater than 60 seconds

Bicycle Level of Service
Intersection:

- Not sensitive to bicycle-specific intersection treatments, such as bicycle boxes, signals, and markings through intersections
- Does not contain a measure of bicyclist delay, so not sensitive to improvements in signal timing or detection that would reduce delay

Link:

- Not sensitive to colored paint in the bicycle lane, striped buffers, or cycle tracks.
- Does not contain a measure of bicyclist crowding, so not sensitive to improvements in capacity that would reduce crowding

Segment:

- The HCM appears to contain an error here. It's nearly impossible to get a segment score of A or B due to the large constant used to calculate segment BLOS.

Source	Focus of study	Location	Number of participants
(Landis, et al., 1997)	Bicycle link	Tampa, FL	145
(Landis, et al., 2001)	Pedestrian link	Pensacola, FL	75 (exact no. not stated)
(Landis, et al., 2003)	Bicycle intersection	Orlando, FL	59 (66% male)
(Petritsch, et al., 2005)	Pedestrian intersection	Sarasota, FL	46 (67% female)

Table 1: Sources of data underlying the Highway Capacity Manual 2010 Bicycle Level of Service and Pedestrian Level of Service

Facility BLOS:

- The above error also makes it nearly impossible to get a facility score above C

The HCM's exhaustiveness and level of detail suggest that it was rigorously tested and validated. It wasn't. The underlying data that form the basis of the PLOS and BLOS models came from the four studies listed below.

In each of these studies, participants walked or biked respectively on a test course comprised of public streets in a city in Florida. Participants were then asked at periodic points along the course to give a letter grade A-F to the section of street they just experienced. The authors then constructed a model for participants' grades, testing variables known at the time to influence the biking or walking experience respectively. To our knowledge, none of the PLOS or BLOS models was ever validated, calibrated, or otherwise tested on roadways and participants other than those used to develop the model. It is little surprise, then, that these models produce some questionable results, and given their age, fail to account for the full range of variables and treatments that are now of interest to planners and policymakers.

1.3 Implications for Policy and Practice

What does this mean for policy and practice? Policy contexts as varied as environmental review, local performance monitoring, and development impact assessment are changing so that auto level-of-service is no longer the sole concern. Many of the policy contexts that originally motivated the creation of multimodal level-of-service have evolved in such a way that a single one-dimensional indicator is no longer appropriate or necessary.

Still, there may be situations where agencies have the resources and reason to calculate and use a metric like PLOS and BLOS. Our hope is that a transparent presentation of MMLOS enables people with broad expertise to scrutinize these models. Development and refinement of a model like PLOS or BLOS is labor-intensive; our hope is that by enabling broader scrutiny of the model we can target resources towards the most crucial improvements for validity and usability. For PLOS and BLOS, we humbly suggest three major changes. First, include tools for agencies to model changes to vehicle volumes and speeds. Many local agencies do not have the capacity to predict these changes, but they are of immense importance in determining the final score. At least allowing agencies to make their assumptions explicit (e.g. no change in volume, assumed range of reductions or increases in volumes) would improve scenario analysis for proposed roadway projects. Second, improve model validity. PLOS and BLOS should be redeveloped with data from the great variety of streets and bicycle and pedestrian facilities seen throughout the U.S., and modelers should test for the exhaustive list of variables that the most recent literature has found to have an impact on bicycling and walking safety and comfort. Further, BLOS should be validated on data other than that used to build the model. Finally, simplify the functional forms to reach validity with the simplest model possible. Varying specifications for BLOS should be tested, and the selection of the final form should keep usability and transparency in mind.

It is possible to improve PLOS and BLOS to make them more valid, more user-friendly, and more sensitive to innovative treatments. Such an effort would be resource-intensive, and we wonder if it would be worth it. Is there a policy context that cries out for a better, more valid MMLOS score? Or have other metrics and more holistic policy revisions subsumed the need for a finely-tuned one-dimensional indicator?

2 Introduction

This paper concerns the methods for calculating Pedestrian Level of Service and Bicycle Level of Service (PLOS and BLOS hereafter) as they are presented in the 2010 Highway Capacity Manual (HCM). To calculate PLOS or BLOS is to assign a grade, A through F, to a portion of roadway. This grade is meant to correspond to the perceived level of service that that roadway provides to pedestrians or bicyclists, respectively.

What variables are included in the calculation of PLOS and BLOS? What significance do each of these variables have in the determination of the final score? What are the implications of the functional forms of each of these indicators, e.g. their formulae and units of analysis? These are the concerns of this paper.

Why ask these questions? First, there is a gap between the concept of "multimodal level of service" as most stakeholders understand it and the real thing as it is written in the HCM. In part, this gap is due to the opacity of the HCM: for various reasons, it can be hard to simply open the HCM and quickly understand how PLOS and BLOS work, what variables they take into account, and how important each of these variables is in determining the final grade. Second, the functional form of these calculations and the process by which they are undertaken by an analyst has consequences for the ways in which PLOS and BLOS make meaning. The technical sensitivity of these calculations to any given variable will influence the extent to which a policy or process employing them will be responsive to such variable. Further, there are existing policies that explicitly require agencies and developers to take action when proposed projects or developments degrade auto LOS, and some have proposed revising these policies to incorporate an MMLOS standard that would include PLOS and BLOS (source). If the MMLOS formulae ignore something, an MMLOS-based policy will ignore that thing. If the MMLOS formulae are very sensitive to something, an MMLOS-based policy will come to hinge on that thing. To cite some specifics up front, consider that PLOS ignores the presence of trees and lighting but puts great stock in the percentage of on-street parking occupied. Thus, here we seek to describe how PLOS and BLOS work so that the implications for policy are clear.

The first few sections of this paper aim to lead the reader through a deliberate, thorough reading of the PLOS and BLOS methodologies. We then offer a brief discussion and critique of the development and background of the PLOS and BLOS formulae. Finally, we offer some thoughts about the implications for policy.

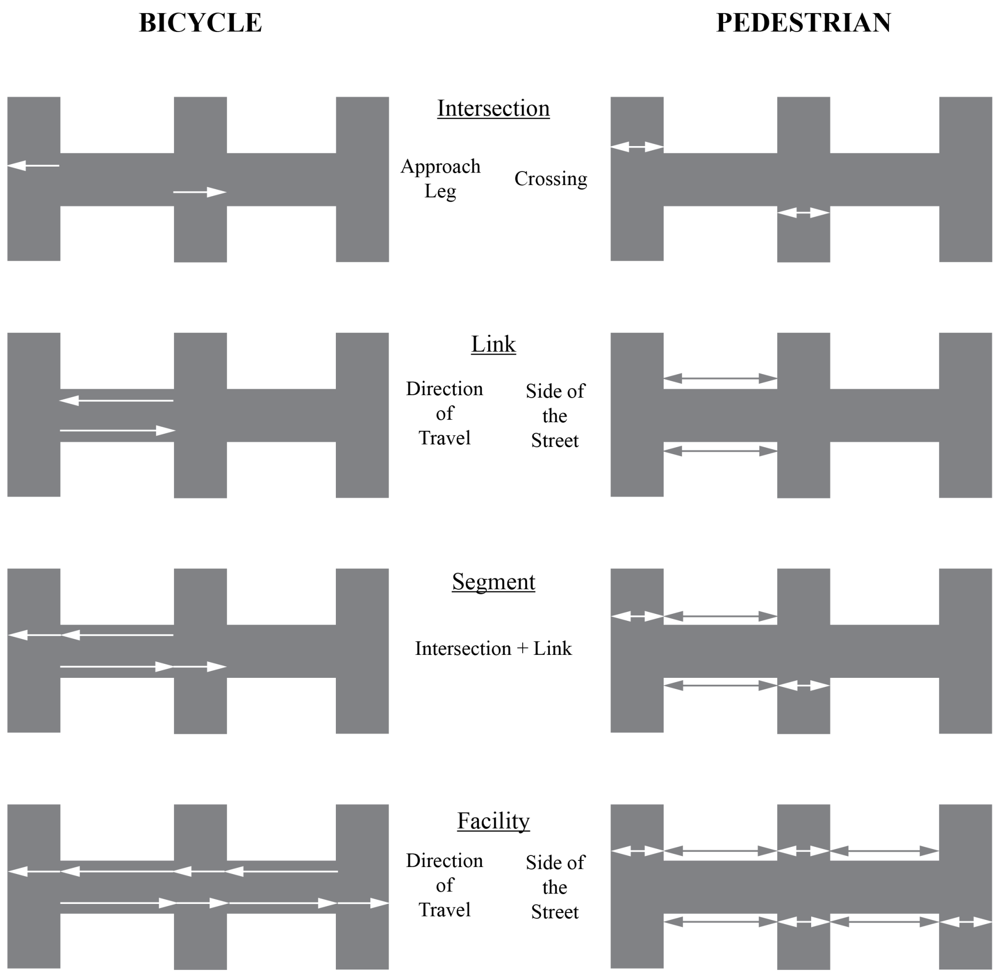

Figure 1: A street is broken up into formal units of analysis, each of which receives a PLOS or BLOS score.

3 Units of Analysis

First, note that the HCM employs very precise formal units of analysis, each of which can receive a unique PLOS or BLOS score. These are 1) the intersection, 2) the link, 3) the segment, and 4) the facility, as shown in Figure 1.

Links can span multiple blocks, when intersections between these blocks are not signalized, or are controlled by either four-way stops or two-way stops where the cross-street to the link stops and traffic on the link does not stop. The boundary of a link is defined as where the link hits a signal or a two-way stop that stops traffic on the link. Segment scores combine link scores and downstream boundary intersection scores with additional segment-wide considerations such as how crowded the segment is and how difficult it is to cross the street. Facility scores are length-weighted averages of segment scores. Intersection and link scores are each given by a set of steps and formulae considering 1) geometric variables (e.g. design features like roadway width, number of lanes) and 2) operational characteristics of the link or intersection (e.g. vehicle volumes and speeds). These ultimately produce a numerical score which the analyst converts to a grade according to the correspondence shown in Table 2. For the purposes of this paper, it will be helpful to memorize Table 2 as follows: the separation between grades is 0.75; an A is anything less than 2; and an F is anything greater than 5. One feature of the HCM that can present a barrier to understanding is that the methods for calculating intersection scores are in a separate chapter from the methods for calculating segment and facility scores. Stop-controlled intersections and off-street pedestrian and bicycle facilities receive treatment in yet additional chapters. If the roadway of interest is sufficiently lengthy, or the analytical scope includes a variety of alternatives, two to four chapters must be consulted.

Grade	Numerical Range
A	$x \leq 2.00$
B	$2.00 < x \leq 2.75$
C	$2.75 < x \leq 3.50$
D	$3.50 < x \leq 4.25$
E	$4.25 < x \leq 5.00$
F	$x > 5.00$

Table 2: Correspondence between numerical scores and grades in BLOS. (Source: Exhibit 17-4, 2010 Highway Capacity Manual)

Second, note that for each of these four units of analysis, the PLOS and BLOS scores are specific to a direction of travel, side of the street, or leg of an intersection. For a two-way roadway, there would be two segment BLOS scores, one for each direction. There are always two PLOS segment scores, one for each side of the street, whether or not there is a sidewalk on both sides of the street. At an intersection, there is a PLOS score for each leg of the intersection. Most intersections have four legs, and most have a legal crossing (typically a marked crosswalk) of each leg. The HCM authors instruct analysts very specifically *not* to combine the direction-specific scores to produce a single score for an intersection or segment. Combinations of intersection, link, or segment scores to form facility scores are permissible given a single direction of travel in the case of BLOS and a given side of the street in the case of PLOS, though the HCM urges caution when doing this.

PLOS and BLOS are also specific to a period of time. The HCM authors instruct analysts to limit the period of time studied to one hour, lest operational conditions (e.g. motor vehicle speeds and volumes, signal cycle parameters) vary too much within the period.

4 The Functional Form of HCM PLOS

By "functional form" we mean the variables, formulae, and process used to calculate PLOS for some unit of the pedestrian environment.

4.1 Intersection PLOS: Variables, Formula, and Sensitivity

Here we consider the methodology for calculating PLOS at a signalized intersection, since these are the types of intersections that form boundaries of segments, which then form facilities. The HCM does give a separate method for analyzing four-way stop controlled intersections, which we do not consider here.

In order to calculate PLOS for an intersection, you must have in hand the information listed in the first column of Table 3.

Name	Variable	Units	Algebraic Terms	Direction of effect on PLOS	Interactions with other variables	Notes on data definitions
number of traffic lanes crossed	N_d	number	$+0.681(N_d)^{0.514}$	Increasing this degrades PLOS.	N_d is in the denominator in the calculation of $n_{15,mj}$. With traffic volume held constant, an increase in the number of lanes improves IntPLOS by reducing $n_{15,mj}$. Also, A related variable, N_{th}, appears in the $F_v = 0.0091\frac{v_m}{4N_{th}}$ term of the Link PLOS score. With traffic volumes held constant, an increase in the number of lanes improves Link PLOS by reducing F_v.	
volume of right turns on red across subject crosswalk	v_{rtor}	vehicles per hour	$0.00569\frac{v_{rtor}+v_{lt,perm}}{4}$	Increasing this degrades PLOS.		In practice, this would often be extrapolated from a 15 minute observation. Vehicle counts typically do not tally right turns on red separately from overall right turning volumes.
volume of left turns across the subject crosswalk that are concurrent with its pedestrian phase	$v_{lt,perm}$	vehicles per hour		Increasing this degrades PLOS.		In practice, this would often be extrapolated from a 15 minute observation. Vehicle counts typically do not tally left turns concurrent with the walk phase separately from overall left turning volumes.
number of right-turn channelization islands	$N_{rtci,d}$	number	$-N_{rtci,d}(0.0027n_{15,mj} - .1946)$	Increasing this improves PLOS if $n_{15,mj} > 72$. Otherwise, increasing this degrades PLOS.	The influence of this variable depends upon the value of N_d, the number of lanes, and $\sum_{i\in m_d} v_i$, the volume of autos making movements that cross the subject crosswalk. When there are 72 movements per lane or greater, adding an island improves PLOS.	
average of volumes for the six movements that cross the subject crosswalk, per lanes in crosswalk	$n_{15,mj}$	vehicles per 15-minutes	$-N_{rtci,d}(0.0027n_{15,mj} - .1946), 0.00013n_{15,mj}S_{85,mj}$	The variable affects both the F_s and F_v terms, in conflicting ways. The effect on F_s degrades LOS, while the effect on F_v can improve LOS when there is a right-turn channelization island.		In practice, this would often be extrapolated from a 15 minute observation.
85th percentile speed "at a midsegment location" on the street the crosswalk traverses	$S_{85,mj}$	miles per hour	$0.00013n_{15,mj}S_{85,mj}$	Increasing this degrades PLOS.	The influence of this variable depends upon the value of $n_{15,mj}$, the number of vehicle movements across the crosswalk in question. The higher that volume, the greater effect the speed has.	
cycle length	C	seconds	$d_{p,d} = \frac{(C-g_{walk,mi})^2}{2C}$	Increasing this degrades PLOS.	Interacts with $g_{walk,mi}$ to determine pedestrian delay	
effective walk time when walking on the minor street*	$g_{walk,mi}$	seconds	$d_{p,d} = \frac{(C-g_{walk,mi})^2}{2C}$	Increasing this improves PLOS, given that cycle length C remains constant. If an increase in the length of $g_{walk,mi}$ is produced by increasing the cycle length C by the same amount, there is no effect on PLOS.	Interacts with C to determine pedestrian delay	This is defined as the amount of time that the pedestrian has the opportunity to enter the crosswalk. HCM advises analysts to include 4 seconds of time in addition to the technical walk phase, to account for the fact that pedestrians enter after the walk phase has transitioned to the pedestrian clear interval (flashing hand or "don't walk" phase). HCM provides separate formulae to account for special cases: 1) signals that 'dwell in walk' 2) signals with no ped heads.

Table 3: Data required to calculate PLOS for a signalized intersection.

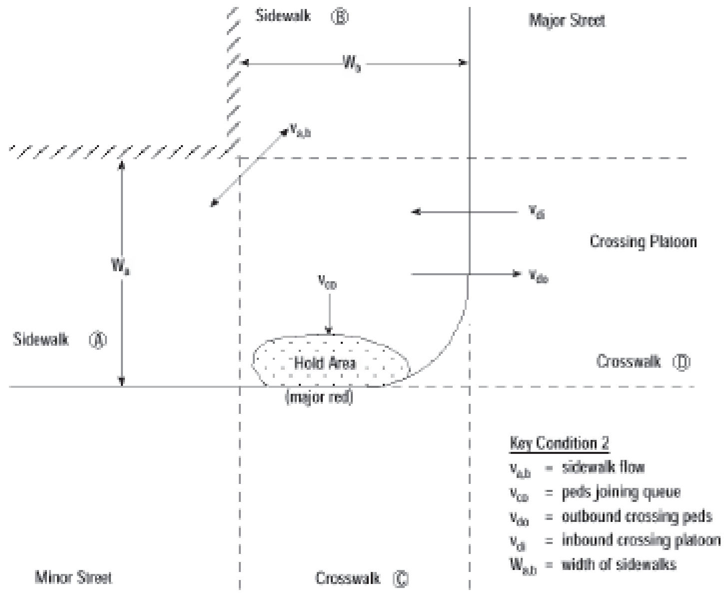

Figure 2: The Highway Capacity Manual illustrates naming conventions used to identify crosswalks and vehicular movements.

A couple of notes on subscripts: "mj" denotes the "major" street. In the presentation of these formulae in the HCM, a convention is defined wherein every intersection has a major and a minor street. Formulae for PLOS at an intersection are then given for a crosswalk crossing a major street. Similarly, HCM's convention names each of the crosswalks in an intersection with a letter A through D. The subscript "d" in the variable names simply identifies this LOS score as concerning crosswalk D, which crosses the major street. "mj" and "D" could be replaced with "mi" for minor and either "A", "B", or "C" if the calculation concerned other crosswalks. Figure 2 illustrates this.

The formula for the Pedestrian Level of Service at an Intersection, $I_{p,int}$, is then

$$I_{p,int} = 0.5997 + F_w + F_v + F_s + F_{\text{delay}}$$

where

$$F_w = 0.681(N_d)^{0.514}$$

$$F_v = 0.00569(\frac{v_{rtor} + v_{lt,perm}}{4}) - N_{rtci,d}(0.0027n_{15,mj} - 0.1946)$$

$$F_s = 0.00013n_{15,mj}S_{85,mj}$$

$$F_{\text{delay}} = 0.0401 \ln(d_{p,d})$$

$$n_{15,mj} = \frac{0.25}{N_d} \sum_{i \in m_d} v_i$$

and

$$d_{p,d} = \frac{(C - g_{walk,mi})^2}{2C}$$

Source: HCM 2010, page 18-69.

It is possible to state this formula in prose. Pedestrian level-of-service on a given crossing at an intersection as defined by the HCM is the sum of four terms. The higher the sum, the worse the score, so each of these terms degrades the score. The terms correspond to the width of the crossing (F_w), the volume of motor vehicles crossing the crosswalk (F_v), the speed of motor vehicles on the street being crossed (F_s), and pedestrian delay (F_{delay}), respectively. The crossing-width term is the approximate square root of the number of lanes crossed (F_w). The motor vehicle volume term accounts for the volume of vehicle movements that cross the crosswalk, with more complex terms that are described in detail below. The speed term is the product of the speeds and volumes on the street being crossed (F_s). The delay term is the natural logarithm of the average number of seconds of delay at the crosswalk. This number of seconds is a function of the effective walk time and the signal cycle length.

The motor vehicle volume term is the most complicated and has two parts. The first part is a sum of motor vehicle turning volumes that may go across the crosswalk during the walk phase. These are right-turn on red volumes and permissive left volumes (i.e. left-on-green without a protected arrow). The second part of F_v is an interactive term that accounts for the presence of right-turn channelization islands and interacts this with all motor vehicle turning volumes that cross the crosswalk ($n_{15,mj}$). This $n_{15,mj}$ can also be thought of as the number of potential conflicts per 15 minutes per lane crossed in the crosswalk. This would include through movements on the street being crossed, as shown

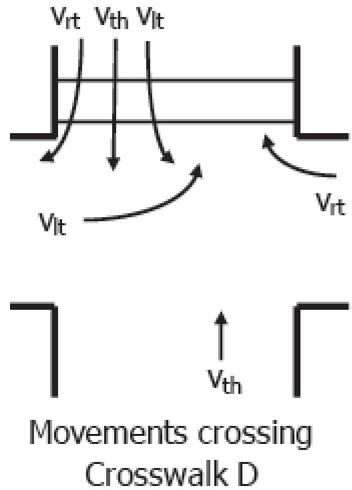

Figure 3: Vehicular movements in potential conflict with the subject crosswalk. Source: 2010 Highway Capacity Manual, page 18-70

in Figure 3.

Note that the second part of F_v can be positive or negative depending upon the value of $n_{15,mj}$. Setting $N_{rtci,d}(0.0027n_{15,mj} - .1946) = 0$ and solving for $n_{15,mj}$ gives 72.074. Thus, if $n_{15,mj}$ (volumes per lane per 15 minutes) is greater than 72, right-turn channelization islands decrease this term, improving PLOS. If volumes per lane are less than 72, adding right-turn channelization islands degrades PLOS. Thus, submerged within the intersection PLOS formula is the prescription that right-turn-channelization islands should not be installed in the presence of vehicle volumes below a threshold of 72 vehicles per lane per 15 minutes, or 288 vehicles per lane per hour. This implied threshold does not specifically concern the volume of right-turning vehicles, which is what a design threshold or warrant would consider. At least the magnitude of this threshold is within the range of warrant volumes for right-turn lanes, which vary from state to state [3]. Warrant volumes range from 200-500 vehicles per hour for through traffic that would queue behind right-turning vehicles, and 5-250 vehicles per hour for right-turning volumes.

In addition, if two intersections are identical and both have right-turn channelization islands, but one has higher traffic volume than the other, the one with higher traffic volume will have the lower value for F_v. This runs counter to common sense, which dictates that the pedestrian crossing environment is of a higher quality when there are fewer vehicle movements through the crosswalk, and that the volume factor, F_v, should increase with higher traffic volumes. In the calculations of intersection PLOS, the effect on F_v is counteracted by the fact that higher motor vehicle volumes increase F_s by raising $n_{15,mj}$, degrading PLOS overall. No explanation is given for the $n_{15,mj} = 72$ threshold. The value 72.074 seems to be an accidental byproduct of the coefficient 0.0027 and the constant -0.1946. These coefficients came from model development, which considered RTCIs in a separate process from other pedestrian variables [4]. RTCIs were modeled by video simulation scores rather than reactions to real physical crossings, because of their relative paucity in the built environment. The problems with HCM model development for PLOS will be discussed later in this paper.

The relative weights on the terms, determining their relative importance in the final score, are difficult to read from the formula due to the varying units involved in each of the terms. For example, F_w concerns the number of lanes crossed (likely to be between 2 and 8), while F_v concerns counts of vehicles and counts of vehicles per lane (likely to be in the hundreds or even thousands), and F_s contains speeds in miles per hour, likely to be between 25 and 65. The weights thus perform two tasks; one is to account for the relative magnitude of the variables in each term and the other is to assign relative importance to the four terms that comprise intersection PLOS. Visual inspection does not readily allow one to discern which terms receive greater or lesser weight.

4.1.1 Sensitivity Analysis

A sensitivity analysis provides a graphic representation of the relative importance of each of the four terms in PLOS, and the independent effects of variables in those terms. Table 4 shows the default parameters used; these represent plausible and common conditions on US streets.

Figure 4 presents the PLOS score broken into its component parts, and provides an understanding of the relative importance of the four terms F_w, F_v, F_s, and F_{delay}. The first column uses the default values shown in Table 4. In order to examine whether the relative importance of the four F terms remains the same with varying input parameters, five additional cases are constructed. In the second column, the number of lanes N_d is doubled to four. In the third column, number of lanes and all volumes are doubled: N_d, $n_{15,mj}$, v_{rtor}, and $v_{lt,perm}$ are all doubled. In the fourth column, 85th percentile speed ($S_{85,mj}$) is doubled. In the fifth column, lanes, volumes, and speed are all doubled. Finally, in

Variable	Name	Value
N_d	Number of lanes crossed	2
$v_{rtor} + v_{lt,perm}$	Sum of turning volumes coincident with walk phase, per 15 minutes	23
$n_{15,mj}$	Sum of all volumes that cross the crosswalk, per hour	835
$S_{85,mj}$	85th percentile speed on the major street	22.2 mph
F_{delay}	Pedestrian delay	26.1 seconds
$N_{rtci,d}$	Number of right-turn channelizing islands on the crosswalk	0

Table 4: Default values employed in sensitivity analysis of intersection PLOS.

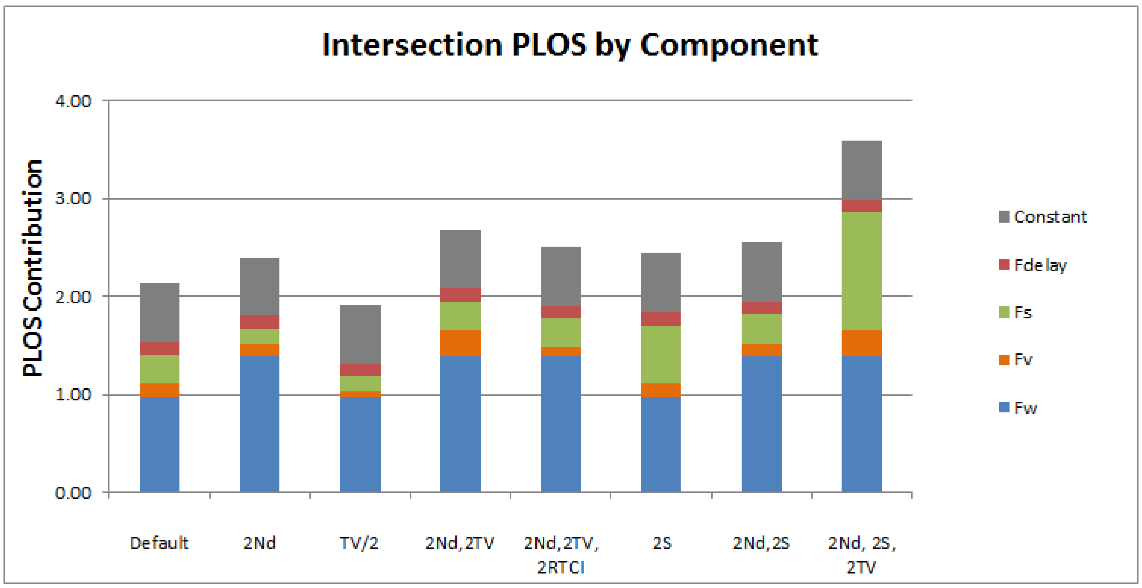

Figure 4: Contribution of component factors to intersection PLOS in a variety of cases.

the sixth column, lanes, volumes, and speed are doubled, and two right-turn channelizing islands are added.

Figure 4 shows that the relative importance of these terms is fairly consistent. F_w, the number of lanes crossed, is the major contributor to PLOS. The constant term contributes significantly. Recall that each of the grades spans an interval of length 0.75, with the exception of A and F. F_s is the next-most-important term, followed by F_v and F_{delay} in that order. In this figure, all of the F terms are shown as having a positive numerical contribution, i.e. degrading PLOS. This is not always the case, as some of the figures below will show.

The following figures then examine how sensitive PLOS is to variations in each of its inputs. We hold all of the variables but one constant, using default values for the remaining variables. We proceed roughly in order of the variables with the most significance as indicated by Figure 4.

The most important factor in determining intersection PLOS is the number of traffic lanes crossed. The effect of this variable is shown in Figure 5. Intersection PLOS increases with the square root of the number of traffic lanes. F_w ranges from 0.68 with one lane of traffic to 2.22 with 10 lanes of traffic. This range of about 1.50 corresponds to two full grades of difference, or the difference between a B and a D.

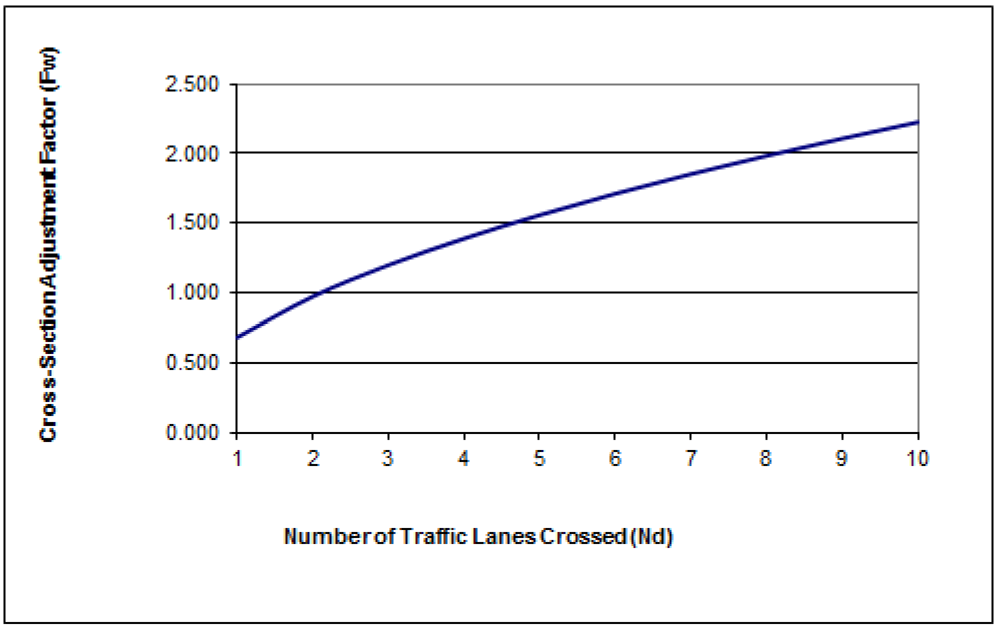

Figure 5: Intersection PLOS as a function of number of traffic lanes crossed.

After number of traffic lanes, motor vehicle volumes are the next most important variable. Several distinct volumes are included in the formula. Right turns on red and permissive lefts, which are movements that can be concurrent with the walk phase, are weighted and summed separately from $n_{15,mj}$ which includes all the movements that cross the crosswalk. The presence or absence of right-turn channelizing islands has a strong effect. In the presence of these islands, high $n_{15,mj}$ can results in a negative value for F_v. Figure 6 shows this relationship for zero, one, and two right-turn channelizing islands. Large negative values of F_v when $N_{rtci} > 0$ and $n_{15,mj}$ is large do not concur with common sense. Because traffic volumes also cause F_s to rise, the overall effect on PLOS is not as dramatic as that shown in the figure.

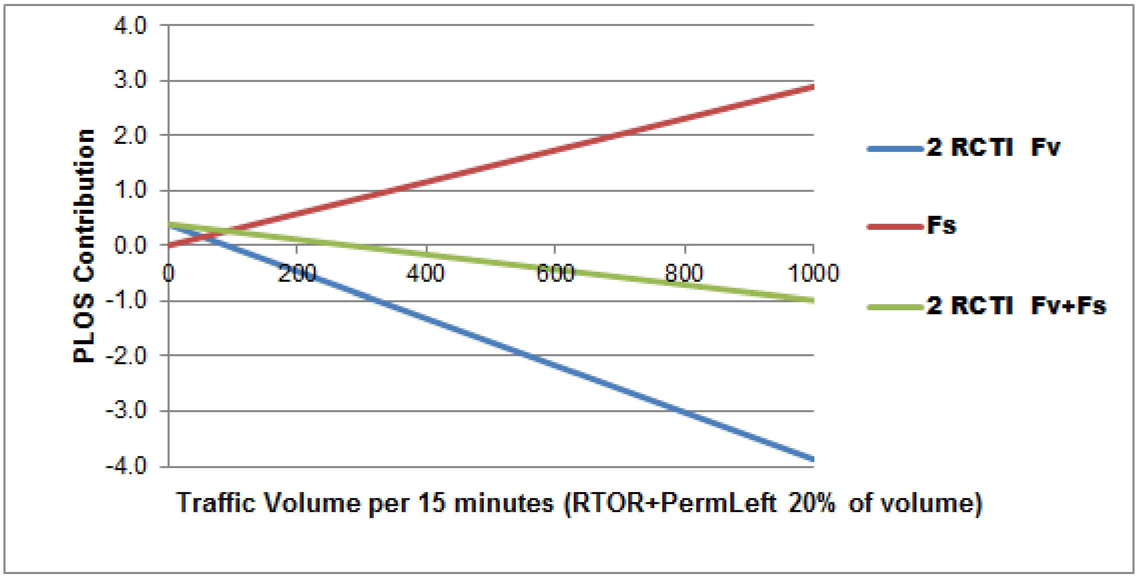

Figure 6: Intersection PLOS as a function of vehicle volumes.

The third most important term in intersection PLOS is the speed term, F_s. Speed and conflicting volumes $n_{15,mj}$ are multiplied to form F_s. The typical relationship between speed and volume is an accepted fundamental dynamic of transportation engineering (e.g. in [9]). At the top of curve, speed is high and flow is low. In the middle of the curve, both speed and flow can be moderately high. At the bottom of the curve, speed is low and flow is low, representing congested conditions. The exact values of speed and flow depend upon the design and capacity of the roadway. Due to this dynamic, we should conceive of intersection PLOS as a function of the position on this curve, rather than thinking of speed and volume as varying independently. Since volume also affects F_v, the PLOS curve reflects the combined effect of changes to F_s and F_v. Figure 7 shows the resulting PLOS curve where the (speed, volume) pair is used as an input, and where we make the assumption that the sum $(v_{rtor} + v_{lt,perm})$ is proportional to $n_{15,mj}$ and to overall directional volumes.

The least important term in intersection PLOS is pedestrian delay. Using our default

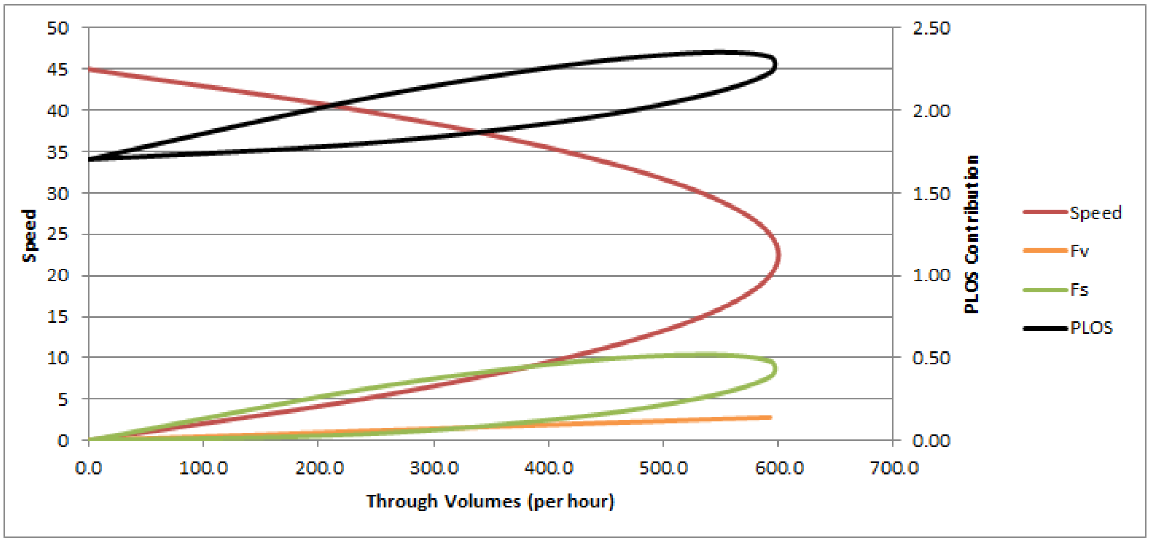

Figure 7: Paradigmatic relationship between traffic speed and traffic flow, or volume, and resulting Intersection PLOS.

values for other variables, varying the number of seconds of delay from 10 to 90 only resulted in a change in F_{delay} from 0.09 to 0.18. This is less than 1/8th of a grade. Figure 8 shows this lack of variance.

We note some variables to which intersection PLOS is *not* sensitive, despite these items receiving considerable attention in planning research and practice. The curb radii are not included in intersection PLOS, despite these being a determinant of motor vehicle turning speeds and pedestrian crossing length, and reduced curb radii being a best practice recognized by the Institute of Transportation Engineers [5]. Likewise, high visibility crosswalks, or continental crosswalks, are not significant. Design features required to comply with the Americans with Disability Act are not included in the calculation of PLOS, despite the Federal Highway Administration having explicitly called for their inclusion [6]. These include curb ramps and audio signals. The length of the walk time relative to the distance being crossed does not appear in PLOS, although this is an important feature, especially for people who walk slowly, such as the elderly. Relatedy, the presence or absence of median refuge islands does not appear in PLOS. Finally, the presence or absence of countdown signals and leading pedestrian intervals, considered best practices in pedestrian planning [7], are not included.

Finally, note that because traffic volumes and speeds figure in the calculation of inter-

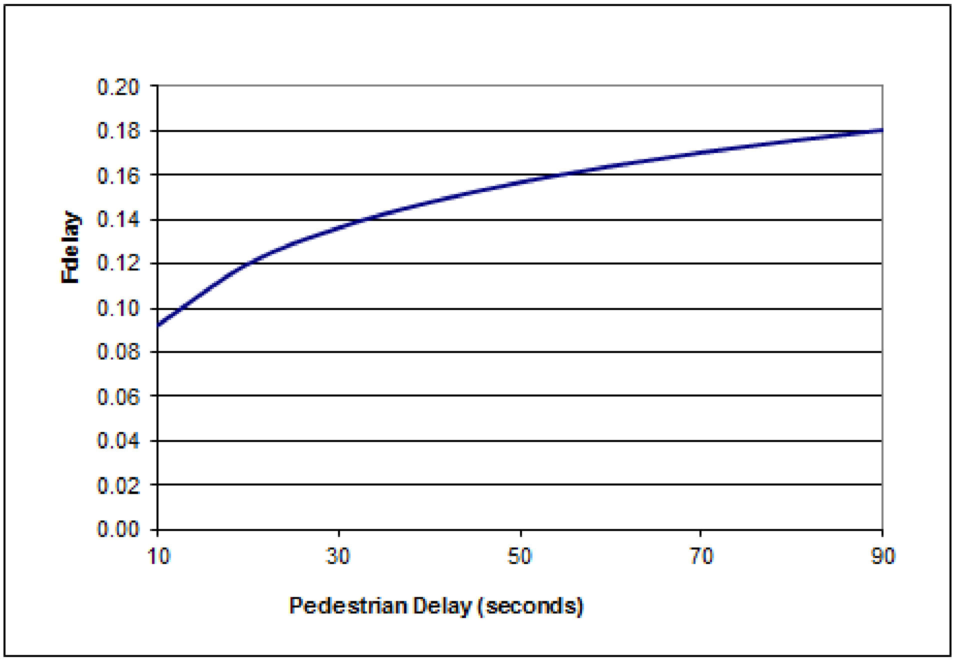

Figure 8: Intersection PLOS as a function of pedestrian delay.

section PLOS, anyone who wants to use PLOS to analyze the effects of proposed changes to a street must predict these variables. This can be difficult, because roadway design is only one of many factors that influence these operational characteristics. The easiest and most readily available option is for an analyst to assume that volumes and speeds will not change, and use measured existing conditions values to calculate intersection PLOS for a proposed scenario. In certain cases this can produce quite counterintuitive results. For example, Carter et al note in [8] that road diets degrade rather than improve PLOS and BLOS, because removing traffic lanes increases traffic density. However, this is only the case if volumes remain the same, which is not always true, depending on the specific parameters of the road diet. Likewise, certain design changes obviously result in significant changes in traffic volumes, for example in the case of prohibiting right-turns or left-turns at an intersection. The HCM does not note this limitation of its models in dealing with proposed changes.

In summary, intersection PLOS is a data-intensive calculation with interactive terms and terms that can counteract one another. It considers the number of lanes being crossed to have great importance, followed by traffic volumes, speeds, and pedestrian delay, in order of decreasing importance. It does not consider a number of factors and treatments that are widely recognized as having significant effects on pedestrian safety and comfort.

4.2 Link PLOS: Variables, Formula, and Sensitivity

Recall that a link is a unit of analysis that can span multiple blocks, where the continuity of the link depends on those blocks being separated by four-way stops or two-way stops where traffic on the link does not stop. The link PLOS considers two distinct elements. One is called the link "score" and is a number determined by a formula, similar to that used to calculate Intersection PLOS. The other part is pedestrian space, which is a measure of how much room a pedestrian has in square feet on the sidewalk. To determine link PLOS, an analyst must calculate the numerical score and the pedestrian space, convert both to letter grades, and then assign the worser of the two grades as the final grade. This process is described below.

4.2.1 Link PLOS Score

In order to calculate the PLOS score for a link, you must have in hand the information listed in the first column of Table 5.

Name	Variable	Units	Algebraic Terms	Direction of effect on PLOS	Interactions with other variables	Notes on data definitions
width of outside through lane	W_{ol}	feet	W_t	Increasing this improves PLOS.	Determines W_v and W_1.	
width of bicycle lane	W_{bl}	feet	W_t	Increasing this improves BLOS.	Determines W_v and W_1.	
width of paved outside shoulder	W_{os}	feet	W_t, W_e	Increasing this improves BLOS.	Determines W_v and W_1.	
presence of curbs	N/A	binary	W_t, W_e	Increasing this degrades BLOS.	Determines W_v and W_1 by determining W^*_{os}.	
proportion of on-street parking occupied	p_{pk}	none	$-1.2276\ln(W_v + \cdots + 50p_{pk} + \cdots)$	Increasing this improves PLOS.	Determines W_v and W_1.	
buffer width between roadway and sidewalk	W_{buf}	feet	$-1.2276\ln(W_v + \cdots + f_b W_{buf} + \cdots)$	Increasing this improves PLOS.	Multiplied by f_b. This variable is also included in the calculation of pedestrian space, where it decreases the space available and thus has the potential to degrade PLOS.	This is zero if there is no sidewalk.
presence of a continuous barrier at least 3 feet high	f_b	number	$-1.2276\ln(W_v + \cdots + f_b W_{buf} + \cdots)$	Increasing this improves PLOS.		It is 5.37 if such a barrier exists, and if not, it is 1.
adjusted available sidewalk width	W_{aA}	feet	$-1.2276\ln(W_v + \cdots + W_{aA} f_{sw})$	Increasing this improves PLOS.	Multiplied by f_{sw}	Determined by very specific instructions. This also has a maximum of 10 feet.
midblock demand flow rate	v_m	veh / hr	$0.0091\frac{v_m}{4N_{th}}$	Increasing this degrades PLOS.	Determines W_v.	
number of through lanes on the street in the direction of travel being considered	N_{th}	lanes	$0.0091\frac{v_m}{4N_{th}}$	Increasing this degrades PLOS.		
vehicle running speed	S_R	miles / hr	$4\left(\frac{S_r}{100}\right)^2$	Increasing this degrades PLOS.		HCM instructs analysts to use a model result from an auto LOS calculation

Table 5: Data required to calculate PLOS for a link.

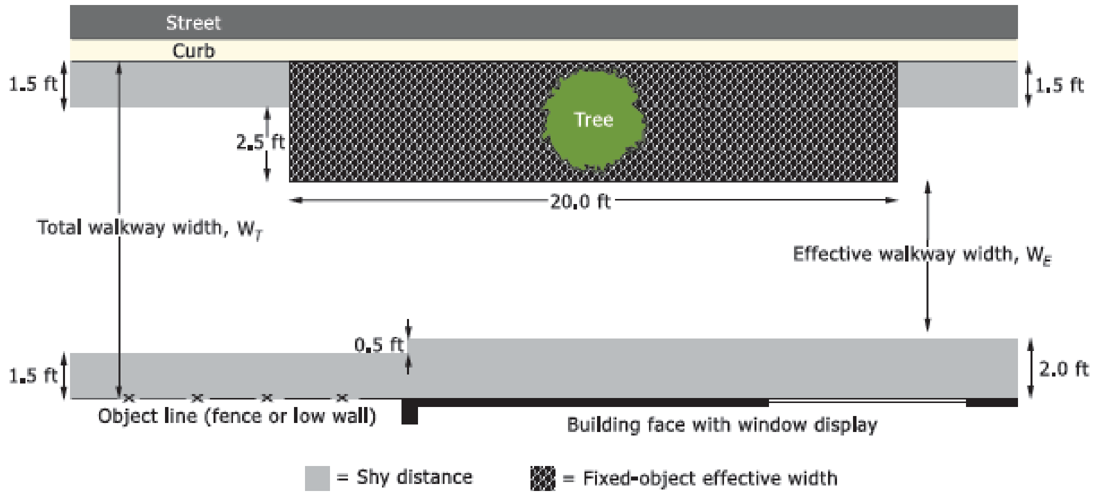

Figure 9: Instructions for calculating effective sidewalk width. Source: HCM Exhibit 17-17.

The HCM authors give very specific instructions for calculating effective sidewalk width and account for fixed objects and shy distances, as shown in Figure 9. On the other hand, they are vague in their directions for how to obtain a single value for a given link. The HCM states that effective sidewalk width is an average value, but it is unclear if the authors intend for analysts to create subsections of uniform effective width and then calculate a weighted average based on the lengths of such subsections.

These original data are then used to define several intermediate variables, which appear in the final formula for link PLOS. One of these is the sidewalk width coefficient, f_{sw}, which is defined as $f_{sw} = 6.0 - 0.3W_{aA}$. Two more variables deal with the width of the separation between vehicles and pedestrians, and concern outside through lane, bicycle lane, and shoulder widths. These are W_v and W_1, and instructions to calculate them are given by the HCM as shown in Figure 10.

Because the HCM's presentation is difficult to follow, we restate these instructions thus: W_v, the effective width of the outside through lane, bike lane, and shoulder, is determined by the percentage of on-street parking that is occupied as well as vehicle volumes adjacent to the side of the street being considered. If $p_{pk} = 0$, or there is no on-street parking occupied, the width of the outside paved shoulder is included in the effective width of the outside lane; if there is any parking occupied, the shoulder width is not included. Then, if volumes are below 160 veh/hr, effective outside width is multiplied by a factor ranging

Condition	Variable When Condition Is Satisfied	Variable When Condition Is Not Satisfied
$p_{pk} = 0.0$	$W_t = W_{ol} + W_{bl} + W_{os}^*$	$W_t = W_{ol} + W_{bl}$
$v_m > 160$ veh/h or street is divided	$W_v = W_t$	$W_v = W_t (2 - 0.005\ v_m)$
$p_{pk} < 0.25$ or parking is striped	$W_1 = W_{bl} + W_{os}^*$	$W_1 = 10$

Notes: W_t = total width of the outside through lane, bicycle lane, and paved shoulder (ft);
W_{ol} = width of the outside through lane (ft);
W_{os}^* = adjusted width of paved outside shoulder; if curb is present $W_{os}^* = W_{os} - 1.5 \geq 0.0$, otherwise $W_{os}^* = W_{os}$ (ft);
W_{os} = width of paved outside shoulder (ft); and
W_{bl} = width of the bicycle lane = 0.0 if bicycle lane not provided (ft).

Figure 10: Calculation of W_v and W_1. (Source: HCM Exhibit 17-18)

from .8 to 2, where the largest multipliers correspond to the lowest traffic volumes.[1]

When parking occupancy is greater than 0.25, W_1, the effective width of the combined bicycle lane and shoulder, is set to 10 feet. Otherwise, it is equal to the actual sum of the bike lane width and the shoulder width. This condition seems intended to reward streets with on-street parking, which presumably increases street quality for pedestrians by acting as a buffer between people walking and motor vehicles. As such, the condition doesn't seem to properly account for situations where parking occupancy is high and there is a wide bike lane (buffered bike lanes can be up to 10 feet in width). In those cases, the effective width can be as great as 17 or 18 feet, but the maximum would set the width to 10 feet.

The pedestrian level of service *score* at a link, or section of street, $I_{p,link}$, is then

$$I_{p,link} = 6.0468 + F_w + F_v + F_s$$

where

$$F_w = -1.2276 \ln(W_v + 0.5W_1 + 50p_{pk} + W_{buf} f_b + W_{aA} f_{sw})$$

$$F_v = 0.0091 \frac{v_m}{4N_{th}}$$

[1] The HCM's presentation of these conditions creates a seemingly inexplicable discontinuity in W_v as a function of v_m. For $0 < v_m \leq 160$, W_v is steadily decreasing from a value of $2W_t$ at $v_m = 0$ to a value of $1.2W_t$ at $v_m = 160$. W_v then jumps to $1W_t$ when $v_m \geq 161$. It's unclear why the authors of the HCM did not set the v_m condition instead at $v_m > 400$, where the function would be continuous: $v_m = 400$ is given by setting $W_t(2 - 0.005v_m) = W_t$ and solving for v_m.

$$F_s = 4\left(\frac{S_r}{100}\right)^2$$

Source: HCM 2010, page 17-50.

where we can refer to F_w as the cross-section factor ("w" again for "width") and F_v as the motorized vehicle volume factor, and F_s as the motorized vehicle speed factor, and where W_v and W_1 are subject to the conditions stated in the rightmost column of Table 5.

To state the formula and methodology in prose, the Pedestrian Level of Service score at a link is the sum of three terms. The higher the sum, the worse the score. The terms correspond to the width of the separation between pedestrians and vehicles (F_w), the volume of motor vehicles traveling adjacent to the sidewalk or shoulder (F_v), and the speed of motor vehicles traveling adjacent to the sidewalk or shoulder (F_s). The separation term has a negative coefficient, and so greater widths improve PLOS. This term is the natural log of a weighted sum of various widths: the width of the outside travel lane for vehicles, the width of any buffer area between the pedestrian travel area and the street, and the width of the sidewalk itself. The HCM gives instructions for calculating these widths that take into account shy distances from various building types and the presence of fixed objects on the sidewalk. The proportion of on-street parking and the volume of motor vehicles are also taken into account in determining the width term. The motor vehicle volume term is just a coefficient multiplied by the volume of vehicles per through lane. The speed term is the vehicle running speed squared, multiplied by a coefficient.

The HCM authors do note that it is possible for links to be nonuniform, wherein different sections of a link have different design features. For example: the sidewalk could end in the middle of a link, creating two subsections with different values for F_w. In these cases, an analyst would calculate separate link scores for each section, weight them by their length and compute a weighted average to obtain the final link score.

4.2.2 Link PLOS: Pedestrian Space

The second part of Link PLOS, pedestrian space on a sidewalk, is a function of 1) effective sidewalk width, accounting for shy distances and fixed objects, 2) pedestrian flow rate (e.g. peds / hour) and 3) walking speed. This calculation is not done for links that do not have sidewalks. To calculate pedestrian space one needs the information in Table 6 below.

Name	Variable	Units	Algebraic Terms	Direction of effect on PLOS	Notes on data definitions
shy distance on the inside of sidewalk	$W_{s,i}$	s	$-W_{s,i}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	generally 1.5 feet according to HCM
shy distance on the outside of sidewalk	$W_{s,o}$	feet	$-W_{s,o}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	"1.5 ft if a fence or low wall is present, 2.0 ft if a building is present, 3.0 feet if a window display is present, and 0.0 ft otherwise"
buffer width between roadway and sidewalk	W_{buf}	feet	$\max(W_{buf}, 1.5)$	Increasing this improves PLOS score, but can degrade PLOS by decreasing the available pedestrian space.	
proportion of sidewalk length adjacent to a window display	p_{window}	decimal	$3.0p_{window}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	
proportion of sidewalk length adjacent to a building face	p_{building}	decimal	$2.0p_{building}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	
proportion of sidewalk length adjacent to a fence or low wall	p_{fence}	decimal	$1.5p_{fence}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	
effective width of fixed objects on inside of sidewalk	$\omega_{O,i}$	feet	$\omega_{O,i} - w_{s,i}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	
effective width of fixed objects on outside of sidewalk	$\omega_{O,o}$	feet	$\omega_{O,o} - w_{s,o}$	Increasing this can degrade PLOS in the presence of high pedestrian volumes.	

Table 6: Data required to calculate pedestrian space, towards determining link PLOS.

Pedestrian LOS Score	LOS by Average Pedestrian Space (ft²/p)					
	>60	>40–60	>24–40	>15–24	>8.0–15[a]	≤ 8.0[a]
≤2.00	A	B	C	D	E	F
>2.00–2.75	B	B	C	D	E	F
>2.75–3.50	C	C	C	D	E	F
>3.50–4.25	D	D	D	D	E	F
>4.25–5.00	E	E	E	E	E	F
>5.00	F	F	F	F	F	F

Note: [a] In cross-flow situations, the LOS E/F threshold is 13 ft²/p.

Figure 11: Look up table to combine pedestrian space and pedestrian score to obtain Link PLOS. HCM Exhibit 17-3

The pedestrian space calculation is easily summarized, so for space considerations we'll not include a full exposition of the 8 equations that are used to calculate pedestrian space. The full calculation is on pages 17-47 through 17-49 of the 2010 HCM. In brief: the number of pedestrians per hour (an observed value) is divided by the effective sidewalk width to determine ped flow per foot of sidewalk width. This is then used to determine average walking speed, based on the fact that the more pedestrians there are per foot of sidewalk width, the more crowded it is, and the slower people walk. Dividing average walking speed (ft/s) by pedestrian flow (peds / hr / ft) gives pedestrian space (ft^2 / ped).

The Pedestrian Level of Service at a link is then finally determined by a look up table that combines the pedestrian space and the link pedestrian level of service score (Figure 11). To achieve a certain grade A-F, links must meet minimum thresholds for both space and LOS score. The worser factor predominates. Note that in practice, an analyst would often make the assumption that there is sufficient pedestrian space, in which case the link PLOS "score" becomes the final value of link PLOS.

4.2.3 Sensitivity Analysis

We perform sensitivity analysis only on the score portion of link PLOS, and not on the pedestrian space calculation. This is because the pedestrian space calculation is a relatively straightforward linear function with only a few discretionary parameters. These concern shy distances from categories of adjacent structures (window displays, buildings, and fences). Pedestrian space is sensitive to anything that reduces the effective width of the sidewalk and to pedestrian volumes.

As with intersection PLOS, the relative importance of F_w, F_v, and F_s in the link PLOS score is difficult to read from the formula itself due to the varying units involved. A sensitivity analysis provides a graphic representation of the relative importance of each of the three terms in link PLOS, and the independent effects of the variables in those terms. We examine the magnitude of link PLOS and the contribution of each of its component terms in with the following default values. These values represent plausible and common conditions on US streets.

Variable	Name	Value
W_{ol}	Width of outside through lane	10.5 feet
W_{bl}	Bike lane width	5 feet
W_{os}	Width of paved outside shoulder	7.5 feet
p_{pk}	Proportion of on-street parking occupied	0.95
W_{buf}	Buffer width between roadway and sidewalk	4 feet
f_b	Buffer area coefficient (5.37 if there is a continuous barrier at least 3 feet high, 1 otherwise)	1
W_A	Available sidewalk width	10 feet
v_m	Mid-link vehicle flow	835 vehicles / hour
N_{th}	Number of through lanes on link in the direction of travel	1 lane

Table 7: Default values employed in sensitivity analysis of Link PLOS.

Figure 12 presents the link PLOS score broken into its component parts, and provides an understanding of the relative importance of the three terms F_w, F_v, and F_s. The first column uses the default values shown in Table 7 above. Subsequent columns vary these input parameters in order to examine the effect, if any, on the relative importance of the three F terms. In the second column, the bike lane width is doubled. Third column: the percent of on-street parking occupied is set to 0. Fourth column: half of the on-street parking is occupied. Fifth column: the width of the buffer between the road and sidewalk is set to 0. Sixth column: a vertical barrier is present where it was not before. Seventh column: the sidewalk width (and thus the adjusted available sidewalk width) is doubled. Eighth column: vehicle running speeds are doubled. Ninth column: vehicle volumes are doubled. Tenth column: vehicle volumes are halved.

Across all these cases, F_w, the cross-section factor, is the term that has the greatest

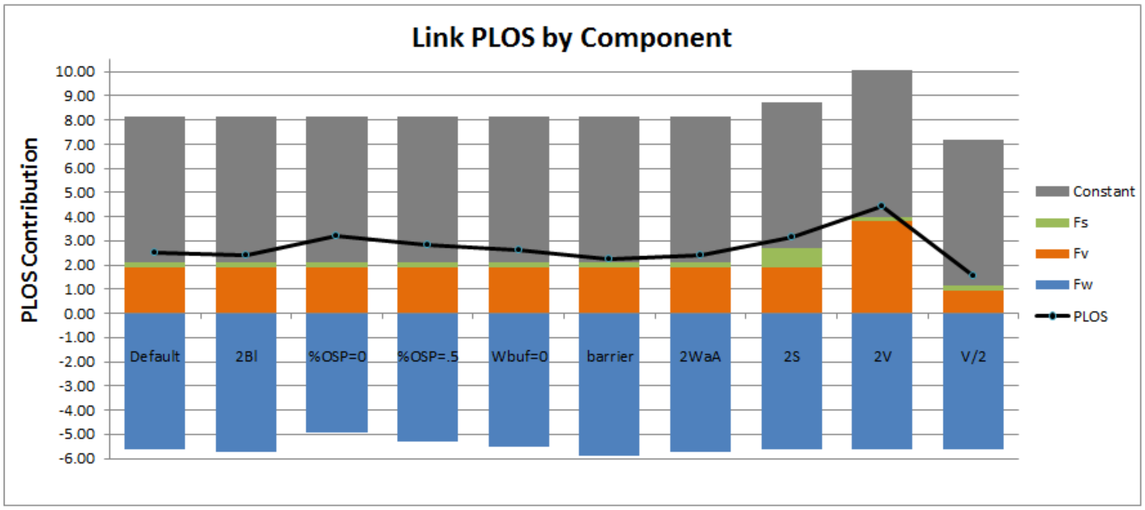

Figure 12: Contributions of F_w, F_v, F_s, and the constant to Link PLOS for a variety of cases.

influence on pedestrian link LOS score. The next most important term is F_v, and F_s has a small effect. Note that F_w takes a negative value, generally between 0 and 6, and that there is a constant of 6.047 included in each score.

The following figures then examine the effect of individual terms and variables on link PLOS. We proceed roughly in order of the variables with the most significance as indicated by Figure 12.

Recall that $F_w = -1.2276 \ln(W_v + 0.5W_1 + 50p_{pk} + W_{buf} f_b + W_{aA} f_{sw})$. Figure 13 examines the resulting PLOS score for a variety of cases with respect to the variables in F_w. On the x-axis is the total width of the bike lane, parking area, and shoulder, which determines W_t, W_v, and W_1. The downward slope of all of these lines reflects the fact that increases in these various street widths improve PLOS. Working from the top of Figure 13, we consider two options for outside lane width: a narrow lane (10') and a wide lane (14'). We also examine the effect of variance in parking occupancy and sidewalk width. Adding 95% parking occupancy significantly improves link PLOS, more than widening the sidewalk from 5 feet to 10 feet or adding a continuous buffer to the sidewalk.

Some of the coefficients in F_w do not make sense. There is a larger penalty to PLOS for having no parking occupied than for having no sidewalk. The treatment of sidewalks is both confusing and lacking in validity. The use of a sidewalk coefficient, f_{sw}, makes it seem as if sidewalk width, W_{aA}, is another linear term within the ln() when it is really a

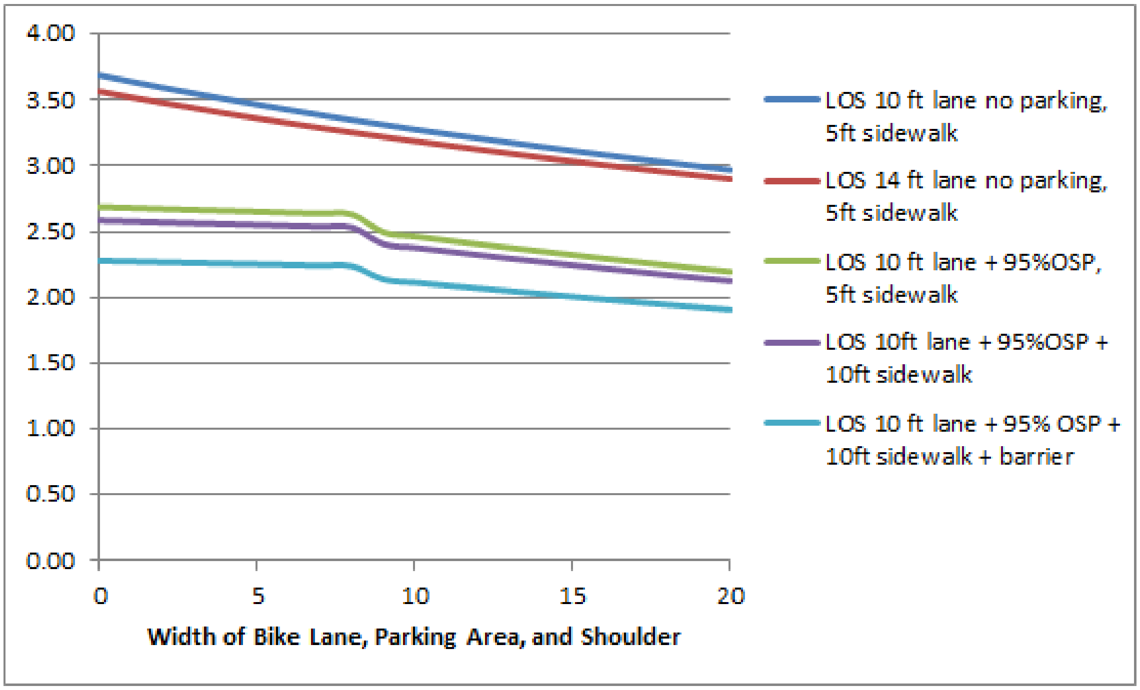

Figure 13: Effect of various components of F_w on Link PLOS.

quadratic term, as $f_{sw}W_{aA} = (6.0 - 0.3W_{aA})W_{aA} = 6.0W_{aA} - 0.3W_{aA}^2$. This quadratic has its maximum at $W_{aA} = 10$. Note that W_{aA} is also defined so that it cannot be greater than 10. For these reasons, increases in sidewalk width above 10 feet do not improve (or have any effect upon) link PLOS.

The next figure considers traffic volumes and speeds. Since these two do not vary independently, but rather covary in a paradigmatic relationship (e.g. in [9]), we first plot the speed-flow diagram, then calculate the resulting link PLOS for each (volume, speed) pair. The parabola depicting speed and volume shows that the same flow can be achieved in at either high speeds or low speeds, with latter representing congested conditions. As Figure 14 shows, the penalty to link PLOS is the highest when flow is maximized, and speeds are relatively high but not free-flow speeds. The difference between the lowest point on this curve (0.5) and the highest point (2) is about two grades.

It is worth noting some of the variables to which Link PLOS is *not* sensitive, despite their importance to planners and policymakers. These include street trees, street lighting, presence of landscaped parkways between the walkway and the street, and crossing

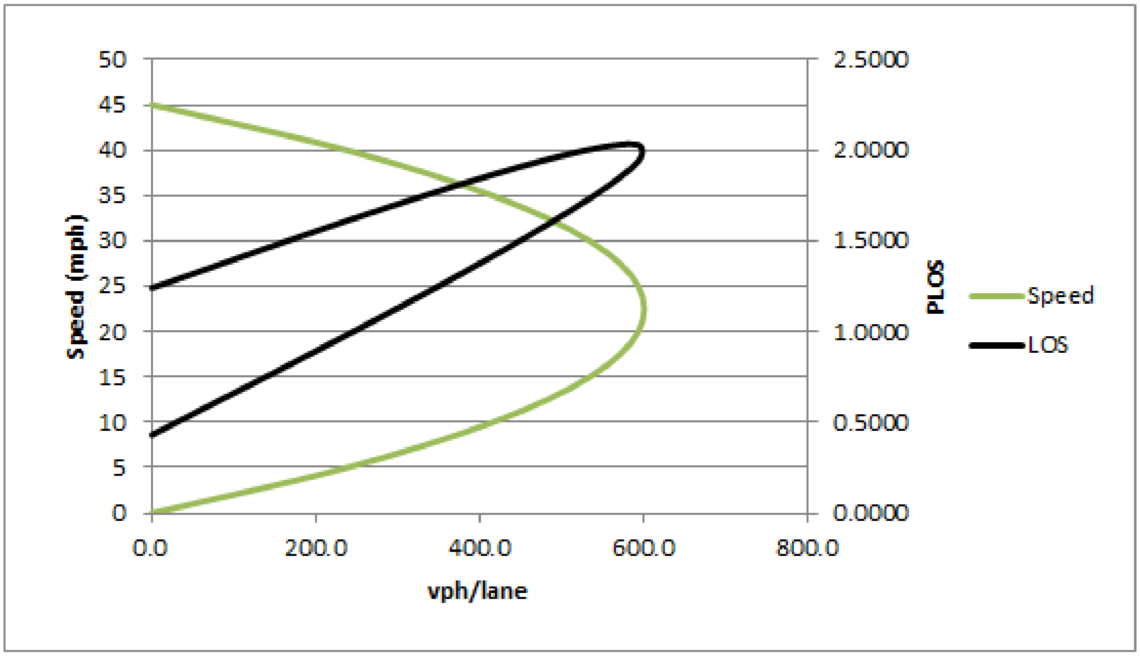

Figure 14: Link PLOS where speed and volume vary according to the fundamental law of traffic engineering.

distances and crossing treatments such as crosswalks and bulb-outs at non-boundary intersections (e.g. those intersections where cross-traffic is controlled by a two-way stop and traffic on the link is uncontrolled). Sidewalk quality is another variable that is not considered, so link PLOS is indifferent, for example, to whether or not the sidewalk is level, whether it is intersected by sloping driveways, and whether or not it is uprooted by tree roots. Additionally, as with intersection PLOS, note that Link PLOS incorporates traffic volumes and speeds, and that analysis of proposed changes thus requires predicting how volumes and speeds will change. As noted in [8], PLOS and BLOS can produce counterintuitive results, such as lane removals that degrade PLOS and BLOS, when the assumption is made that these variables do not change.

To summarize, pedestrian level-of-service at a link, or successive series of block faces, is a data-intensive calculation with interactive terms and terms that can counteract one another. It draws heavily on measurements of the physical space that pedestrians have to walk in. Link PLOS has two parts, the "score" and the pedestrian space calculation, and the final link PLOS grade is determined by the worser of these two. The score takes into account sidewalk width and separation from vehicles, as well as vehicle volumes and speeds. It gives great importance to the width of outside lanes and parking occupancy, followed by sidewalk widths, traffic volumes, and speeds, in order of decreasing importance. The pedestrian space calculation considers pedestrian volumes, average walking speeds, and sidewalk widths and obstructions. Pedestrian delay may significantly affect the final score if the street is quite crowded.

4.3 Segment PLOS: Variables and Formula

Recall that a segment is a link and an adjacent intersection, where segments are specific to a direction of travel and it is always the downstream intersection that is combined with the link.

Segment PLOS is a function of link PLOS and intersection PLOS, with the addition of one new factor. It is the roadway crossing difficulty factor, F_{cd}. Recall that links can span multiple blocks, when these blocks are not separated by signals or other intersection controls that cause vehicles to stop or yield. So, for example, a link may span many blocks of an urban arterial, where cross streets of that arterial are controlled by two-way stop signs. A four-way stop, signalized intersection, or traffic circle would define a link boundary. F_{cd} is thus a measurement of how difficult it is to cross the link, taking two options into consideration. First, a pedestrian might walk to the end of the link and cross at an intersection. Second, a pedestrian may cross mid-link, presuming that this is legal. Unless the link is just one block with signalized intersections at both ends, in California it would otherwise always be legal to cross mid-link: either there are uncontrolled intersections, at which the pedestrian would have the right-of-way, or the pedestrian could cross mid-block, in which case he or she would yield to vehicle traffic (California Vehicle Code 21949-21971).

The calculation of F_{cd} considers both of these options. First, an analyst would calculate d_{pd}, the pedestrian diversion delay, which corresponds to the first option and the time the person spends walking to the end of the link, crossing, and reaching his or her destination on the other side. The calculation is relatively straightforward and non-technical, though it does require the analyst to reference d_{pc}, the pedestrian delay when crossing at the signal. d_{pc} is also an intermediary in the calculation of intersection PLOS. [2] What the

[2] The HCM authors have the confusing habit of changing variable names when discussing the same variable in different contexts: where d_{pc} is originally defined on page 18-68 of the HCM it is denoted as d_p, and where it is defined on p. 18-69 as an operand of F_{delay} in PLOS, it is denoted as $d_{p,d}$. Nomenclature-wise, we are in the confusing situation of having to calculate d_{pd} which is a function of d_{pc}, which in turn

analyst is doing here is calculating 1) the time it takes for the pedestrian to “divert” along the sidewalk to the nearest boundary intersection, given a measured distance D_d and an assumed pedestrian speed S_p; and 2) the time d_{pc} it takes to cross the street there. The analyst must make some judgments about whether or not pedestrian demand is uniform along the link, or if there are common origin and destination points motivating the crossing. These determine D_d.

To continue in the calculation of F_{cd}, the analyst would then consider d_{pw}, the time it takes to cross mid-link, corresponding to the second crossing option. d_{pw} is defined as a required input variable on p. 17-23. The calculation is involved, and is presented in a separate chapter (pages 19-31 through 19-36). d_{pw} accounts for two-stage crossings enabled by medians, variable driver yielding rates due to various crossing devices such as crossing signs and flashing beacons, probabilistic calculations of gaps in vehicle traffic, possible pedestrian platooning, and other factors. In lieu of a full explication of d_{pw}, for which we welcome the reader to reference the aforementioned pages of the HCM, we’ll limit the presentation here to the variables involved, example formulae, and the direction of each variable’s effect on d_{pw}.

Table 8 lists the variables employed in the calculation of d_{pw}. The algebraic terms shown in this table should be taken as examples to give the reader a sense of the calculations involved. We won’t define all of the intermediate variables which appear in those terms.

is at times denoted by $d_{p,d}$.

Name	Variable	Units	Algebraic Terms	Direction of effect on PLOS	Role in determining d_{pw}	Notes on data definitions
two-stage crossings	N/A	number	N/A	Increasing this improves PLOS.	Results in a two-part calculation of d_{pw}, with the two parts being summed, rather than exponential and multiplicative compounding of delay over all the lanes of the street. Reference row 9 of this table for an example of this compounding.	Engineering judgement is used to determine two-stage crossings. These are enabled by median refuge islands.
crosswalk length	L	feet	$t_c = \frac{L}{S_p} + t_s$	Increasing this degrades PLOS.	Used to determine the critical headway between vehicles that allows a pedestrian to cross. Longer crossings require a longer headway.	It's confusing that the HCM uses the variable L to denote both this and the number of lanes crosssed.
pedestrian walking speed	S_p	seconds	$t_c = \frac{L}{S_p} + t_s$	Increasing this improves PLOS.	Also used to determine the critical headway. When vehicles travel faster, a longer headway is needed.	
pedestrian start-up time and end clearance time	t_s	seconds	$t_c = \frac{L}{S_p} + t_s$	Increasing this improves PLOS.	Used to determine the critical headway.	
number of pedestrians in any crossing platoons observed	N_c	peds	$\lfloor \frac{8.0N_c - 1}{W_c} \rfloor + 1$	Increasing this degrades PLOS.	Used to adjust the critical headway to account for the longer headway necessary for a platoon of pedestrians to cross.	Here we assume that the HCM authors mean the floor function when they use the notation "Int[ ]"
crosswalk width	W_c	feet	$\lfloor \frac{8.0N_c - 1}{W_c} \rfloor + 1$	Increasing this improves PLOS.	Used to determine pedestrian platooning to adjust the critical headway to account for groups of pedestrians.	
pedestrian flow rate	v_p	peds / second	$N_c = \frac{v_p e^{v_p t_c} + v e^{-v t_c}}{(v_p + v) e^{(v_p - v) t_c}}$	Unclear (I personally can't read this from the formula, can you?)	Used to determine pedestrian platooning to adjust the critical headway to account for groups of pedestrians.	e here is the base of the natural logarithm
vehicular flow rate	v	veh / second	$N_c = \frac{v_p e^{v_p t_c} + v e^{-v t_c}}{(v_p + v) e^{(v_p - v) t_c}}$	Unclear (I personally can't read this from the formula, can you?)	Used to determine pedestrian platooning to adjust the critical headway to account for groups of pedestrians.	
number of through lanes crossed	L	number	$P_b = 1 - e^{\frac{-t_{c,G} v}{L}}$, and $P_d = 1 - (1 - P_b)^L$	Increasing this degrades PLOS.	Used to determine P_b, the probability of a blocked lane, and thus P_d, the probability of crossing delay	It's confusing that the HCM uses the variable L to denote both this and the length of the crosswalk.
presence of crossing devices such as pedestrian beacons or signs	N/A	present or not present	$d_p = \sum_{i=1}^{n} h(i - 0.5) P(Y_i) + \left(P_d - \sum_{i=1}^{n} P(Y_i)\right) d_{gd}$	Increasing this improves PLOS.	Used to estimate reduction in delay due to yielding vehicles by determining $P(Y_i)$, the probability that a motorist will yield	
observed motorist yielding rate	N/A	yields / crossing events	$d_p = \sum_{i=1}^{n} h(i - 0.5) P(Y_i) + \left(P_d - \sum_{i=1}^{n} P(Y_i)\right) d_{gd}$	Increasing this improves PLOS.	Used to estimate reduction in delay due to yielding vehicles by determining $P(Y_i)$, the probability that a motorist will yield	

Table 8: Data required to calculate d_{pw}, the crossing delay for a pedestrian, towards calculation of Segment PLOS.

With d_{pw} in hand, the analyst now finds the minimum of three quantities, all in units of seconds per pedestrian:

$$d_{px} = \min(d_{pd}, d_{pw}, 60).$$

This finally enables the calculation of F_{cd}, the roadway crossing difficulty factor, and finally the Segment PLOS:

$$F_{cd} = 1 + \frac{0.10d_{px} - (0.318I_{p,link} + 0.220I_{p,int} + 1.606)}{7.5}$$

$$I_{p,seg} = F_{cd}(0.318I_{p,link} + 0.220I_{p,int} + 1.606)$$

where $I_{p,link}$ and $I_{p,int}$ are the link and the intersection PLOS respectively.

The HCM authors present segment PLOS as the weighted sum of intersection PLOS and link PLOS. However, because F_{cd} itself includes such a weighted sum (with suspiciously identical coefficients), segment PLOS is really a linear function of d_{px}, the crossing delay, and a weighted sum of the *squares* of intersection PLOS and segment PLOS. d_{px} is also capped at 60 seconds, for reasons not made apparent.

To summarize in English, pedestrian level-of-service for a "segment," which is a technical unit of analysis defined in the HCM as a link and its downstream intersection, is primarily a quadratic function of the link and intersection's pedestrian level of service. In addition to these, segment PLOS includes a term for crossing delay. This term is capped at 60 seconds. It considers two crossing options, one in which the pedestrian crosses mid-link and another in which the pedestrian walks to the nearest boundary intersection and crosses there. The latter of these is found by a relatively simple formula considering the signal cycle length and the length of the walk phase. To calculate the delay for a pedestrian crossing mid-link involves considering many variables and cases, and an onerous multi-step process requiring an extensive list of physical measurements and observations. This process accounts for such dynamics as crossing treatments, vehicle spacing, and pedestrian platooning. The crossing option that results in less delay to the pedestrian is used in calculating segment PLOS, presuming that one or both of these is less than 60 seconds.

For brevity and because segment PLOS is primarily a function of intersection and link PLOS, we do not present a sensitivity analysis for segment PLOS.

Pedestrian LOS Score	LOS by Average Pedestrian Space (ft²/p)					
	>60	>40–60	>24–40	>15–24	>8.0–15[a]	≤ 8.0[a]
≤2.00	A	B	C	D	E	F
>2.00–2.75	B	B	C	D	E	F
>2.75–3.50	C	C	C	D	E	F
>3.50–4.25	D	D	D	D	E	F
>4.25–5.00	E	E	E	E	E	F
>5.00	F	F	F	F	F	F

Note: [a] In cross-flow situations, the LOS E–F threshold is 13 ft²/p.

Figure 15: Thresholds for pedestrian space and PLOS score used to determine Facility PLOS.

4.4 Facility PLOS: Variables and Formula

Finally, to calculate PLOS for a facility, one combines scores and variables previously calculated for its component segments. Facility PLOS is a function of 1) pedestrian space and 2) component segments' PLOS scores. Pedestrian space for the facility is a relatively simple function of pedestrian space on the component segments. Let the set of $A_{p,i}$ be the pedestrian space for segments $1, \cdots i \cdots m$ that compose the facility, and let L_i be each such segment's length. $A_{p,F}$, the pedestrian space (ft^2 per pedestrian) on the facility, is then given by

$$A_{p,F} = \frac{\sum_{i=1}^{m} L_i}{\sum_{i=1}^{m} \frac{L_i}{A_{p,i}}}.$$

Likewise, PLOS for the facility is a weighted sum of segment PLOS scores:

$$I_{p,F} = \frac{\sum_{i=1}^{m} I_{p,seg,i} L_i}{\sum_{i=1}^{m} L_i}$$

where $I_{p,F}$ is facility PLOS and $I_{p,seg,i}$ is segment PLOS for segment i.

Finally, to determine the facility PLOS, an analyst references the thresholds for space and PLOS score given in Figure 15. The table is similar to the one employed in determining the final link PLOS. To achieve a certain grade A-F, facilities must meet minimum thresholds for both space and LOS score. The worser factor predominates.

The HCM authors also instruct analysts to examine pedestrian travel speed, and give a formula and instructions for doing so, but this speed doesn't figure in the final facility PLOS score.

The HCM authors warn analysts to interpret facility PLOS with caution, because a facility PLOS score can mask variation in the component segments' scores. According to the HCM authors, facility PLOS "can suggest acceptable operation of the facility when, in reality, certain segments are operating at an unacceptable LOS." It's striking that this caution appears now, when intersection, link, and segment PLOS arguably suffer from the same potential disconnect between the grade that the PLOS score "suggests" and what the street is like "in reality." The HCM authors appear quite concerned about aggregating over multiple segments to reach a single grade for a longer facility, but don't show similar caution about combining multiple dimensions of quality (e.g. delay, comfort) in the calculation of intersection, link, and segment PLOS.

Again, for brevity and because facility PLOS is a linear function of the component segment PLOS scores, we do not present a sensitivity analysis.

5 The Functional Form of HCM BLOS

We now consider the variables, units of analysis, formulae, and processes employed in the calculation of Bicycle Level-of-Service (BLOS) as it is presented in the 2010 Highway Capacity Manual.

5.1 Units of Analysis

BLOS calculations consider the same four units of analysis that PLOS calculations do. These are the intersection, the link, the segment, and the facility, as previously defined. BLOS for an intersection pertains to a specific approach to that intersection. Link, segment, and facility BLOS are specific to a direction of travel.

5.2 Intersection BLOS: Variables, Formula, and Sensitivity

Here we consider the methodology for calculating BLOS at a signalized intersection, since these are the types of intersections that form boundaries of segments, which then form facilities. The HCM does give a separate method for analyzing four-way stop controlled intersections, which we do not consider here. In order to calculate BLOS for an intersection, you must have in hand the information listed in the first column of Table 9.

Name	Variable	Units	Algebraic Terms	Direction of effect on BLOS	Notes on data definitions
curb-to-curb width of the cross street	W_{cd}	feet	$0.0153W_{cd} - 0.2144W_t$	Increasing this degrades BLOS.	
left-turn demand flow rate	v_{lt}	vehicles per hour	$0.0066\frac{v_{lt}+v_{th}+v_{rt}}{4N_{th}}$	Increasing this degrades BLOS.	This is the flow on the subject street, not the cross-street. The HCM's language makes it unclear if this should be a *measured* quantity or a *modeled* quantity
through demand flow rate	v_{th}	vehicles per hour	$0.0066\frac{v_{lt}+v_{th}+v_{rt}}{4N_{th}}$	Increasing this degrades BLOS.	As above.
right-turn demand flow rate	v_{rt}	vehicles per hour	$0.0066\frac{v_{lt}+v_{th}+v_{rt}}{4N_{th}}$	Increasing this degrades BLOS.	As above.
number of through lanes (shared or exclusive)	N_{th}	number	$0.0066\frac{v_{lt}+v_{th}+v_{rt}}{4N_{th}}$	Increasing this with volumes held constant improves BLOS. Since adding lanes may result in increased volumes, the effect is uncertain.	
width of the outside through lane	W_{ol}	feet	$W_{ol} + W_{bl} + I_{pk}W^*_{os}$	Increasing this improves BLOS, unless W_{cd} is increased in which case this variable has a conflicted effect.	
width of the bicycle lane	W_{bl}	feet	$W_{ol} + W_{bl} + I_{pk}W^*_{os}$	Increasing this improves BLOS, unless W_{cd} is increased in which case this variable has a conflicted effect.	This is 0 if there is no bicycle lane.
on-street parking occupancy	p_{pk}	percentage	Used to define $I_{pk} = 0$ if $p_{pk} > 0$. Otherwise $I_{pk} = 1$.	When curbs are present, increasing this above 0 degrades BLOS.	
width of paved outside shoulder	W_{os}	feet	W_{os}	Increasing this improves BLOS, unless W_{cd} is increased in which case this variable has a conflicted effect.	
presence of curbs	N/A	binary	If curb is present, and $W_{os} \geq 1.5$, $W^*_{os} = W_{os} - 1.5$. Otherwise, $W^*_{os} = W_{os}$.	If this is non-zero, BLOS is degraded.	

Table 9: Data required to calculate BLOS for a signalized intersection.

Note that these original data are used to define a few intermediate variables, each of which appears in the final formula for Intersection BLOS. The first of these is I_{pk}, the indicator variable for on-street parking occupancy. This is 1 if *any* parking is occupied. It's zero if parking is not allowed or there is no parking occupied. The second of these is W^*_{os}. This is an adjusted shoulder width, where if a curb is present, 1.5 feet is subtracted from the shoulder width to account for shy distance from the curb.

The formula for Bicycle Level of Service at an Intersection, $I_{b,int}$, is then

$$I_{b,int} = 4.1324 + F_w + F_v$$

where

$$F_w = 0.0153 W_{cd} - 0.2144 W_t,$$
$$F_v = 0.0066 \frac{v_{lt} + v_{th} + v_{rt}}{4N_{th}},$$

and

$$W_t = W_{ol} + W_{bl} + I_{pk} W^*_{os}.$$

Compared to the formula for Intersection PLOS, the formula for Intersection BLOS is much less complex and involves less interaction between variables. BLOS at an intersection is the sum of two terms and a constant. The terms correspond to the width of the cross-street (F_w) and the vehicle volumes at the approach (F_v). The width term, F_w, is the total width of the cross-street (W_{cd}) minus the sum of three widths that determine bicyclists' operating space: that of the outside lane, the bike lane (if any exists), and the shoulder (W_t). The coefficient on W_t is negative and about 14 times larger than the coefficient on W_{cd}. F_w is thus typically negative, and contributes positively to BLOS. The greater the width of W_t is relative to the streets' width, the greater the contribution of this F_w term. The volumes term is vehicle volume per lane per 15 minutes.

The relative weights on the two terms, as well as on the variables they contain, are difficult to read from the formula, again due to the various units involved.

5.2.1 Sensitivity Analysis

A sensitivity analysis provides a graphic representation of the relative importance of each of the terms in intersection BLOS, and the independent effects of the variables in those terms. Table 10 shows the default values chosen for the sensitivity analysis; these represent plausible and common conditions on U.S. streets.

Variable	Name	Value
W_{cd}	curb-to-curb width of the cross street	66
v_{lt}	left-turn demand flow rate	200
v_{th}	through demand flow rate	400
v_{rt}	right-turn demand flow rate	300
N_{th}	number of through lanes (shared or exclusive)	1
W_{ol}	width of the outside through lane	11
W_{bl}	width of the bicycle lane	6
I_{pk}	on-street parking occupancy	0.85
W_{os}	width of paved outside shoulder	7

Table 10: Default values employed in sensitivity analysis of intersection BLOS.

Figure 16 then presents the intersection BLOS score broken into its component parts, providing an understanding of the relative importance of F_w and F_v. The first column of Figure 16 uses the default values shown above. Subsequent columns vary these input parameters in order to examine the effect on the relative magnitude of F_w and F_v. In the second column, the cross-street is made very wide, 100 feet. In the third column, the traffic volumes are doubled. In the fourth column, the number of through lanes is doubled. In the fifth column, two through lanes remain, and the bike lane is removed, with the assumption that the resulting width is converted to outside through lane. The sixth column is identical to the fifth column, with on-street parking removed. The seventh column simulates a road diet given the parameters used in column 5, so the number of through lanes is reduced and the bike lanes are widened by about 6' each, and some reduction in traffic volumes is assumed.

Across all these cases, the width term predominates. The exception is the third column, where there are quite large input volumes (400 lefts, 800 through, and 600 rights per hour).

The fourth and fifth columns are identical to illustrate that intersection BLOS is indifferent to whether operating space comes in the form of bike lane or outside through lane. If a bike lane is added by restriping excess width in a through lane, intersection BLOS does not change, because there would be no change in the width term $W_t = W_{ol} + W_{bl} + I_{pk}W^*_{os}$. The seventh column illustrates that reducing the number of lanes can increase F_v, by reducing the denominator in the traffic density term. In this case, the reduction in F_w outweighs the increase in F_v, making the road diet something that on the whole improves

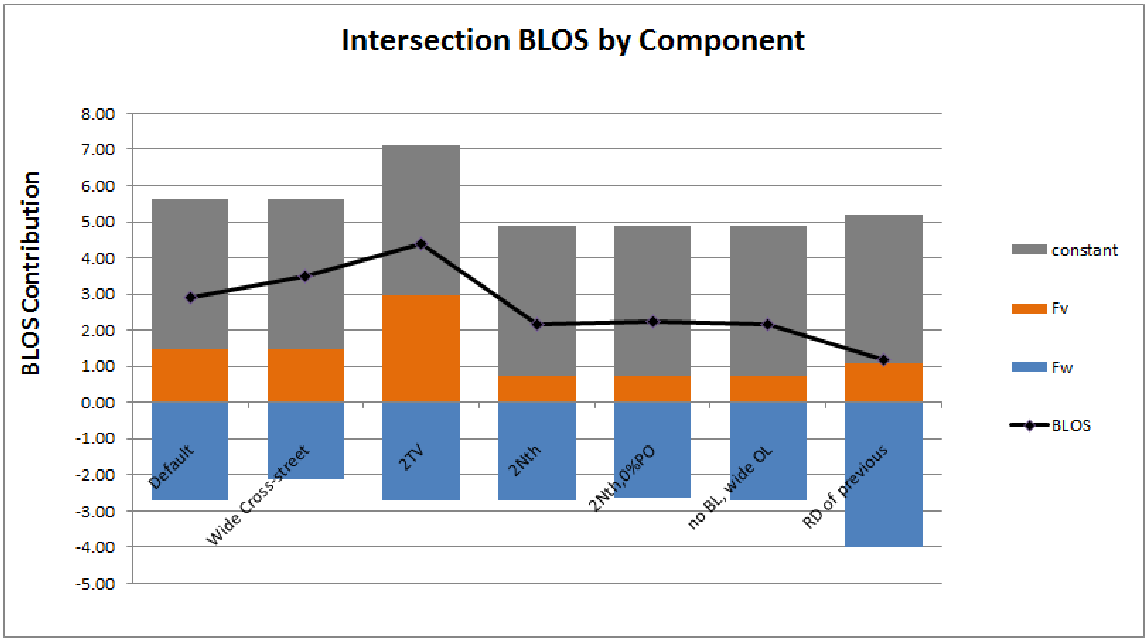

Figure 16: Contributions of F_w, F_v and the constant to intersection BLOS for a variety of cases.

intersection BLOS.

Because the formulae for intersection BLOS are so much simpler than the other PLOS and BLOS models, we do not present figures showing how intersection BLOS varies according to individual variables. Rather, we note that intersection BLOS is linear with respect to all of its input variables, and that widths of outside through lane and bike lanes only count toward the improvement of intersection BLOS if on-street parking occupancy is less than 85%.

There are a few things worth questioning in Intersection BLOS. First, why does parking occupancy appear in the calculation at all? Parking is almost always prohibited on intersection approaches, so its effect on bicycle level-of-service would seem to be a property of the link, not the intersection. Second, why does F_v only consider the number of through lanes? One would think that increases in the number of turning lanes would also degrade bicyclist comfort and safety. Double right-turn configurations, and through/right-turn lanes, are considered poor practice in roadway design to accommodate bicycles. Finally, why does intersection BLOS not account for delay? A method for calculating bicycle delay is given in the HCM as a separate, independent calculation, but it is not incorporated into intersection BLOS, nor is it included in link, segment, or facility BLOS. The HCM authors account for delay in the calculation of PLOS and, presumably, auto LOS, and they don't offer any reasoning as to why delay to bicyclists is treated differently.

It is worth noting those variables to which intersection BLOS is not sensitive despite their importance in policy and planning. Intersection BLOS is indifferent to intersection treatments such as bicycle boxes, striping through intersections, and bicycle-only signal phases. It's indifferent to whether or not a signal can detect bicycles, or to the presence of a push-button oriented towards bicyclists allowing them to activate the signal. It is indifferent to the length of the green and yellow phase, which can often be insufficient for slow-moving bicyclists to clear the intersection. Also, the HCM does not give a methodology for BLOS at two-way stop controlled intersections. Although agencies have improved difficult crossings at these intersections via such treatments as signs and bicycle-length medians, BLOS would be indifferent to such improvements. Additionally, note that intersection BLOS incorporates traffic volumes and speeds, and that analysis of proposed changes to the roadway thus requires predicting how volumes and speeds will change. As noted in [8], PLOS and BLOS can produce counterintuitive results, such as lane removals that degrade PLOS and BLOS, when the assumption is made that these variables do not change.

In summary, intersection BLOS is a relatively simple calculation that takes into account three things: the width of the cross-street, the width of bicyclist's operating space, and vehicle volumes per through lane. These variables have counteracting effects. The bicyclist's operating space is subtracted from the width of the cross-street to form an overall width factor F_w which is typically negative. In determining bicyclist operating space, intersection BLOS also considers parking occupancy.

5.3 Link BLOS: Variables, Formula, and Sensitivity

Recall that link BLOS is specific to a direction of travel. In order to calculate BLOS for a link, you must have the following information in hand. The presentation in the HCM does not allow the reader to readily distinguish between original data and intermediate variables (see Exhibit 17-21). Here we list only original data, and note that the HCM defines two intermediate variables, W_t and W_v.

Name	Variable	Units	Affects which intermediate and final variables?	Direction of effect on BLOS	Notes on data definitions
parking occupancy	p_{pk}	percentage	W_t, W_e	Increasing this degrades BLOS, first through the condition on W_t, and then through the adjustment to W_v to obtain W_e.	
midsegment demand flow rate	v_m	vehicles per hour	W_v	Increasing this degrades BLOS, up to $v_m = 160$. Increases above 160 do not affect BLOS.	The HCM's language makes it unclear if this should be a *measured* quantity or a *modeled* quantity
width of outside through lane	W_{ol}	feet	W_t	Increasing this improves BLOS.	
width of bicycle lane	W_{bl}	feet	W_t	Increasing this improves BLOS.	
width of paved outside shoulder	W_{os}	feet	W_t, W_e	Increasing this improves BLOS.	
presence of curbs	N/A	binary	W_t, W_e	Increasing this degrades BLOS.	
percentage heavy vehicles in the midsegment demand flow rate	P_{HV}	percentage	P_{HVa}	Increasing this degrades BLOS.	
motorized vehicle running speed	S_R	miles per hour	S_{Ra}	Increasing this degrades BLOS.	
number of through lanes in the subject direction of travel	N_{th}	number	v_{ma}	Increasing this improves BLOS, if v_{ma} remains unchanged.	The condition $v_m < 4N_{th}$ is here to prevent $\ln\left(\frac{v_{ma}}{4N_{th}}\right)$ from being negative in the formula for F_v.
pavement condition rating	P_c	number		Increasing this improves BLOS.	Takes on values between 0.0 and 5.0 as defined in Exhibit 17-7.

Table 11: Data required to calculate BLOS for a link.

From these data, values for final variables W_e, v_{ma}, S_{Ra}, and P_{HVa} are given by Figure 17:

Condition	Variable When Condition Is Satisfied	Variable When Condition Is Not Satisfied
$p_{pk} = 0.0$	$W_t = W_{ol} + W_{bl} + W_{os}^*$	$W_t = W_{ol} + W_{bl}$
$v_m > 160$ veh/h or street is divided	$W_v = W_t$	$W_v = W_t(2 - 0.005\ v_m)$
$W_{bl} + W_{os}^* < 4.0$ ft	$W_e = W_v - 10\ p_{pk} \geq 0.0$	$W_e = W_v + W_{bl} + W_{os}^* - 20\ p_{pk} \geq 0.0$
$v_m(1 - 0.01\ P_{HV}) < 200$ veh/h and $P_{HV} > 50\%$	$P_{HVa} = 50\%$	$P_{HVa} = P_{HV}$
$S_R < 21$ mi/h	$S_{Ra} = 21$ mi/h	$S_{Ra} = S_R$
$v_m > 4\ N_{th}$	$v_{ma} = v_m$	$v_{ma} = 4\ N_{th}$

Notes: W_t = total width of the outside through lane, bicycle lane, and paved shoulder (ft);
W_{ol} = width of outside through lane (ft);
W_{os}^* = adjusted width of paved outside shoulder; if curb is present $W_{os}^* = W_{os} - 1.5 \geq 0.0$, otherwise $W_{os}^* = W_{os}$ (ft);
W_{os} = width of paved outside shoulder (ft);
W_{bl} = width of bicycle lane = 0.0 if bicycle lane not provided (ft);
W_v = effective total width of outside through lane, bicycle lane, and shoulder as a function of traffic volume (ft);
p_{pk} = proportion of on-street parking occupied (decimal);
v_m = midsegment demand flow rate (veh/h);
P_{HV} = percent heavy vehicles in the midsegment demand flow rate (%), and
S_R = motorized vehicle running speed (mi/h).

Figure 17: Instructions for calculating effective widths and adjusted vehicle operating variables. (Source: Exhibit 17-21, 2010 Highway Capacity Manual)

This exhibit deserves explication. The first three rows are step-by-step adjustments to the sum $W_{ol} + W_{bl} + W_{os}^*$ to obtain W_e, the effective operating width for bicyclists. The calculation of W_e hinges on several conditions for parking occupancy (p_{pk}), traffic volumes (v_m), bike lane width (W_{bl}), shoulder width (W_{os}), and the presence of curbs. First, if any parking is occupied ($p_{pk} > 0$), the shoulder width is not included in the calculation of bicyclist operating space, W_t. Note that the curb-adjusted shoulder width W_{os}^* is used, where the presence of curbs results in a 1.5 foot loss of the effective shoulder width. We then calculate a volume-adjusted operating space, W_v. This can be nearly twice W_t if volumes are below the threshold of 160 vehicles per hour and the roadway is not divided. Presumably this accounts for the fact that vehicles can give bicyclists a wider passing berth on very low volume roads. If those conditions are not met, $W_v = W_t$. The third condition on $W_{bl} + W_{os}^*$, the combined width of bicycle lane and shoulder, dictates that W_v is adjusted downward proportional to the parking occupancy, and that the width of the bike lane and the outside shoulder are only included in W_e when this combined width is greater than 4. Parking occupancy carries a greater penalty when the bike lane and shoulder are included in W_e, presumably because when these variables are not included, the shoulder is too narrow to park in.

The last three conditions in Figure 17 adjust each of P_{HV}, S_R, and v_m, to prevent the terms they appear in from being either very large or negative. First, if more than 50% of vehicles are heavy vehicles $P_{HV} > 50$ and the number of non-heavy vehicles is less than 200, the analyst must set $P_{HV} = 50$. In other words, when overall volumes are low, there is a cap on the percentage of heavy vehicles that the HCM authors allow to enter the final formula for link BLOS. It's not clear why the HCM authors impose this cap; it may be because P_{HVa} is so powerful in the final formula, as our sensitivity analysis will show. Second, if running speeds are less than 21 miles per hour, we set $S_{Ra} = 21$ miles per hour. In other words, running speeds below 21 miles per hour are all considered as equivalent to the case when running speeds are 21 miles per hours. This condition ensures that the quantity $S_{Ra} - 20$, which appears in the link BLOS formula, is never less than 1. If it were, that would enable F_S to be negative, so we must presume that the HCM authors do not under any circumstances want a negative F_S. Finally third, if in the very unlikely case that traffic volumes are less than or equal to four times the number of through lanes $v_m \leq N_{th}$, we set $v_{ma} = 4N_{th}$. As with the previous condition, this ensures that $\frac{v_{ma}}{4N_{th}}$, which appears in the link BLOS formula for the volume term F_v is never less than 1. If this quantity could be less than 1, F_v would be negative.

Finally, Bicycle Level-of-Service for a link is given by the following formulae:

$$I_{b,link} = 0.760 + F_w + F_v + F_S + F_p$$

where

$$F_w = -0.005W_e^2$$

$$F_v = 0.507 \ln\left(\frac{v_{ma}}{4N_{th}}\right)$$

$$F_S = 0.199\,(1.1199\ln(S_{Ra} - 20) + 0.8103)\,(1 + 0.1038P_{HVa})^2$$

$$F_p = \frac{7.066}{P_c^2}$$

That is, link BLOS is the sum of a constant and four terms. Again, the higher the sum, the worse the score. Some of these terms can take on negative values. The width term F_w, is negative, and corresponds to the amount of operating space a bicyclist has on

Pavement Condition Rating	Pavement Description	Motorized Vehicle Ride Quality and Traffic Speed
4.0 to 5.0	New or nearly new superior pavement. Free of cracks and patches.	Good ride.
3.0 to 4.0	Flexible pavements may begin to show evidence of rutting and fine cracks. Rigid pavements may begin to show evidence of minor cracking.	Good ride.
2.0 to 3.0	Flexible pavements may show rutting and extensive patching. Rigid pavements may have a few joint fractures, faulting, or cracking.	Acceptable ride for low-speed traffic but barely tolerable for high-speed traffic.
1.0 to 2.0	Distress occurs over 50% or more of the surface. Flexible pavement may have large potholes and deep cracks. Rigid pavement distress includes joint spalling, patching, and cracking.	Pavement deterioration affects the speed of free-flow traffic. Ride quality not acceptable.
0.0 to 1.0	Distress occurs over 75% or more of the surface. Large potholes and deep cracks exist.	Passable only at reduced speed and considerable rider discomfort.

Figure 18: Criteria for determining P_c. (Source: Exhibit 17-7, 2010 Highway Capacity Manual)

the link. The volumes term, F_v, is positive, corresponds to the density of motor vehicles, or the traffic volumes per lane on the streeet. The speed term F_S is positive, and is a relatively complex function of the motor vehicle operating speeds and the percentage of heavy vehicles. The pavement quality term F_p is positive, and corresponds to a pavement quality rating given by the analyst, according to the criteria in Figure 18.

The speed term F_s is the most complex and deserves further explication. This term allows running speeds and the percentage of heavy vehicles to interact. F_s can be expanded algebraically. Sparing you the details of this expansion, let us simply state that

$$\begin{aligned} F_S &= 0.199\,(1.1199 \ln S_{Ra*} + 0.8103)\,(1 + 0.1038 P_{HVa})^2 \\ &= .1612 + .2229 \ln(S_{Ra} - 20) + .0463 \ln(S_{Ra} - 20) P_{HVa} + .0024 \ln(S_{Ra} - 20) P_{HVa}^2 \\ &\quad + .0335 P_{HVa} + .0017 P_{HVa}^2 \end{aligned}$$

This expansion makes it more clear that $\ln(S_{Ra} - 20)$ and P_{HVa}^2 interact. It also more plainly shows the values of the constant and the various coefficients.

5.3.1 Sensitivity Analysis

Due to the various units of measurement involved as well as the interactive terms, the relative weights of the various F terms are difficult to read from the formula. A sensitivity analysis provides some insight into the relative importance of each of the four terms as well as the independent effect of the variables involved. Table 12 shows the default values used in a sensitivity analysis. These represent plausible and common conditions on US streets.

Variable	Name	Value
p_{pk}	parking occupancy	0.95
v_m	midsegment demand flow rate	232
W_{ol}	width of outside through lane	10.5
W_{bl}	width of bicycle lane	5
W_{os}	width of paved outside shoulder	7.5
N/A	presence of curbs (binary)	1
P_{HV}	percentage heavy vehicles in the midsegment demand flow rate	5
S_R	motorized vehicle running speed	22.2
N_{th}	number of through lanes in the subject direction of travel	1
P_c	pavement condition rating	3

Table 12: Default values employed in sensitivity analysis of link BLOS.

Figure 19 shows the relative importance of the various components of BLOS under these default values, and in seven cases generated by variation of these parameters. The columns correspond to the following cases. In each case, default values are used unless otherwise specified. In the second column, parking occupancy is 50%. Third column: pavement quality is raised to 5. Fourth column: running speed is raised to 30 mph. Fifth column: the vehicle flow is doubled. Sixth column: heavy vehicles constitute 10% of the vehicle flow. Seventh column: the bike lane is widened to 10' (without any concomitant changes to the outside lane width or any other parameters). The eighth and final column combines the changes in the sixth and seventh columns: a 10' bike lane is present along with 10% heavy vehicles.

Across these cases, the volume factor F_v tends to have the largest contribution to link BLOS. Under high values of heavy vehicles, F_s can have a large contribution as well. Similarly, with very wide bike lanes, F_w can have a substantial negative contribution. In all

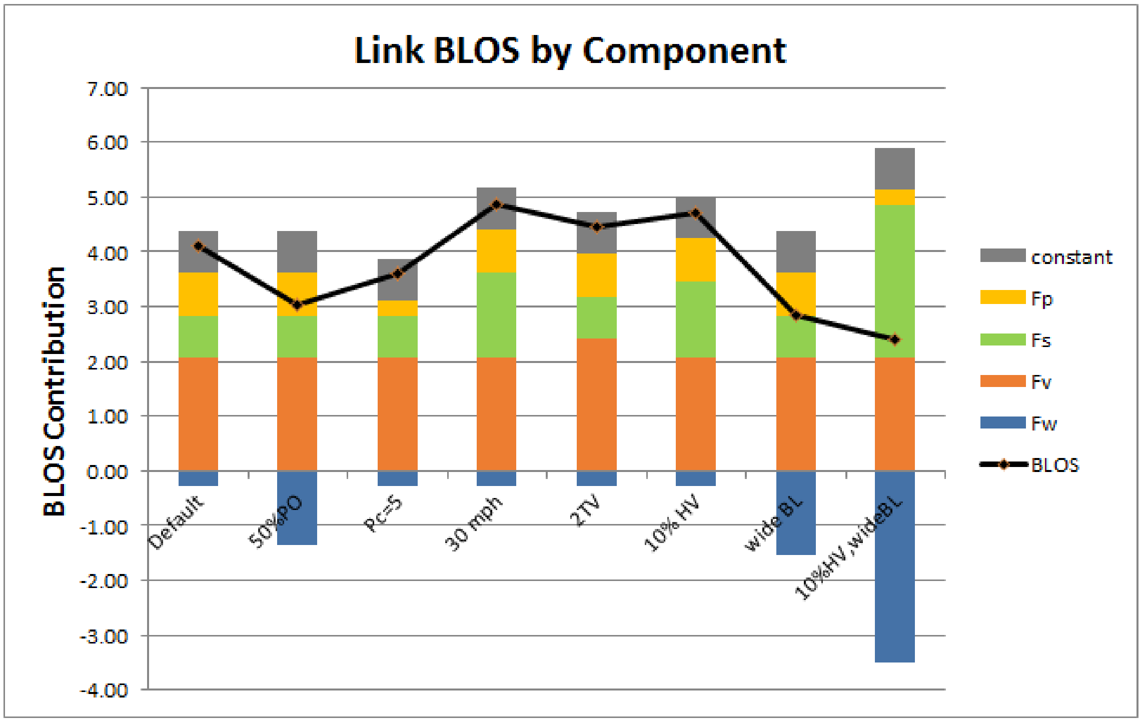

Figure 19: Contributions of F_w, F_v, F_s, F_p and the constant to link BLOS for a variety of cases.

cases, F_p, the pavement quality factor, has a relatively small contribution. It's also worth noting that enough operating width for the bicycle can counteract the negative effect of speeds, volumes, and heavy vehicle volumes in link BLOS. F_w is the square of the available width, and can grow without bound. The volume and speed factors F_v and F_s, on the other hand, contain ln() terms, so that F_v and F_s increase more slowly with increasingly large input values of S_{Ra} and v_{ma}. F_s does contain a squared term for P_{HV}, which means that large percentages of heavy vehicles can degrade link BLOS by a substantial amount, up to the $P_{HV} = 50$ cap.

The following figures examine how sensitive link BLOS is to variations in each of its inputs. We hold all of the variables but one constant, using the default values for the remaining variables.

Two of the most important input variables in link BLOS are the volume of vehicles (v_{ma}) and the number of lanes in the subject direction of travel (N_{th}). The ratio of these, the volume of vehicles per lane, determines F_v, the volume factor. In Figure 20, we vary

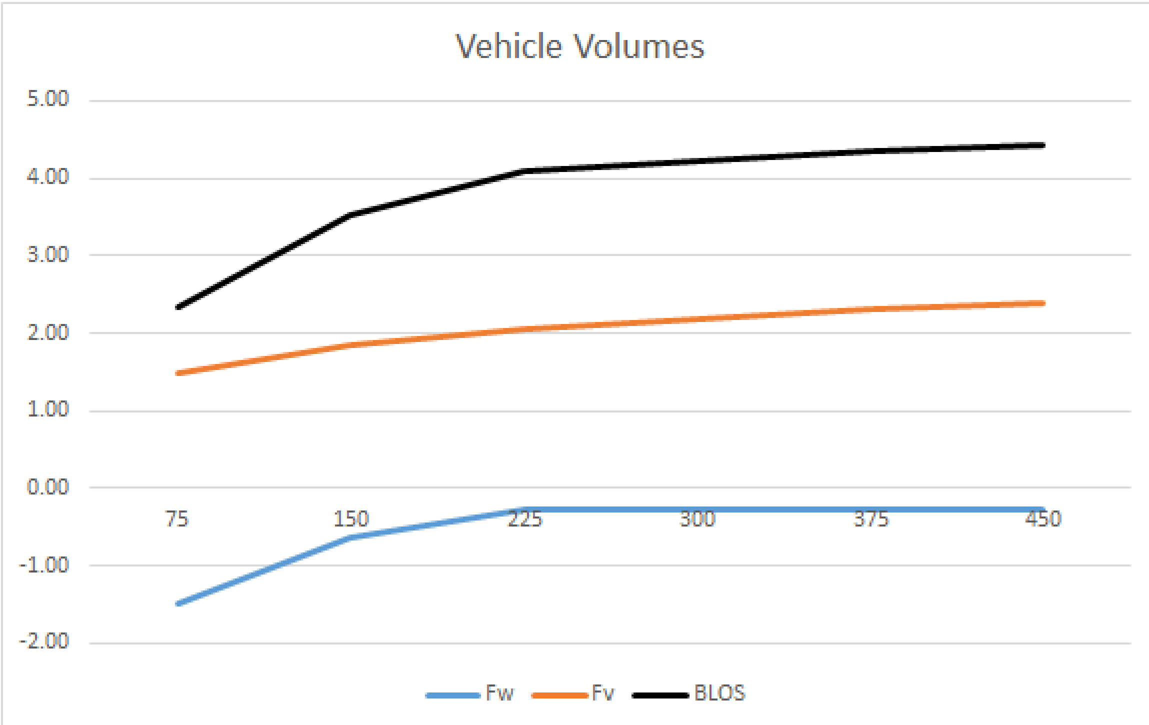

Figure 20: Sensitivity of link BLOS to variations in traffic volume.

traffic volume while holding the number of lanes and all other variables constant.

The figure shows, all other things being equal, that streets with a greater flow of vehicles per lane will have worse link BLOS scores. Vehicle flow per lane affects both F_w and F_v. When volumes are below 160, v_m is used to adjust the total width W_t downward to obtain a volume adjusted width, $W_v = W_t(2 - 0.005v_m)$. For all ranges of v_m, F_v is proportional to the natural log of vehicle volumes. The combined effect is that link BLOS is more sensitive to traffic volumes at lower volumes. Increasing volumes above, say, 225 vehicles / hour does not have the great effect that increasing volumes at lower ranges does.

Of course, policymakers generally can't change traffic volumes without also changing other features of the street, such as the number of lanes. At the same time, changes in traffic volumes can bring about changes in travel speeds and other operational characteristics. For an analyst employing PLOS or BLOS to understand the effect of proposed changes to the street, one of the chief difficulties is modeling the relationship between volumes, speeds, number of lanes, and other related variables. When you consider this sensitivity analysis,

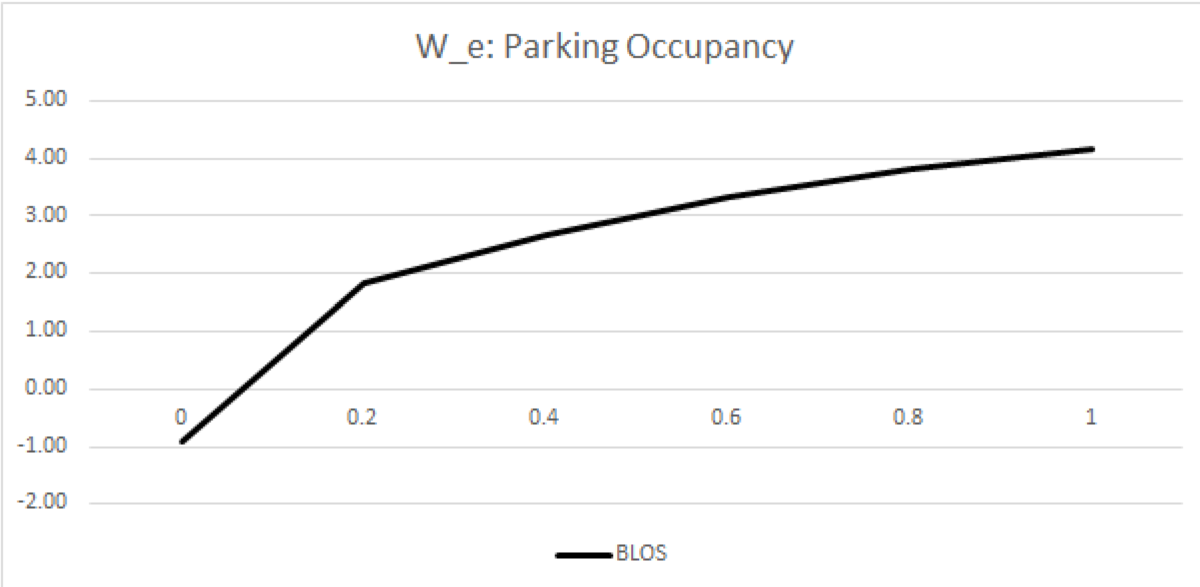

Figure 21: Sensitivity of Link BLOS to variations in parking occupancy

rather than thinking about a single street with the traffic volumes varying over a number of cases or over time, think of this analysis as applicable to how link BLOS would vary across a number of streets with similar characteristics and varying traffic volumes.

Next, F_w, the width factor, is a negative term that can have a quite large affect on link BLOS. It is a function of W_e^2, with a small negative coefficient 0.005. W_e in turn is a function of quite a few variables, including the parking occupancy, traffic volumes, the widths of the outside through lane and bicycle lane, the width of the shoulder, and the presence of curbs. Because of the step-by-step manner in which W_e is determined by intermediate variables W_t and W_v, it can be difficult to understand the independent effect of these variables by reading the link BLOS formulae and exhibits.

Figure 21 shows how link BLOS varies with respect to parking occupancy. Here we use the default values presented in Table 12 for all variables aside from parking. When parking occupancy is zero, there is a substantial improvement to link BLOS due to the fact that the width of the shoulder is included in W_t (and thus in W_v and W_e). Once parking occupancy is anything greater than zero, F_w is a shallow quadratic function of parking occupancy. Increasing the parking occupancy from 20% to 80% results in a penalty to link BLOS of about 2.3, the equivalent of three letter grades.

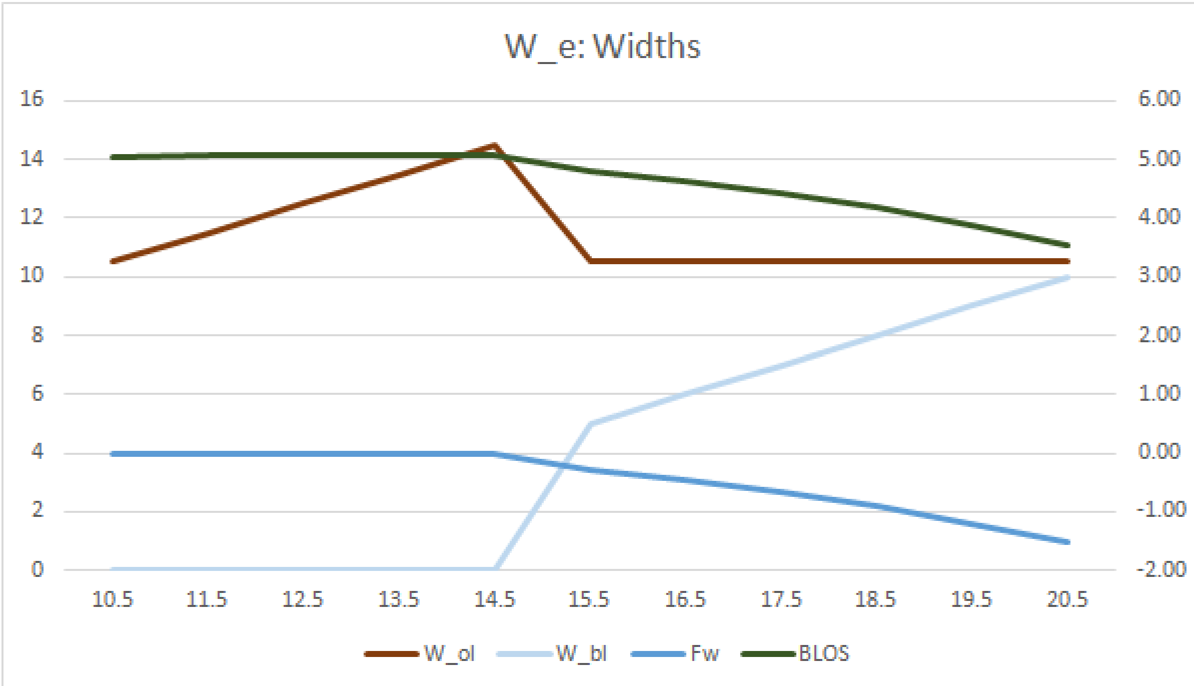

Figure 22: Sensitivity of Link BLOS to variations in bicyclists' operating width.

Figure 22 depicts how link BLOS varies with respect to the bicyclists' operating width. Recall that this width is a function of the outside lane width, the bike lane width, the shoulder width, traffic volumes, and the presence of curbs. Here we assume that curbs are present, that the shoulder width is 7.5 feet (a typical value for the on-street parking area) and that all other variables are equal to their default values shown in Table 12. The x-axis shows the total width of the outside through lane and the bicycle lane. Because of the minimum design widths for travel lanes and bicycle lanes (10' and 5') respectively, the width of the bike lane is zero until the total width exceeds 15'. For widths greater than 15', we assume that the travel lane is kept at a width of 10.5' and that each extra foot is added to the bike lane. As the bike lane width increases from 5' to 10', link BLOS decreases as a quadratic function of W_{bl}. Note that link BLOS is sensitive to whether additional operating space is bicycle lane or wider outside travel lane. Adding width to a bike lane will result in greater improvements to link BLOS than adding width to the outside travel lane.

Next, we consider F_s which is a function of two variables, vehicle running speed (S_{Ra})

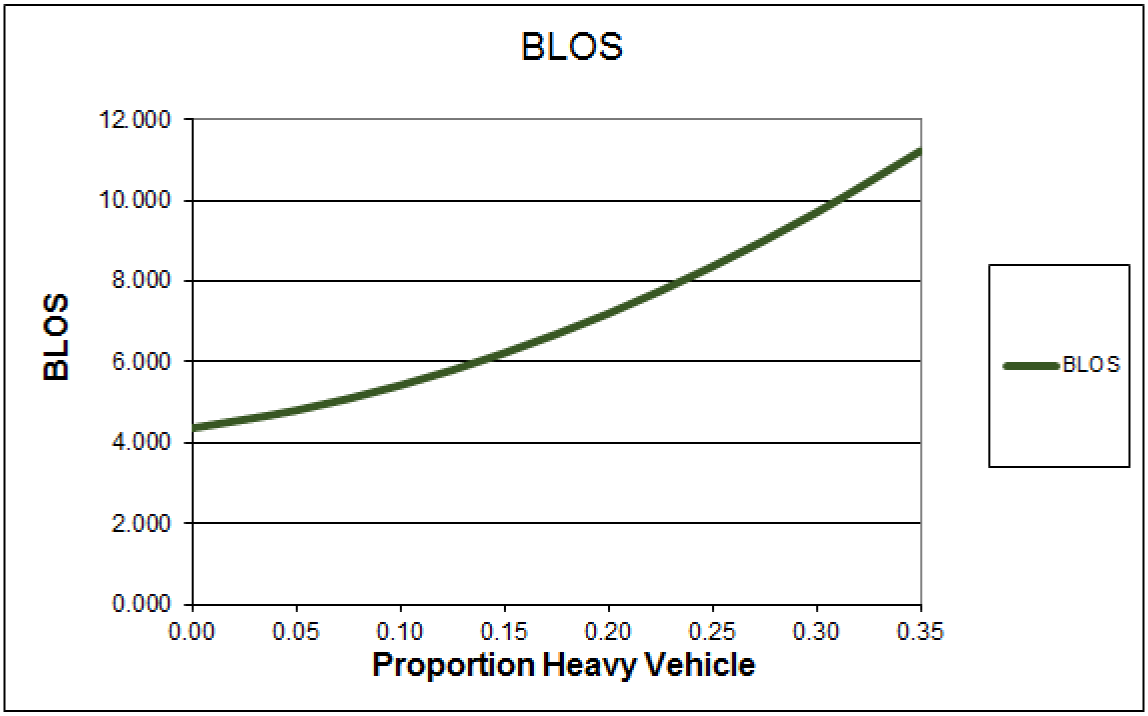

Figure 23: Sensitivity of Link BLOS to variations in the percentage of heavy vehicles.

and percent heavy vehicles (P_{HVa}). The percent heavy vehicles has a very strong influence on link BLOS, as Figure 23 shows.

As the proportion of heavy vehicles varies, F_s and link BLOS increase along a relatively steep quadratic. With running speed at the default value of 22.2, raising the percent heavy vehicles from 0 to 0.35 results in raising F_s from nearly zero to over 7. Anything above 5 is an F, so heavy vehicles alone can cause link BLOS to produce a failing grade, unless F_w has a large negative value.

Figure 24 depicts how link BLOS varies with respect to motor vehicle operating speeds. As operating speeds increase, F_s and link BLOS increase on a logarithmic curve, with the slope of increase tapering off at higher running speeds. While an increase in speeds from 20 mph to 25 mph produces an increase of 0.8 (just over one grade), an increase in speeds from 50 mph to 55 mph only results in an increase of 0.07 to link BLOS.

It is worth noting some variables to which link BLOS is *not* sensitive despite their importance to planners and policymakers. Link BLOS is indifferent to physical separation between bicyclists and vehicles; it cannot distinguish between bike lane striping and a cycle

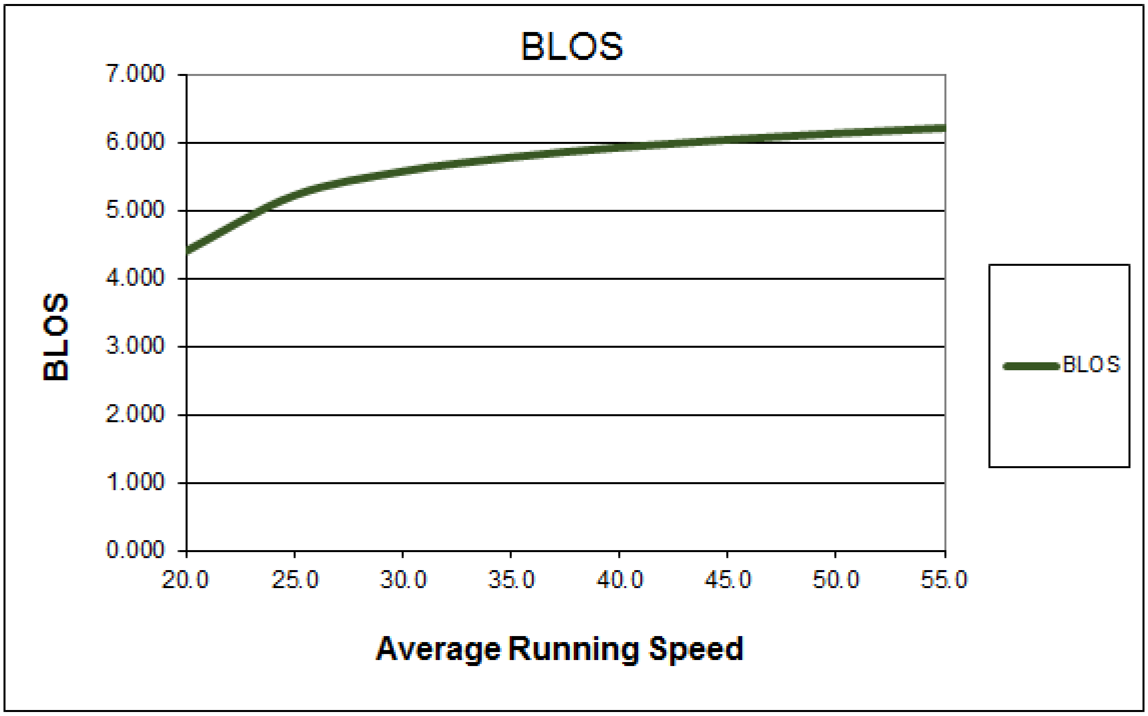

Figure 24: Sensitivity of Link BLOS to variations in vehicle speeds.

track. Similarly, the methodology is indifferent to other innovative bikeway treatments, such as colored paint or striping across non-boundary intersections. Additionally, note that Link BLOS places great importance on traffic volumes and speeds, and that analysis of proposed changes to the roadway thus requires predicting how volumes and speeds will change. As noted in [8], PLOS and BLOS can produce counterintuitive results, such as lane removals that degrade PLOS and BLOS, when the assumption is made that these variables do not change.

In summary, link BLOS is a data-intensive calculation that accounts for traffic volumes, cross-section measurements corresponding to bicyclist operating space (e.g. bike lane and outside travel lane width) the percentage of heavy vehicles on the street, and vehicle operating speeds. Each of the first three can be quite significant in determining the final score if the values are large. Speed is the least important variable in determining link BLOS.

5.4 Segment BLOS: Variables, Formula, and Sensitivity

Recall that a segment is a link and an adjacent intersection, where segments are specific to a direction of travel and it is always the downstream intersection that is combined with the link. Segment BLOS is a function of intersection BLOS and link BLOS, with one additional factor: the number of access point approaches on the right side in the subject direction of travel, per segment length. This is a measure of the frequency of potential conflict between bicyclists and vehicles that are turning into or out of such access points. With intersection BLOS ($I_{b,int}$) and link BLOS ($I_{b,link}$) in hand, the calculation of segment BLOS is relatively straightforward:

$$I_{b,seg} = 0.160 I_{b,link} + 0.011 F_{bi} e^{I_{b,int}} + 0.035 \frac{N_{ap,s}}{L/5280} + 2.85$$

where F_{bi} is an indicator variable that is 1 if the intersection is signalized, and 0 if it is not, and L is the length of the segment.

5.4.1 Sensitivity Analysis

Two figures show the relative importance of intersection BLOS, link BLOS, and access points in determining segment BLOS. The first, Figure 25 considers the contributions of intersection BLOS and link BLOS, with $N_{ap,s}$ set at a default value of 0.

The most notable feature of Figure 25 is the large constant, which makes it impossible to achieve a segment score better than C. This appears to be an error; a negative constant would make more sense. Figure 25 also shows that link BLOS has a slightly greater contribution to segment BLOS, until link and intersection BLOS scores exceed about 4, at which point intersection BLOS predominates. Since link and intersection BLOS can both range above 5, it is possible for large values of intersection BLOS to drive segment BLOS.

Figure 26 shows the effect on segment BLOS of adding access points. Each additional access point adds about 0.27 to the score, which means that each access point degrades segment BLOS by about 1/3 of a grade.

We note one variable to which segment BLOS is not sensitive. The HCM authors' definition of $N_{ap,s}$, which specifies right-side access points, would be inappropriate in analysis of left-side bicycle lanes, which are common on one-way streets.

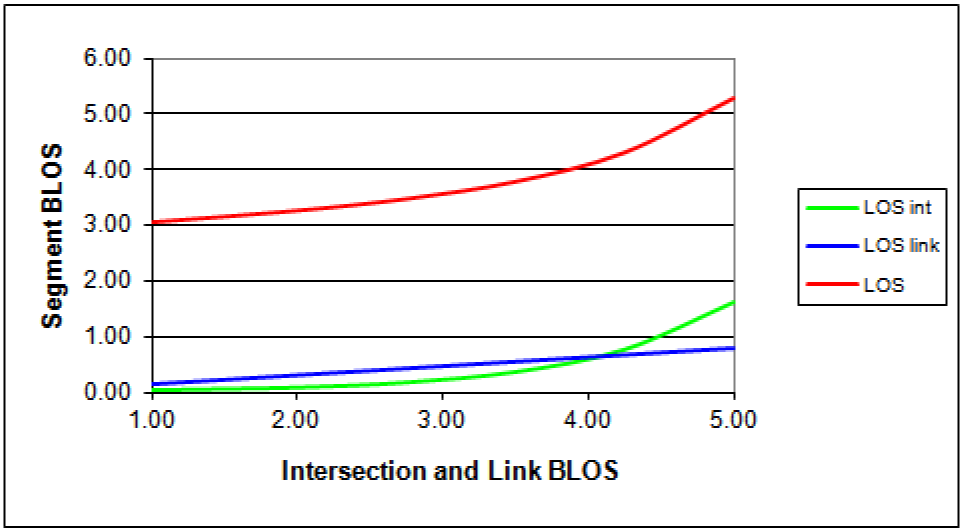

Figure 25: Sensitivity of segment BLOS to component intersection and link scores.

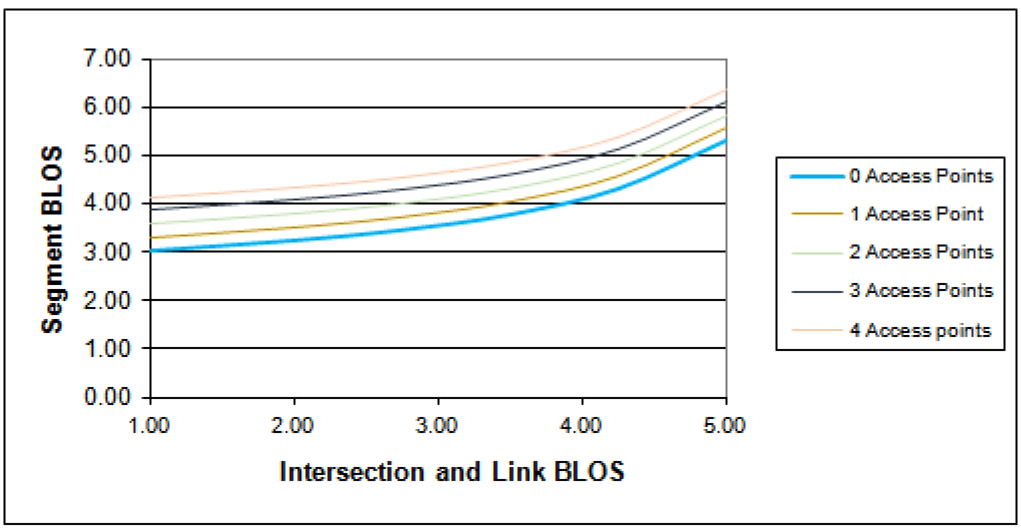

Figure 26: Sensitivity of segment BLOS to the number of right-side access points.

5.5 Facility BLOS: Variables and Formula

Recall that a facility is a formal unit of analysis that is a section of street, comprised of successive segments and specific to a direction of travel. Bicycle level-of-service for a facility is a straightforward length-weighted linear combination of BLOS on the segments that comprise the facility. Let $I_{b,seg,i}$ be each component segment i's BLOS, and let L_i be the length of each such segment. Then BLOS on the facility is $I_{b,F}$ as follows:

$$I_{b,F} = \frac{\sum_{i=1}^{m} I_{b,seg,i} L_i}{\sum_{i=1}^{m} L_i}.$$

The analyst converts this score to a grade using the familiar correspondence table.

As with facility PLOS, the HCM authors warn analysts to interpret facility BLOS with caution, because it can suggest high performance of a facility when some of the component segments are failing. Again, this caution seems out of place for a methodology that so readily combines different aspects of quality into a single score.

Because facility BLOS is a linear function of the component segment BLOS scores, we do not present a sensitivity analysis.

6 Implications for Policy and Practice

Having so thoroughly narrated the HCM's methodology for pedestrian level-of-service and bicycle level-of-service, a few concluding observations are in order. PLOS and BLOS are data-intensive, mathematically involved, multi-stage calculations. They generally are not sensitive to the full range of variables of interest to planners and policymakers, and deal particularly poorly with innovative treatments. We have at times also questioned the validity of PLOS and BLOS in dealing with specific variables, such as sidewalk widths and striping of bicycle lanes. In addition, the extent to which these methods are useful for analyzing proposed changes to a street depends to a great extent on the analyst's ability to predict changes in operational variables that are not directly controlled by street design, such as traffic volumes and speeds. Finally, the PLOS and BLOS models are quite specific to formal units of analysis such as the intersection and link, and are specific to a direction of travel in the case of BLOS and a side of the street or crossing in the case of PLOS. There's a trade-off in providing this level of detail: model results are more defensible, but also take longer to calculate and are less legible to the average user.

It is worth stating how the PLOS and BLOS models were developed, as this process

Source	Focus of study	Location	Number of participants
(Landis, et al., 1997)	Bicycle link	Tampa, FL	145
(Landis, et al., 2001)	Pedestrian link	Pensacola, FL	75 (exact no. not stated)
(Landis, et al., 2003)	Bicycle intersection	Orlando, FL	59 (66% male)
(Petritsch, et al., 2005)	Pedestrian intersection	Sarasota, FL	46 (67% female)

Table 13: Sources of data underlying the Highway Capacity Manual 2010 Bicycle Level of Service and Pedestrian Level of Service

explains some of the problems we observe. The development of link BLOS is described in [2]. One hundred and fifty (150) bicyclists of varying ages, genders, and abilities rode on a test course in Tampa, Florida. Test proctors stopped participants and had them complete response cards, grading the segment they just rode on on a scale from A to F. Landis et al then performed linear regression of these ordinal scores by converting them to real numbers. This choice alone means that a number of questionable assumptions are incorporated into the model: the model's creators assumed that users can perceive six distinct categories of quality, that these categories are equally spaced, and that a user's demographics and experience have a negligible effect on the final score. Landis et al then tested for the effects of variables identified in the literature on bicyclists' quality of service as of 1997. Best-fit regression produced the coefficients that appear in the HCM and in the formulae presented in this paper. A similar process was followed for intersection BLOS using 60 participants on a course in Orlando, Florida. These intersection and link models were then taken as a priori inputs in further experiments used to develop segment and facility BLOS using participant ratings of video clips of various streets. This process is described in [1].

Likewise, the development of link PLOS is described in Landis et al (2001) and employed 75 participants walking on a course in Pensacola, FL. Similar experiments were conducted to develop intersection PLOS scores. As with BLOS, these models were then taken as a priori inputs to develop segment and facility PLOS and BLOS using participant ratings of video clips of various streets. The underlying data for each of the bicycle and pedestrian level of service models is shown in Table 13.

To our knowledge, none of the PLOS or BLOS models was ever validated, calibrated, or otherwise tested on roadways and participants other than those used to develop the model. It is little surprise, then, that these models produce some questionable results, and given their age, fail to account for the full range of variables and treatments that are now of interest to planners and policymakers.

What does this mean for policy and practice? Perhaps in part due to the weaknesses of the MMLOS models, policies are increasingly moving away from the holy grail of one-dimensional metrics to replace auto level-of-service. Auto level-of-service had been ubiquitous in transportation planning in a variety of policy contexts. These include 1) transportation impact analysis in environmental review, under laws such as the California Environmental Quality Act (CEQA) and the National Environmental Protection Act 2) local nexus fee assessment to real estate development and 3) street and highway performance evaluation and project prioritization. Multimodal Level-of-Service, including PLOS and BLOS, grew out of a desire to consider modes aside from the auto in these contexts. Yet many of these policies are changing such that a single graded score is no longer appropriate or necessary. Consider the following two recent examples. California is overhauling CEQA to eliminate the use of auto level-of-service in analyzing transportation impacts in transit-rich neighborhoods. In the process of selecting new impact metrics, the Governor's office identified auto-trips-generated (ATG) and vehicle-miles-traveled (VMT) as top candidates. MMLOS was not a top candidate. Both ATG and VMT represented more holistic policy changes such that evaluation of the street itself was no longer the focus of the analysis. VMT is now the recommended metric for transportation impact evaluation under CEQA. As a second example, numerous agencies who are rethinking their performance metrics are seeking exhaustive multimodal metrics, but MMLOS has often not appeared among them. As part of its General Plan update, Pasadena, CA is currently considering 12 new performance metrics, including six that deal with pedestrian and bicycle mobility. These include, for example, Resident Bike Facility Access, which is defined as the percent of dwelling units within a quarter mile of a bike path, bike lane, or neighborhood bicycle-friendly street. This kind of metric captures quality by presuming that these bikeway types represent quality, rather than trying to model quality by accounting for all the geometric and operational variables that might comprise it.

Still, there may be situations where agencies have the resources and reason to calculate and use a metric like PLOS and BLOS. Our hope is that a transparent presentation of MMLOS enables people with broad expertise to scrutinize these models. A look inside the black box quickly reveals the practical challenges in any quality of service model for bicycling or walking. The experience of bicycling and walking is highly subjective, and varies across user groups and experience levels. Development and refinement of a model like PLOS or BLOS is labor-intensive; our hope is that by enabling broader scrutiny of the model we can target resources towards the most crucial improvements for validity and usability. For PLOS and BLOS, we humbly suggest three major changes. First, include tools for agencies to model changes to vehicle volumes and speeds. Many local agencies do not have the capacity to predict these changes, but they are of immense importance in determining the final score. Allowing agencies to make their assumptions explicit (e.g. no change in volume, assumed range of reductions or increases in volumes) would improve scenario analysis for proposed roadway projects. Second, improve model validity. PLOS and BLOS should be redeveloped with data from the great variety of streets and bicycle and pedestrian facilities seen throughout the U.S., and modelers should test for the exhaustive list of variables that the most recent literature has found to have an impact on bicycling and walking safety and comfort. Further, the models should be validated on data other than that used to build the model. Finally, simplify the functional forms to reach validity with the simplest model possible. Varying specifications should be tested, and the selection of the final form should keep usability and transparency in mind.

It is possible to improve BLOS and PLOS to make them more valid, more user-friendly, and more sensitive to innovative treatments. Such an effort would be resource-intensive, and we wonder if it would be worth it. Is there a policy context that cries out for a better, more valid MMLOS score? Or have other metrics and more holistic policy revisions subsumed the need for a finely-tuned one-dimensional indicator?

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