BICYCLE LEVEL OF SERVICE: ACCOUNTING FOR PROTECTED LANES, TRAFFIC EXPOSURE, AND DELAY

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ABSTRACT

Motorized traffic exposure and delay are two critical factors for bicycle level of service (LOS). Unfortunately, the current Highway Capacity Manual's methodology for bicycle LOS fully accounts for neither. At the intersection level, motorized traffic speed and bicycle delay are not considered at all; and at the link level there is no account for one of the most effective traffic-exposure mitigating infrastructure types, separated bicycle lanes. This creates a systemic problem, enabling the design of roadways that ignore bicycle exposure and delay (i.e., comfort and safety), while giving approving LOS grades to otherwise poor roads and intersections. This paper presents several proposed revisions to the existing Highway Capacity Manuals methodology for bicycle LOS. The proposed revisions include methodologies to account for separated bicycle lane buffers along links, estimated bicycle delay from right-turning motorists, estimated bicycle delay when performing one- and two-stage left turns, and the motorized traffic speed exposure of bicycles at intersection. The proposed revisions are largely comprised existing methodologies (e.g., pedestrian delay at two-way stop-controlled intersections) and classical analytical approaches that fall seamlessly into the existing Highway Capacity Manual's formulaic approach.

Keywords: level of service, bicycle delay, bicycle left turns, right hook, traffic exposure, two-stage left turns

INTRODUCTION

As urban populations continue to grow and automobile congestion becomes an intractable problem in city centers, bicycling remains a vitally important transportation alternative due to its spatial efficiency and environmental sustainability. For example, a bicycle produces zero emissions, costs very little to own and operate, and typically requires 0.1% of the steel and energy that an automobile does to manufacture. Furthermore, a conventional automobile traffic lane can carry between 1,800-2,200 vehicles per hour per 12-ft lane, while for bicycles its about 1,500 bicycles per hour per 2.5-ft lane (*1*). This means for every car lane that carries approximately 2,000 automobiles per hour, it could carry approximately 6,000 bicycles per hour with zero emissions and a public health bonus. Given the recent pandemic and ensuing economic shocks, these properties make bicycling an essential transportation alternative as personal incomes are constrained, limiting car usage, and public health concerns are prohibitive to public transportation usage. However, bicycling as an alternative transportation mode depends on the quality of bicycle infrastructure and facilities available to support it. Thus, the evaluation of bicycling infrastructure and its LOS becomes paramount for effective resource allocation and infrastructure improvement.

LOS in transportation is an objective measure of roadway quality and performance. It is a critical component of asset management used to determine which roads require more attention or resources. While automobile LOS assessment using the Highway Capacity Manual (HCM) methodology has been in use for over a half-century, bicycle level of service (BLOS) (*2*) is a relatively recent introduction. Traditionally for automobiles, LOS focused on congestion and capacity measures to evaluate LOS (*3*). However, in the United States there are very few, if any, cases where bicycle lane capacity is a concern. Instead, the primary source of service quality reduction is through safety (i.e., exposure to automobile traffic) and delay caused by bicycle-vehicle conflict (*4*). Two prominent sources of bicycle-vehicle conflict are when right-turning motorists encroach on a bike lane obstructing bicycles, and when a bicycle attempts a left turn. Left turning bicycles must either wait for a gap in traffic in a permissive one-stage left-turn or perform a two-stage left-turn, crossing with traffic and waiting on the corner for the signal to change. Unfortunately, the HCM BLOS methodology does not fully account for this traffic exposure and additional bicycle delay.

In addition to these technical shortcomings, the HCM BLOS also lacks many contextual features important to urban design concepts involving bicycles (e.g., traffic calming, network connectivity, etc.). Amongst the most prominent is "Compete Streets". Complete Streets is an initiative to return streets to a more traditional role as a public space, conveying all transportation modes, not only automobiles. Complete Streets, however, is not an official codified set of standards, but rather an emerging and evolving concept aimed at improving city streets. Given the diversity of cities and their needs across the United States, a growing number of Complete Streets LOS evaluation methodologies have been developed. To name a few, there is the San Francisco's Bicycle Environment Quality Index (BEQI) (*5*), Charlotte Urban Street Design Guide (CUSDG) (*6*), [Bicycling] Deficiency Index (DI) (*7*), Level of Traffic Stress (LTS) (*8–10*). A recent paper by Zuniga et al. (*11*) provides a thorough comparison of each methodology and the features covered in each methodology, revealing that HCM lacks many features covered by other methodologies.

Although the HCM BLOS method does not include the most individual factors (e.g., street trees, land use, slope, etc.), it does rely almost entirely robust analytical models and objective measures as opposed to subjective survey weighted scores (e.g., BEQI, CUSDG, and DI methods). Many other methods try to capture user preference through surveys, providing a weighted score for individual road features. While this captures inherent subjectivity, it also limits the flexibility and transferability in the method. Flexibility is limited for new or unique roadway features, as adding a novel or unique new roadway feature requires further surveys to determine new weights. The survey-based weights will also be biased to the local population, limiting the transferability to a new location, such as from one city to another. Furthermore, the analytical nature of the HCM methodology also does not require sophisticated simulation or data-heavy geospatial analysis (e.g., LTS), making it accessible to a wider audience of users (e.g., local municipalities). While the HCM methodology has clear contextual limitations, its fundamental objectivity provides a strong foundation for further improvement.

The objective of this paper is to provide several revisions to the current HCM BLOS methodology. The paper proposes a revised bicycle LOS calculation for the following situations:

- Account of separated bike lane buffer size in link cross-section factor.
- Motorized traffic exposure factor at intersections.
- Bicycle delay from right turning vehicle conflict in bicycle lanes at intersections.
- Bicycle delay for left-turning bicycles performing one- and two-stage left turns

These proposed revisions are not meant to be exhaustive, but merely an incremental improvement to the HCM LOS methodology for bicycles. The intent is that these revisions are accessible to a wide audience of practitioners, helping inform better street design and evaluation with bicyclists. The study is part of a research project to develop improved analysis methodologies and control strategies for complete streets (*12*).

METHODOLOGY

The methodology is organized as follows. First the current HCM BLOS methodology is discussed in greater detail. Following this, each of the specific proposed revisions are described. These revisions include a modified cross-section factor for links to account for separated bike lanes, a motorized traffic speed exposure factor introduced for intersections, a bicycle delay estimation model from right-turning motorists, and a bicycle delay estimation model for one- and two-stage left turning bicycles.

Highway Capacity Manual Bicycle Level of Service

The current version of the HCM does not account of bicycle delay and traffic speed for intersection LOS, nor does it include separated bike lanes for link LOS. This lack of bicycle delay and traffic speed is problematic as it implies that when designing intersections, bicycle delay can be ignored, and high-speed traffic is not a concern for bicycles. Although traffic speed is accounted for at the link level (i.e., midsegment), it offers no mitigating features (e.g., separated bike lanes). Moreover, automobiles can still travel through an intersection at high-speed, which could be argued is where most bicycle-vehicle crashes occur. Motorists speeding through intersections not only affects safety and comfort, but operationally by causing delay for left-turning bicyclists. Addressing these issues, the formula for determining BLOS in the HCM methodology is shown with proposed revisions highlighted in red:

- *Segment:* $$I_{b,seg} = 0.160 I_{b,link} + 0.011 F_{b,link} e^{I_{b,int}} + 0.035 \frac{N_{ap,s}}{L/5280} + 2.85 \quad (1)$$
- *Link:* $$I_{b,link} = 0.760 + F_{wL} + F_v + F_s + F_p \quad (2)$$
- *Intersection:* $$I_{b,int} = 4.1324 + F_{wI} + F_v + F_s + F_{delay} \quad (3)$$

where:

I is the LOS score (0 = A and 5 = F) for links, intersections, and segments, respectively;
F_v is motorized vehicle volume adjustment factor,
F_s is motorized vehicle speed adjustment factor, and
F_{delay} is bicycle delay adjustment factor,

$F_{wL} = -0.005W_e^2$ is cross-section adjustment factor for links, and

$F_{wI} = 0.0153W_{cd} - 0.2144W_t$ is cross-section adjustment factor for intersections. W_t is the total width of the outside through lane, bicycle lane, and paved shoulder; W_{cd} is the curb to curb width of the cross street.

While the speed factor can be easily calculated, there does not yet exist a robust delay calculation for bicycles. Bicycles may technically experience the same signal delay as vehicles, but bicycles also experience additional delay because conflicting bicycle-vehicle movements (e.g., bicycles performing permissive left-turns or right-turning vehicles encroach on bike lane). At signalized intersections, right-turning vehicles frequently encroach upon bicycle lanes to better position themselves for a right-turn. At intersections with a mixing zone (bicycle lane and right-turn lane are shared) or dedicated right-turn lane, this encroachment is intentional by design to mitigate right-hook crashes. However, whether encroachment is intentional or not, it effectively reduces the capacity of a bicycle lane, thus causing delay.

Bicycles are a unique mode in that they are vulnerable slow-moving road users, like pedestrians, but are not pedestrians and typically must abide by the same traffic laws as motorized vehicles. Although bicycle traffic laws vary, motorized vehicles in the United States are generally not expected to yield to bicycles as they would for pedestrians. Thus, in permissive situations such as left turns, bicycles tend to face additional delay waiting for an adequate gap in traffic to cross. Bicycles attempting left turns must either perfectly time their crossing through oncoming traffic while maintaining momentum and balance, or put a foot down and stop, inevitably facing the ire of impatient drivers behind them. Furthermore, the fact that bicycle lanes are typically located as the outer-most lane means left-turning bicycles must crossover adjacent through-moving traffic lanes as well as oncoming traffic, effectively doubling the traffic streams crossed compared to typical left-turns.

Alternatively, a bicyclist could attempt a two-stage left turn. In this maneuver, bicycles first move parallel with traffic, then stop at the corner and waiting for the light to change, similar to crossing diagonally as a pedestrian (*13*, *14*). This is a common maneuver at especially large or high-volume intersections where a one-stage left turn is intimidating or impossible. Some bicycle infrastructure treatments intend to facilitate this with green painted "bicycle queue boxes", informing bicycles where to stop and wait. However, this alternative maneuver can add significantly more delay by having to wait for signals to change. At worst case, arrival on red means a bicyclist must wait two red phases before completing a left turn. This forces the unfortunate choice between substantial delay in a two-stage turn, or an intimidating and potentially dangerous single-stage left turn, ultimately discouraging the less confident potential bicyclists from bicycling at all.

To date, studies have estimated bicycle-vehicle conflict delay and two-stage left turns, but these studies are primarily simulation based (*14*, *15*). While a simulation-based approach may provide precise results, is it not as generalizable as analytical models typically used in the HCM (i.e., closed-form equations), nor is it easily accessible, requiring an engineer or technician to build and run simulations to extract results. Although less precise, an analytical model has the advantage of being accessible to a wider audience of potential users needing only a basic calculation device for small scale implementation, such as local municipal levels.

The following bicycle LOS calculations are largely based on existing methodologies in the HCM and from working papers by Kittelson & Associates, Inc. developed as part of the NCHRP Project 17-87 titled "Enhancing Pedestrian Volume Estimation and Developing HCM Pedestrian Methodologies for Safe and Sustainable Communities" (*16*).

Cross-section adjustment factor with separated bicycle lanes

In the current HCM, a cross-sectional width factors for links are calculated as $F_w = -0.005W_e^2$ where W_e is the effective pavement width. The larger the effective width, the greater the LOS improvement and mitigation of other LOS degrading factors (e.g., traffic speed and volume). The effective width is determined using Exhibit 17-21 in the HCM which accounts for a variety of features, such as lane width, parked cars, speed, volume, and curbs. However, missing from Exhibit 17-21 is any account for separated bicycle facilities with delineated buffer or vertical separation (e.g., parking protected, striping, rumble strip, planters, bollards), which has been shown to provide increased levels of comfort to bicyclists (*17*). Several common bicycle lane configurations compared to the standard bicycle lane with curbside parking is shown in Figure 1.

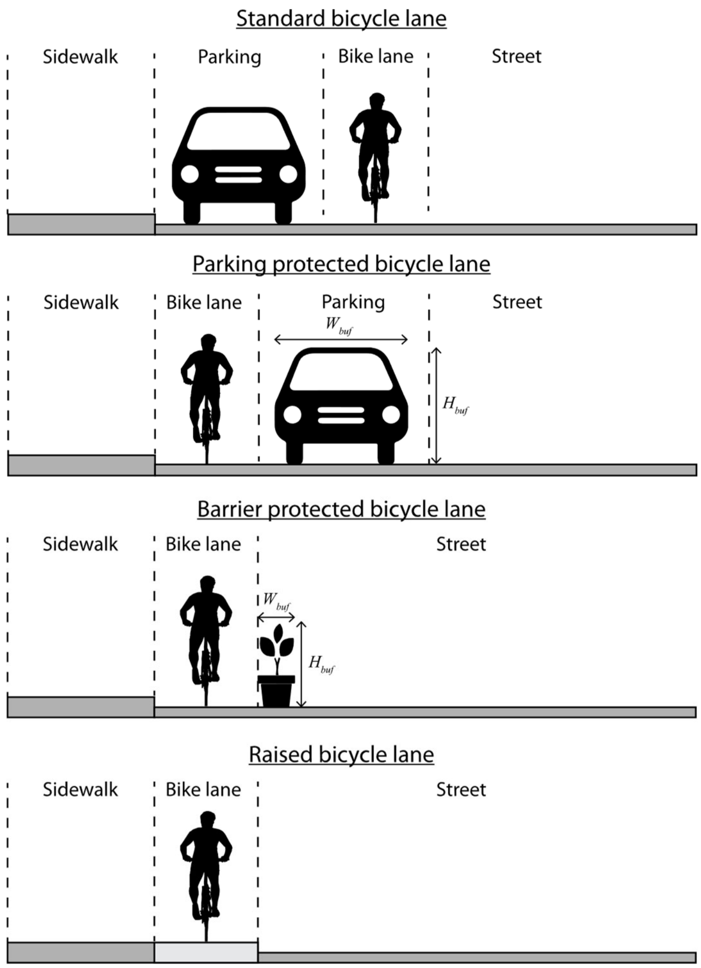


Figure 1: Example bicycle lane configurations

The configurations in Figure 1 are not an exhaustive list, and only present a few common and generic examples. There is a multitude of creative bicycle lane configurations tailored to unique street and traffic environments, making it difficult to individually account for the LOS impact of each. The table from Exhibit 17-21 is intended to address this by being generalized but lacks an account for separated bicycle lanes. The existing table in Exhibit 17-21 is modified and expanded in Table 1 to account for separating features, while remaining as generalized as possible. Changes are shown in red.

Table 1: Proposed revisions to effective cross-section width adjustment factor table in HCM (Exhibit 17-21)

Condition	Variable when condition is satisfied	Variable when condition is not satisfied
$P_{pk} = 0.0$	$W_t = W_{ol} + W_{bl} + W_{os}^* + W_{buf}^*$	$W_t = W_{ol} + W_{bl} + W_{buf}^*$
$v_m > 160\ {veh}/{hr}$ or street is divided	$W_v = W_t$	$W_v = W_t(1.8 - 0.005v_m)$
$\boldsymbol{W_{bl} + W_{os}^* < 4\ ft}$	$W_e = W_v - 10P_{pk}^* \geq 0.0$	$W_e = W_v + W_{bl} + W_{os}^* - 20P_{pk}^* \geq 0$
$\boldsymbol{v_m(1 - 0.01P_{HV}) < 200\ {veh}/{hr}}$ and $P_{HV} >$ 50%	$P_{HVa} = 50\%$	$P_{HVa} = P_{HV}$
$S_R < 21\ {mi}/{hr}$	$S_{Ra} = 21\ {mi}/{hr}$	$S_{Ra} = S_R$
$v_m > 4N_{th}$	$v_{ma} = v_m$	$v_{ma} = 4N_{th}$
Curb present?	$W_{os}^* = W_{os} - 1.5 \geq 0$	$W_{os}^* = W_{os}$
Parking protected[a] or $\boldsymbol{H_{buf} > 0}$	$P_{pk}^* = 1$	$P_{pk}^* = P_{pk}$

where
W_t is the total width of the outside through lane, bicycle lane, and paved shoulder and/or buffer (ft),
W_{ol} is the width of the outside through lane (ft),
W_{os} and W_{os}^* are the width and adjusted width of the paved outside shoulder, respectively (ft),
W_{bl} is the width of the bicycle lane, 0 if none provided (ft),
W_v is the effective total width as a function of traffic volume (ft),
P_{pk} is the proportion of on-street parking occupied (decimal),
v_m and v_{ma} are the midsegment and adjusted midsegment demand flow rate (veh/hr),
P_{HV} is the percent heavy vehicles in the midsegment demand flow rate (%),
S_R and S_{Ra} are the running speed and adjusted running speed of motorized vehicles (mph),
H_{buf} is the height of the buffer barrier between the bicycle lane and motorized traffic (ft), and
W_{buf} and W_{buf}^* are the width and effective width of the buffer between the bicycle lane and traffic.

[a]Note: Parking protected means the parking lane is the buffer between the bicycle lane and the street. In this case the buffer width ($\boldsymbol{W_{buf}}$) only includes additional buffer zone and excludes the paved outside shoulder width ($\boldsymbol{W_{os}}$). A default buffer height can be assumed to be H_{buf} = 4.5 ft, the height of a typical sedan and

To account for separated bicycle facilities in the street cross-section factor, the formula for effective width W_e, is modified to include the effective buffer distance, calculated as

$$W_{buf}^* = 4\left({W_{buf}}^2 + 24H_{buf}\right)^{\frac{1}{4}} \tag{4}$$

This effective buffer width accounts for horizontal buffer distance W_{buf}, between the street and a bicycle lane, but also any vertical separation height H_{buf}, such as barrier or raised bicycle lane. Intuitively, excessive buffer width and height will only provide diminishing returns. Meaning a after a certain point a taller barrier or a wider buffer will provide little or no additional benefit. This is accounted for with the proposed effective buffer width function for W_{buf}^*. In addition to this function, a minor revision has been made to the W_v calculation. Currently, the conditional nature of the function causes a discontinuity to occur as traffic volume crosses 160 veh/hr. Simply adjusting the constant from 2 to 1.8 eliminates the discontinuity.

Motorized traffic speed exposure

The proposed revisions build upon existing HCM methodology for pedestrian LOS at intersections, which have F_{delay} and F_s, as factors for delay and traffic speed, respectively, and are calculated as:

$$F_{delay} = 0.0401 ln(d_b) \quad (5)$$

$$F_s = \frac{\sqrt{n_{15,mj}} S_{85,mj}}{200} \quad (6)$$

where d_{pd} is average pedestrian delay, $n_{15,mj}$ is the number of cars traveling the midsegment in a 15 minute increment, and S_{85mj} is the 85th percentile speed for the midsegment. The current traffic speed factor function in the HCM was revised from $F_s = 0.00013 n_{15,mj} S_{85,mj}$ to be more sensitive to speed. The underlying functions can be repurposed, but it is likely that the calibration constants (i.e., 200, and 0.0401) will require recalibration.

Delay from Right-Turning Automobiles

This step describes a procedure for evaluating the performance of one intersection approach. It is repeated for each approach of interest. At most signalized intersections, the only delay for bicycles is *technically* caused by the signal because bicycles have the right-of-way over right-turning vehicles. However, in practice bicycle delay could be longer if right-turning motorists encroach or block the bike lane, forcing bicycles to weave with right-turning traffic. This effectively reduces bike lane capacity and causes delay.

Precise bicycle lane capacity is largely undetermined in the industry with little research on the subject. The Highway Capacity Manual use 2,000 bicycles per hour per bicycle lane but notes that this is merely an estimated guess to be used as a starting value. The complexity comes from highly variable bicyclist speeds and lack of discrete lane configurations as with automobiles. For example, bicycles may bunch up into multiple queues within a single bicycle lane. More in depth research has found the saturation flow rate of bicycles to be approximately 1,500 bicycles per hour per whole 2.5-foot "sub-lane" (*1*, *17–19*). The saturation flow rate of a bike lane is calculated as

$$s_b = max\left[1500 \times \left\lfloor \frac{W_b}{2.5} \right\rfloor, 1500\right] \quad (7)$$

where W_{bl} is bike lane width. When no bike lane is present, we will conservatively assume bicycles will queue in single file, thus choosing the maximum of the two in the function. Intersection capacity becomes more complex as right-turning automobiles will block the bicycle lane, forcing bicycles to stop, or take a risky weaving maneuver. The intrusion of right turning automobiles effectively reduces bike lane capacity by occupying its space.

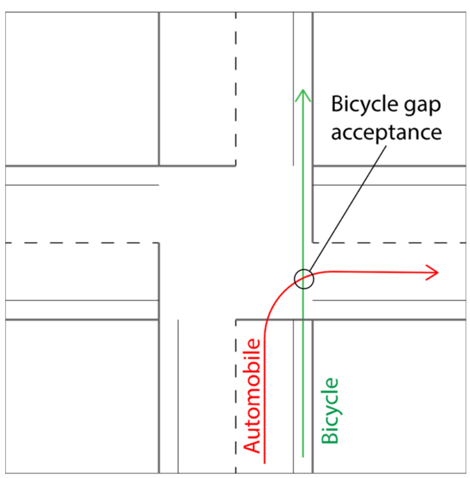


Figure 2: Right turn vehicle conflict with through moving bicycle

This occupancy goes beyond physical size, but the critical headway required by bicyclists to avoid the turning vehicles. The capacity reduction is analogous to intersecting flows at an intersection with a priority street. A function can be drawn which reduces the bicycle capacity by some factor as a function of right-turning vehicle volume.

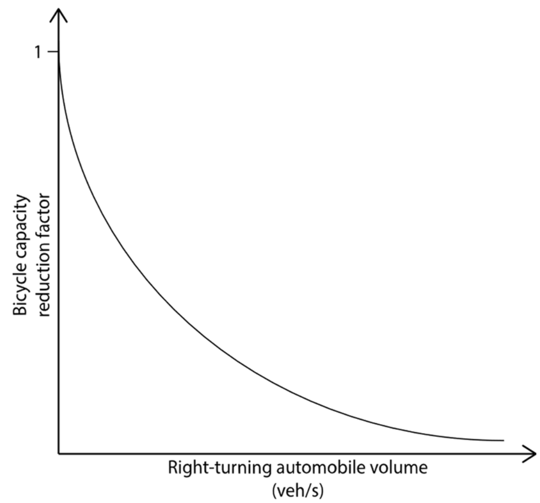


Figure 3: Right-turning vehicle impact on bicycle lane capacity

This function is hypothetical but has drawn inspiration from Siegloch's (1973) very simple function can be used to describe the capacity reduction due to right-turning vehicle flows intersecting with bicycle through flows:

$$f_{RTV} = e^{-v_{RTV} t_c} \tag{8}$$

where

f_{RTV} is right turning vehicle capacity reduction factor,
v_{RTV} is is the right turning automobile flow (veh/s), and
t_c is the critical gap for bicycles (default = 5s, requires further research).

The critical gap also requires research for more precise determination. It is likely that this number will vary depending on the right turning vehicle speed, which in turn depends upon the corner radius. Meaning that tighter corner radii would likely require a smaller t_c by reducing vehicle turning speeds. The capacity of the bicycle lane at a signalized intersection may be computed as the product of the bicycle saturation flow rate, the capacity reduction factor, and the available green time:

$$c_{be} = s_b \times f_{RTV} \times \frac{g_b}{C} \tag{9}$$

where

c_b is capacity of the bicycle lane (bicycles/h),
g_b is effective green time for the bicycle lane (s), and
C is cycle length (s).

Signalized intersection bicycle delay is computed with:

$$d_{bS} = \frac{0.5C\left(1 - \frac{g_b}{C}\right)^2}{1 - min\left[\frac{v_b}{c_{be}}, 1.0\right]\frac{g_b}{C}} \tag{10}$$

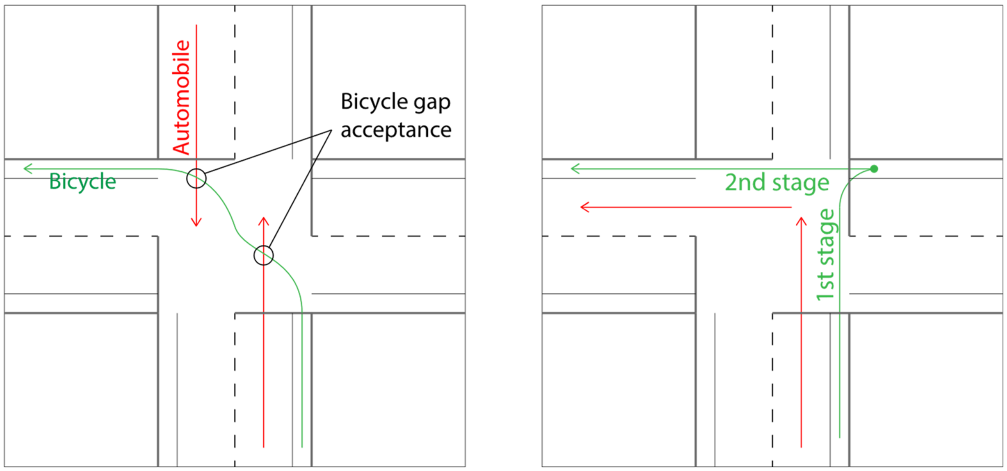
where

d_{bS} is bicycle delay (s/bicycle) from the signalized intersection itself,

v_b is bicycle flow rate (bicycles/h), and other variables are as previously defined.

Left-turning bicycle delay

At signalized intersections, bicycles typically perform a left turn using one of two maneuvers.



a) One-phase left-turn bicycle maneuver *b) Two-phase left-turn maneuver*

Figure 4: Left-turn bicycle conflict with through traffic

Single-phased permissive left using gaps in traffic flow. These maneuvers are typically performed at most intersections with small or moderate traffic volumes. Even upstream mixing lanes or center-line left turn lanes still require a bicyclist to cross a lane of traffic before making a permissive left. Mitigation includes an advanced start leading bicycle/pedestrian signal phasing or bicycle boxes. Calculation of delay in this case is analogous to a pedestrian crossing at a two-way stop controlled (TWSC) intersection where delay is encountered when waiting for an acceptable gap in each traffic lane crossed.

Two-staged maneuver where the bicycle moves parallel with traffic in each signal phase. These maneuvers are typically performed at larger intersections with high volume and/or multiple traffic lanes that makes permissive left turns difficult or impossible to perform safely. Mitigation includes "left-turn queue boxes" and "protected intersections" which help encourage two-staged turns by providing guidance on the roadway, physically separated lanes, and even dedicated bicycle signal phases. Delay calculation for this maneuver is analogous to two-staged (diagonal) pedestrian crossing.

Although one-stage left turns typically incur less delay than two-stage left-turns, the maneuver can be intimidating for most bicyclists and only a small percentage of "strong and fearless" (*21*) bicyclists may feel comfortable performing one-stage left-turns at busy intersections. Especially cautious bicyclists may even dismount from their bicycle to invoke right-of-way as a pedestrian in a crosswalk, but this transition will further delay and inconvenience the bicyclist, as well as interfere with pedestrian movement.

To determine overall intersection bicycle delay, it is the sum of signal delay plus turning maneuver delay. The overall bicycle delay is then calculated with:

$$d_b = d_{bS} + P_L[(1 - P_{L2})d_{bL1} + P_{L2}d_{bL2}] \quad (11)$$

where

d_b is overall average bicycle delay (s/bike),
d_{bS} is signal delay, including incurred by right-turning vehicles (s/bike),
d_{bL1} is bicycle delay for one-stage left turns (s/bike),
d_{bL2} is bicycle delay for two-stage left turns (s/bike),
P_L is the proportion of left turning bicycles (decimal), and
P_{L2} is the proportion of left turning bicycles using two-stage maneuver (decimal).

A two-stage left-turn will generally incur more delay in most cases than a one-stage. However, a substantial portion of bicyclists may still choose to do so out of safety concerns and comfort. Research is needed in this area to determine typical proportions of bicyclists making each maneuver depending on intersection size, operation, and volume. Furthermore, if a large proportion of bicyclists perform two-stage maneuvers despite incurring significantly more delay, this would highlight a measurable safety concern from bicyclists, regardless of LOS.

The bicycle delay for one- and two-staged left turns are calculated in following subsections.

One-stage left turn delay
The proposed methodology for a one stage left-turn bicycle delay is modified from the HCM's existing methodology for Two-Way Stop Controlled (TWSC) intersections as well as the proposed revisions from the NCHRP Project 17-87 by Kittelson & Associates, Inc. working paper titled "Appendix D: Revised Model for Predicting the Pedestrian Delay at Uncontrolled Intersections" (*16*). The existing methodologies have then been further tailored for bicycles (e.g., bicycle startup and cruising speeds). The justification for this adaptation is that much like a pedestrian crossing a TWSC intersection, the delay for experienced by left-turning bicycles is due to waiting for an acceptable gap in traffic to cross both parallel and opposing traffic streams.

The methodology begins by determining the critical headway, which is the minimum time in seconds that a bicycle will not attempt to cross traffic. While gap acceptance varies, it is assumed a bicycle will cross if the available headway is greater than the critical headway, calculated as

$$t_{cb} = \frac{L}{S_b} + t_{sb} \tag{12}$$

where
t_{cb} is critical headway for a single left-turning bicycle (s),
S_b is average bicycle crossing speed (ft/s) (Assumed 10 ft/s),
L is width of street crossed (ft), and
t_{sb} is bicycle start-up time and end clearance time (s).

The spatial distribution of "platooned" or grouped left-turning bicycles can be calculated as N_b. Otherwise if platooning does not occur, the number is assumed to be 1.

$$N_b = max\left[\frac{2.5N_c}{W_{bl}}, 1.0\right] \tag{13}$$

where
N_b is spatial distribution of bicycles (bikes),
N_{cb} is total number of bicycles in the crossing platoon,
W_{bl} is width of bike lane (ft), and

2.5 is default effective sub-lane width used by a single bicycle (ft).

The number of platooning bicyclists is calculated as:

$$N_{cb} = \frac{v_b e^{v_b t_{cb}} + v_m e^{-v_m t_{cb}}}{(v_b + v_m) e^{(v_b - v_m) t_{cb}}} \tag{14}$$

where

N_{cb} is total number of bicycles in the crossing platoon (bikes),
v_b is bicycle flow rate (bikes/s), and
v_m is motorized vehicular flow rate (veh/s).

The critical headway of the group is determined with:

$$t_{cb,G} = t_{cb} + 2(N_b - 1) \tag{15}$$

where

$t_{cb,G}$ is group critical headway (s), and
N_b is spatial distribution of bicycles (bikes).

From this critical headway, the probability that a bicycle will *not* incur any turning delay is equal to the likelihood that the bicycle will encounter a sufficient gap equal to or larger than the critical headway. Assuming random arrivals of automobiles and equal distribution among traffic lanes, the probability of a blocked lane P_b is used to determine the probability of non-zero delay when making left turn P_d.

$$P_b = 1 - e^{\frac{-t_{cb,G}\, v_m}{N_L}} \tag{16}$$

$$P_d = 1 - (1 - P_b)^{N_L} \tag{17}$$

where

P_b is probability of a blocked lane,
P_d is probability of a delayed left turn, and
N_L is number of through lanes crossed.

Assuming no automobiles yield to bicycles, the average delay experienced by bicyclists waiting for an adequate gap is calculated as

$$d_{bg} = \frac{1}{v}\left(e^{v_m t_{cb,G}} - v_m t_{cb,G} - 1\right) \tag{18}$$

where d_{bg} is average bicycle gap delay (s). The average non-zero delay for left-turning bicycles (i.e., bicycles that cannot immediately turn left on arrival) is calculated as:

$$d_{bgd} = \frac{d_{bg}}{P_d} \tag{19}$$

where d_{bgd} is average gap delay for bicycles who incur non-zero delay. When left-turning bicyclists are delayed at intersections, they will wait until one of two situations occur:

(a) a gap greater than the critical headway is available, or

(b) motor vehicles yield and allow the bicycle to cross.

While most jurisdictions treat bicycles as vehicles and do not require automobiles to yield to bicycles, there are cases where motorists do yield to bicycles. The yield rate for motorist yielding to bicycles is likely to be substantially lower than for pedestrians, and can vary due to a multitude of factors, such as road geometry, speed, local culture, and law enforcement.

When motorists do yield to bicycles, it is possible for actual delay to be less than d_{bg} because of yielding vehicles. The likelihood of this situation depends on the motorized vehicle volumes, yield rate, and number of through lanes. A bicycle turning left will wait for an opportunity to cross, with conflicting vehicles arriving with a headway of h seconds (*22*). The headway is calculated as

$$h = \frac{\frac{1}{v_m} - \left(t_{cb,G} + \frac{1}{v_m}\right) e^{-v_m t_{cb,G}}}{1 - e^{-v_m t_{cb,G}}} \qquad (20)$$

where h is average headway of all headways less than the group critical gap (s). Note that the conflicting vehicular flow rate v_m is for each lane crossed.

With a potential yielding event occurring every h seconds, $P(Y_i)$ is the probability that a motorist yields to the left-turning bicycle. Assuming vehicles arrive randomly, each potential yielding event is considered independent and the bicycle may only cross if vehicles in each lane choose to yield. If the motorist does not yield, the process will repeat until the wait exceeds the expected delay required for an adequate gap in traffic (d_{bgd}), at which point adequate gap to cross without yielding motorists will occur on average. Accounting for potential yielding motorists, the average one-stage left-turn bicycle delay is calculated as

$$d_{bL1} = \sum_{i=0}^{n} h(i - 0.05)P(Y_i) + \left(P_d - \sum_{i-0}^{n} P(Y_i)\right) d_{bgd} + d_R \qquad (21)$$

where

d_{bL1} is average bicycle delay for one-stage left turn (s),

i is crossing event (i = 1 to n),

d_R is the average delay for bikes that arrive on red phase (s),

$P(Y_i)$ is probability that motorists yield to pedestrian on crossing event i, and

$n = \text{int}\left[\frac{1}{e^{-v_m t_{cb,G}}}\right]$ is average number of crossing events before an adequate gap is available.

The first term in the equation (i.e., $\sum_{i=0}^{n} \mathrm{h(i - 0.05)P(Y_i)}$) represents expected delay when motorists yield, the second term (i.e., $(\mathrm{P_d} - \sum_{\mathrm{i-0}}^{\mathrm{n}} \mathrm{P(Y_i)})d_{bgd}$) represents expected delay waiting for adequate gap, and the third term (i.e., d_R) is merely the additional delay incurred on average from arriving at a red signal phase. The average delay for bicycles arriving on red can be calculated as

$$d_R = \frac{C - g}{C}\left(\frac{C - g}{2}\right) + l + t_{sb} \qquad (22)$$

where

g is the green time (s),

C is the cycle time (s),

l is clearance time (s), and

t_{sb} is startup time for bicycle to begin moving from a full stop.

The equation requires the calculation of $P(Y_i)$, which is the probability that motorists yield for a given number of potential left-turn crossing events *i*. This calculation differs depending on the number of lanes crossed. Each lane crossed includes both adjacent parallel traffic and opposing traffic. For example, a one-lane left-turn crossing may be when a bicycle performs a left from a median-located bicycle lane or one-way street. A two-lane crossing would be a typical street with one lane in each direction. The calculation of $P(Y_i)$ for one, two, three, and four lane crossings are described below.

The probability of motorist yielding is effectively calculated as the product of the probability of a delayed crossing, P_d, the motorist yield rate, M_y, and the probability that the motorist did not yield in the previous *i* to *n* crossing events. A multi-lane left turn crossing, $P(Y_i)$ requires that either motorists yield in both lanes, or that one motorist yields if the other lane(s) are clear. For any number of potential left-turn events *i*, the probability of a motorist yielding with successful crossing is calculated as:

- One-lanes: $P(Y_i) = P_d M_y (1 - M_y)^{i-1}$ (23a)
- Two-lanes: $\mathrm{P}(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j)\right]\left[\frac{P_b^3 M_y^3 + 3P_b^2(1-P_b)M_y^2 + 3P_b(1-P_b)^2 M_y}{P_d}\right]$ (20b)
- Three-lanes: $P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j)\right]\left[\frac{P_b^3 M_y^3 + 3P_b^2(1-P_b)M_y^2 + 3P_b(1-P_b)^2 M_y}{P_d}\right]$ (20c)
- Four-lanes: $P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j)\right] \times \left[\frac{P_b^4 M_y^4 + 4P_b^3(1-P_b)M_y^3 + 6P_b^2(1-P_b)^2 M_y^2 + 4P_b(1-P_b)^3 M_y}{P_d}\right]$ (20d)

where

M_y is motorist yield rate (decimal),

i is crossing event (*i* = *1* to *n*), and

$P(Y_0) = 0$.

The formula to calculate the probability of motorist yielding at four-lane crossings includes an assumed correction where the cubed exponent is placed outside the parenthesis (i.e., $(1 - P_b)^3$), not inside as current shown in Chapter 19 of the Highway Capacity Manual, 6th edition.

Two-stage left turn delay

The methodology for two-stage left-turn bicycle delay is developed using the existing HCM methodology for pedestrian delay at signalized intersections, as well as revisions proposed in the NCHRP Project 17-87 working paper titled “Appendix C: "Revised Model for Predicting the Pedestrian Delay at Signalized Intersections".

For two-stage left turns, two situations can occur:

- A bicycle arrives during a green phase at the first stage.
    - The delay is the average remaining green time from the first approach before the signal changes, plus a startup time.
- A bicycle arrives during a red phase at the first stage.
    - The delay is the average remaining red time in the first approach plus the entire red time in the second approach, plus two startup times.

The respective delay for each case is then calculated as:

$$d_{bL2G} = \frac{g_1}{2} + l_1 + t_{sb} \tag{24}$$

$$d_{bL2R} = \frac{C - g_1}{2} + g_1 + l_1 + 2t_{sb} \tag{25}$$

where

d_{bL2R} is left turn bicycle delay given arrival is during a red phase (s/bike),

d_{bL2G} is left turn bicycle delay given arrival is during a green phase (s/bike),

g_1 is the green time in the first approach (s),

C is the cycle time (s),

l_1 is clearance time for first approach (s), and

t_{sb} is startup time for bicycle to begin moving from full stop.

Assuming bicycles arrive randomly at the first approach, the total two-stage left turn delay is then calculated as the sum of the product of the delay and proportion of bicycles arriving in each case, expressed as:

$$d_{bL2} = \frac{g_1}{C} d_{bL2G} + \frac{C - g_1}{C} d_{bL2R} \tag{26}$$

where

d_{bL2} is bicycle delay for two-stage left turn (s/bike),

$\frac{g_1}{C}$ is the proportion of bicycles arriving during green, and

$\frac{C-g}{C}$ is the proportion of bicycles arriving during red or yellow.

PROPOSED METHODOLOGY APPLICATION

To demonstrate the proposed revisions' resulting effects, the following subsections provide numerical examples of the revisions in comparison to results from the existing HCM methodology. The following four subsections providing numerical results for the proposed revisions. It is organized as follows, first the bicycle delay incurred by right-turning automobiles is presented, followed by left-turning bicycle delay, the traffic speed exposure factor, and finally the combined effect of these revisions on bicycle LOS compared to the existing methodology.

The numerical examples below have simplified parameters approximated from conditions found at intersections along Hearst Avenue in Berkeley, California. The intersections are signalized with a 90 second cycle length, 31.7 second green phase, and 3.3 second clearance time. Each of the automobile lanes are 12 ft wide, with 5-ft bicycle lanes. Unless otherwise varied, bicycle volume is set to 250 bicycles per hour and the right and left turn volumes are assumed to be one-sixth of the total volume for bicycles and vehicles, respectively.

Link cross-section adjustment factor with separated bicycle lanes

The cross-sectional width factor F_w is intended to provide a compensating effect, improving LOS due to wider street and bicycle lane. The function has been revised to now include the width and height of separated bike lane buffers. A numeric demonstration is shown in Figure 5, showing the LOS compensating value as buffer width and height vary for a 5-ft bicycle lane and no outside shoulder.

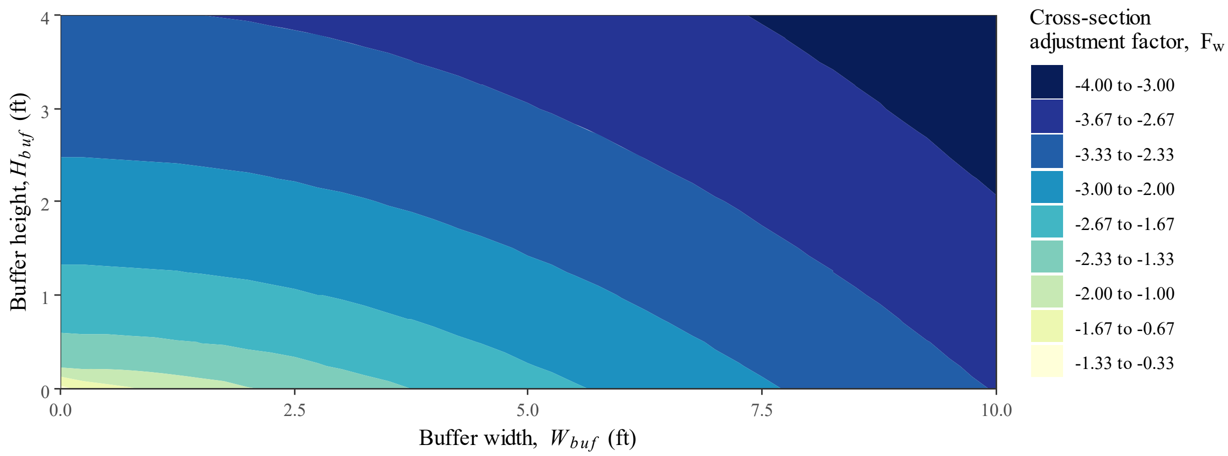
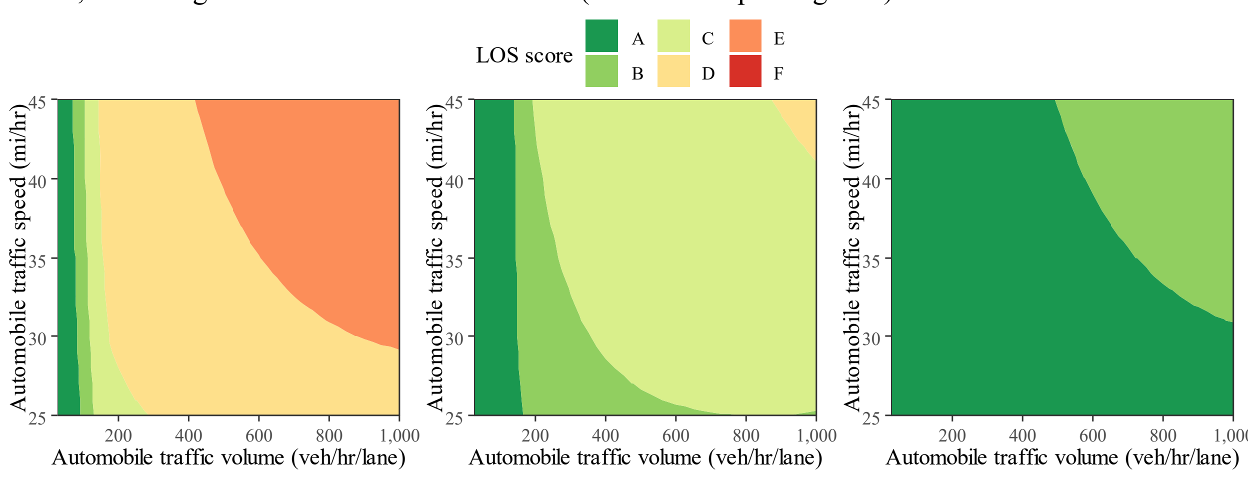


Figure 5: Cross-section factor adjustment for separated bike lane buffer size

In practice, even a small vertical barrier (e.g., a raised bicycle lane) can have a profound improvement in bicyclist comfort compared to horizontal distance alone by providing a physical barrier between bicycles and motorized traffic. For this reason, the function is designed to be asymmetric such that height provides a greater effect than width alone. However, after a certain point buffer height and width no longer increase bicyclist comfort. For example, the comfort improvement from a 5 to 6-ft barrier is likely far less than from 0 to 1-ft. To account for this, the function yields a steep improvement with size, but gradually diminishes. Although the model is intended to reflect reality, it is not calibrated or validated, but merely meant as a starting model to be calibrated in further research.

Link Bicycle Level of Service

The revised cross-section factor to account for separated bicycle lane buffer size has the simple effect of reducing (i.e., improving) the LOS score with its negative value. The concept is that a separated buffer will improve bicyclist comfort with increasing buffer size, regardless of ambient traffic conditions. A numerical demonstration is provided in Figure 6 for three buffer sizes: a) no buffer, b) a small 3-ft wide and 1-ft tall buffer, and a large 10-ft wide and 4-ft tall buffer (the size of a parking lane).



a) No buffer: $W_{buf} = 0$ and $H_{buf} = 0$ b) Small buffer $W_{buf} = 3$ and $H_{buf} = 1$ c) Large buffer $W_{buf} = 10$ and $H_{buf} = 4$

Figure 6: Bicycle LOS for links with proposed separated bike lane revisions

The resulting effect of the buffer size is pushing the region of LOS A and B to a wider spectrum of road speeds and traffic volumes from what is originally restricted to very low-speed and low-volume roads below 160 veh/hr. This demonstrates that separated lanes can provide an immediate and immense benefit to bicyclists but are not necessary for quiet low-volume roads and are not a blanket solution. Furthermore, it cannot be stated strongly enough that these proposed revisions require further research. Not only for field calibration and validation, but to consider collateral effects from exogenous factors, such as intersection crash risk with lack complementary infrastructure (e.g., mixing zones and bicycle signals) (*23*, *24*).

Intersection motorized traffic exposure factor

The current HCM methodology for evaluating bicycle LOS at intersections does not account for bicyclists' exposure to traffic speed. This is problematic as bicycling near high-speed traffic is not only uncomfortable for most bicyclists, but unsafe. To account for traffic speed exposure in intersection bicycle LOS, an exposure factor is calculated from Equation (3) and introduced to the LOS score function in Equation (1), similarly to the pedestrian intersection LOS score function. A numerical demonstration is shown in Figure 6, which varies the speed and volume of traffic through an intersection. The numerical example has one lane in both directions for all approaches. This factor effectively increases the LOS score value (i.e., providing a worse grade) based on the speed and volume of traffic through the intersection.

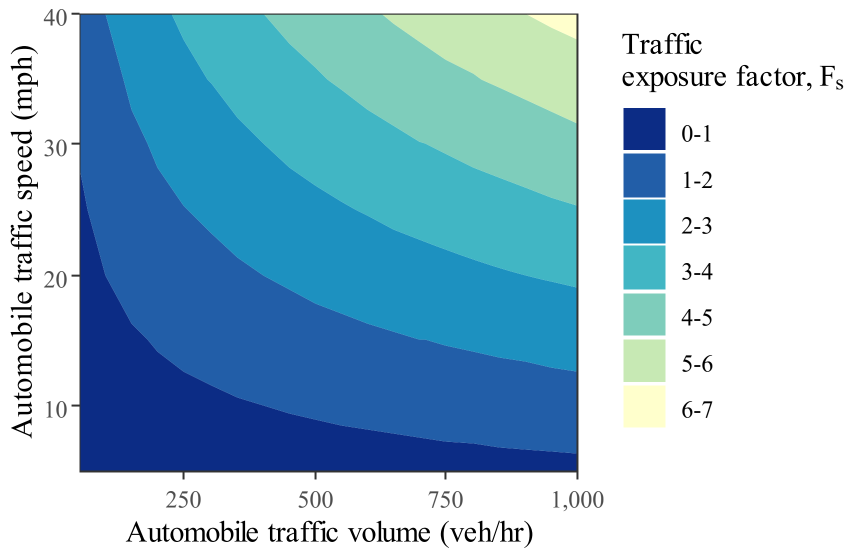


Figure 7: Traffic speed exposure for bicycle LOS at intersections

Intersection bicycle delay from right-turning automobiles

In the current HCM, bicycle delay at intersections does not account for delay caused by right-turning motorists encroaching or blocking the bicycle lane. The proposed bicycle delay is model functions by reducing bicycle lane capacity as right-turning motorist volume increases. This reduction in bicycle lane capacity thus increases bicycle delay experienced at signalized intersections. A numerical example in Figure 4 compares the proposed and current HCM models.

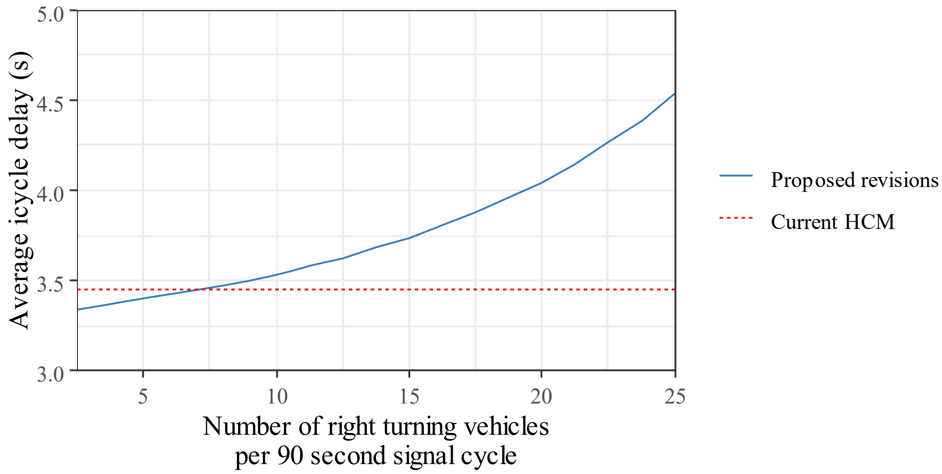


Figure 8: Bicycle delay incurred by right-turning automobiles

The demonstration example in Figure 4 shows the average bicycle delay experienced at a signalized two-lane (one in each direction) intersection while varying the volume of right-turning motorists. The results clearly show the proposed bicycle delay model (solid blue line) gradually increases exponentially while the existing HCM model (dashed red line) remains constant, regardless of right-turning motorist volume.

The proposed model is a substantial improvement over the existing approach, which does not account for bicycle delay due to right-turning motorist conflict at all. However, real-world driver and bicycle behavior on a microscopic level (i.e., individual drivers and bicyclists) is difficult to model analytically and the proposed model for average bicycle delay may require field calibration.

Intersection left-turn bicycle delay

A major obstacle for many bicyclists is performing left-turns, particularly at signalized or busy intersections. Traditional one-stage maneuvers (i.e. a permissive left) from a standard bicycle lane requires two lanes to be crossed using gaps in traffic. This maneuver may incur less delay in most cases but can be very intimidating for bicyclists. Alternative two-stage left-turns, where bicyclists move with traffic then wait for the signal to change, may be much safer and more comfortable but guarantees a high fixed delay while waiting for the signal phase to change. A numerical example is demonstrated in Figure 5, showing average bicycle delay for the two-staged left turns (dashed line) is constant relative to the quickly increasing delay of one-stage left turns (solid lines).

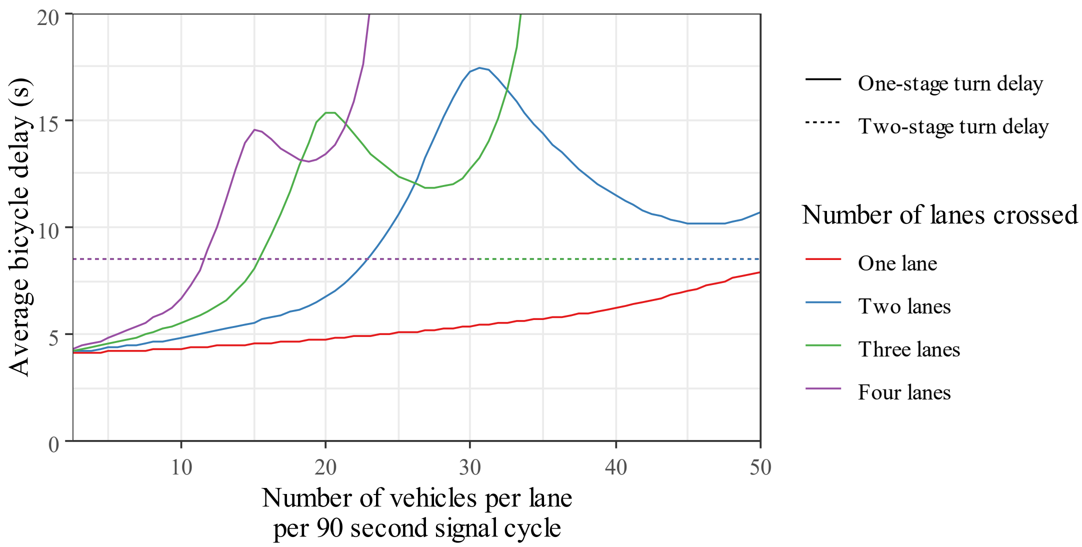
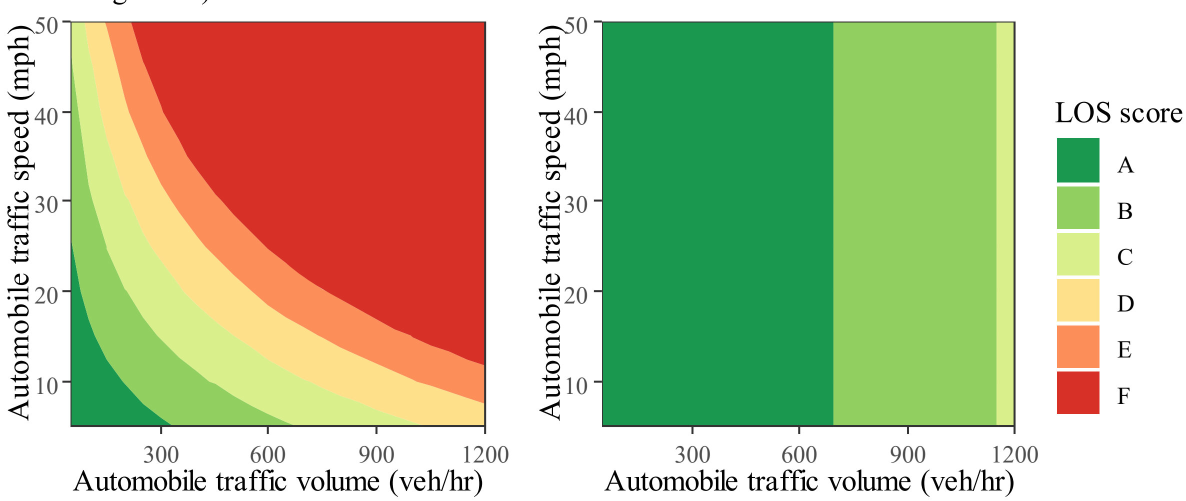


Figure 9: Left-turning bicycle delay

Figure 5 also shows bicycle delay increases much faster as the number of lanes increase. This makes intuitive sense as all lanes need to be clear for a left-turn, making it more difficult and increasing delay. The unusual nonmonotonic (i.e., increase-decrease-increase) form of the multilane delay function is due to vehicle yielding, which was set at yield rate of 5%. As volume increases the probability of a motorist yielding catches up with the lack of adequate gaps in the traffic stream.

Intersection bicycle Level of Service

The combined effect of bicycle delay from right-turning motorists, left-turn bicycle delay, and traffic speed exposure on bicycle LOS for intersections in a numerical demonstration is shown in Figure 7. The proposed revisions (shown in Figure 7a) yields a far stricter LOS score compared to the current HCM methodology (shown in Figure 7b).



a) Proposed revisions to bicycle LOS *b) Current HCM methodology for bicycle LOS*

Figure 10: Bicycle LOS at intersections with proposed revisions and current HCM methodology

The proposed revisions not only account for traffic speed exposure, which has no effect on LOS in the current HCM methodology, but also appears to be much more sensitive to traffic volume. This is due to the additional bicycle delay from right-turning motorists and left-turning bicyclists included in the proposed revisions. As through moving motorist traffic volume increases it increases left-turning bicyclist delay, and as right-turning motorists volume increases it increases overall bicycle delay.

CONCLUSIONS

This research developed several proposed revisions to the current HCM methodology bicycle LOS evaluation. The proposed revisions include methodologies to account for:

- separated bicycle lane buffers along links,
- estimated bicycle delay from right-turning motorists,
- estimated bicycle delay when performing one- and two-stage left turns, and
- the motorized traffic speed that bicyclists are exposed at an intersection.

The current HCM methodology for bicycle LOS at intersections has no account for these features. The objective for the revisions is to improve the current HCM evaluation methodology for bicycle LOS, while remaining consistent with the manual's simple analytical-based approach (i.e., non-simulation based). Providing an analytical methodology helps ensure it is assessable to a wider audience and not dependent on a sophisticated simulation or costly bespoke models. The proposed revisions, as well as the current HCM LOS methodology for bicycles and pedestrians, have been developed into an open source package for *R,* available at https://github.com/nick-fournier/complete-streets-los.

The proposed revisions are also intended to be generalized, targeting broader sources of bicycle-vehicle conflict and delay, rather than specific infrastructure types. While other LOS methodologies are excellent at accounting for a variety of different bicycle infrastructure and streetscape features, such as San Francisco's Bicycle Environment Quality Index (*5*), these features are empirically weighted making it difficult to account for novel bicycle infrastructure. Since bicycle infrastructure is highly varied and continually evolving, it may be important to leave this evaluation generalized to accommodate a wider array of mitigating strategies that are difficult to individually account for (e.g., smaller street corner radii that reduces traffic speed or bicycle specific signals that reduce bicycle delay).

While the proposed revisions achieved the research objectives, there are several concerns and limitations to be addressed. The proposed methodology relies on rigid analytical formulae and classical assumptions. This makes the methodology robust and simple to calculate but is less precise than a simulation-based method and not always applicable to complex situations. For complex intersections it is recommended to employ a more sophisticated approach, such as simulation, to estimate delay more accurately. Furthermore, the proposed revisions require calibration and validation to determine the accuracy of the proposed models, and to calibrate the relative weight of newly introduced LOS factors for traffic speed exposure and bicycle delay. Future study is needed to address these calibration and validation issues.

AUTHOR CONTRIBUTION STATEMENT

The project was conceived and supervised by Alexander Skabardonis. Data collection and the methodological literature review was performed by Amy Huang. The model formulation and analysis were performed by Nicholas Fournier. The manuscript was drafted by Nicholas Fournier, with review and editing by Alexander Skabardonis. All authors reviewed the results and approved the final version of the manuscript.

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