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Improved Analysis Methodologies and Strategies for Complete Streets

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ABSTRACT

Complete streets movement is a national effort to return to traditional streets in our cities to enhance livability, safely, accommodate all modes of travel, provide travel choices, ease traffic congestion, and promote healthier communities. The California Department of Transportation (Caltrans) and several local agencies in the State have developed implementation plans for complete streets. In this project, we are developing and testing improved strategies and analysis methodologies for complete streets, taking into consideration the emerging advances in technology on control devices and data availability from multiple sources. This working paper describes the work performed to date on the project that consists of improved methodologies for estimating Level of service for bicycles and signal control strategies for transit vehicles.

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SECTION 1. INTRODUCTION

1.1. Problem Statement

"A complete street is a transportation facility that is planned, designed, operated, and maintained to provide safe mobility for all users, including bicyclists, pedestrians, transit vehicles, truckers, and motorists, appropriate to the function and context of the facility." [1, 2]. The complete streets movement is a national effort to return to traditional streets for enhanced livability, provide increased travel choices, ease congestion, and promote healthier communities.

Central to the complete streets concept implementation are the safe and effective facility designs and control strategies that facilitate the movements of all road users; these designs may include but not limited to exclusive lanes for selected travel users (bus lanes, bicycle lanes), islands, intersection modifications, etc. It has been established that the roadside design features of a travel corridor strongly affect the users travel behavior and safety [3]. The assessment of these designs is mostly based on empirical procedures largely derived from agencies' experiences and field observations. For example, the San Francisco Department of Public Health (SFDPH) developed the Pedestrian Environmental Quality Index (PEQI), and the Bicycle Environmental Quality Index (BEQI) [4] that has been used by several agencies throughout the country. The PEQI is an extensive observational tool that measures five factors that influence walkability: intersection safety, traffic volume, street design, land use, and perceived safety. Each of the PEQI factors was selected for its scientifically established connection to travel behavior. SFPDH consulted with transportation planners and bicycle and pedestrian safety advocates during the tool's development. It is updated to reflect new research in transportation and public health. BEQI measures factors pertaining to the bicycle infrastructure: safety, traffic, and land use. Research at Mineta Transportation Institute produced an index to assess the ease of bicycle movements in road networks [5].

The traffic performance of urban arterials has been traditionally based on the average travel speeds of motor vehicles, which was used to determine the Level of Service (LOS) on the highway facility under study. Starting with the 2010 Highway Capacity Manual (HCM) [6], a multi-modal LOS (MMLOS) methodology has been developed that provides separate estimates of the traffic performance for auto, bicycle and transit users and pedestrians. The MMLOS methodology provides LOS estimates separately for each user class [6, 7].

The above-described analysis methodologies are not widely used because require extensive local data and are based on subjective indices that are not easily transferable. Therefore, complete streets implementation projects rely mostly on qualitative assessment and limited evaluation based on performance measures.

The objective of this research project is to develop and test an improved methodology for evaluating the traffic performance of alternative designs for complete streets. We also develop signal control strategies to improve the travel experience at signalized intersections for all users.

1.2. Organization of the Report

The remaining three chapters in this report are organized as follows. Chapter 2 contains a review of existing methodologies in literature and practice, identifying the various approaches, their strengths, weaknesses, and gaps. Chapter 3 discusses in detail the proposed improvements to the HCM methodology for bicycle LOS, specifically revisions to account for protected bicycle lanes, traffic exposure, bicycle delay and pavement quality index. In Chapter 4 signal control strategies for complete streets is presented, which includes signal optimization for pedestrians and bicycles and Transit Signal Priority along major travel corridors in San Francisco. Chapter 5 summarizes the results of the study and outlines the ongoing work in the project.

SECTION 2. LITEATURE REVIEW

A literature review was performed on complete streets strategies and evaluation procedures. Emphasis was placed on ongoing research and implementations that are still unpublished. Contacts were established with researchers and practitioners, as well as TRB Committees including but not limited to the *Context-Sensitive Design–Solutions Task Force, Committee ABE30 Transportation Issues in major Cities*, *Committee AHB25 Traffic Signal Systems,* and *Committee AHB40 Highway Capacity and Quality of Service.*

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) [4], Charlotte Urban Street Design Guide (CUSDG) [8], [Bicycling] Deficiency Index (DI) [9], Level of Traffic Stress (LTS) [10–12].

The Highway Capacity Manual (HCM) 6th edition provides a methodology for multimodal "Level of service" (LOS). Figure 1 shows the MMLOS analysis framework based on the HCM. Pedestrian LOS is based on the presence and width of sidewalks and the lateral separation between people walking and vehicles. Bicycle LOS is based on pavement condition and the presence of trucks. Transit LOS is based on waiting times, frequency, and amenities at transit stops. It can be seen how the geometric and control elements affect the LOS for each travel mode but the interrelationships across modes are not considered.

Level of Service 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 and other modes level of service (BLOS) [6] is a relatively recent introduction, and there is a need for improving the methods used, especially for bicycles and pedestrians as implemented in this framework.

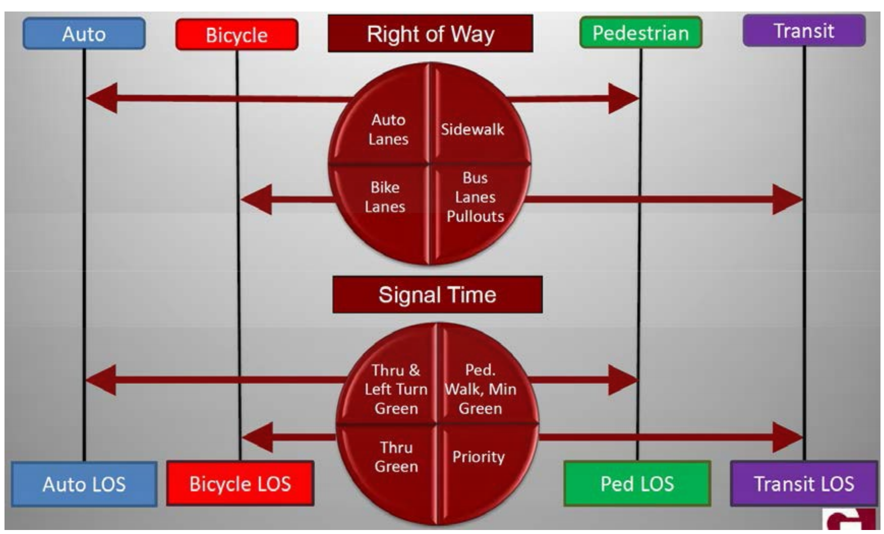

Figure 2-1: Multi-Modal Level of Service Methodology Framework (HCM 2010)

A recent paper by Zuniga et al. [13] provides a thorough comparison of each methodology and the features covered in each methodology, revealing that HCM lacks many features covered by other methodologies (see **Error! Reference source not found.**). The paper also reports that the application of these MMLOS methods on an arterial facility indicated significant differences on the predicted performance that question the reliability of the analysis procedures [13].

Table 2-1: Review of Existing MMLOS Methodologies (source: Zuniga-Garcia et al. [13]**)**

Mode	Characteristic	HCM / TCQSM	CUSDG	BEQI / PEQI	LTS	BCI	DI
Pedestrian	Presence of sidewalk	X	X				X
	Sidewalk width	X		X			X
	Sidewalk quality						X
	Side street geometry	X	X	X			
	Vehicle volume and speed	X		X			
	Vehicle right turns and permitted lefts	X	X	X			
	Pedestrian volume	X					X
	Pedestrian signal type	X	X	X			
	Presence of physical barrier and buffers	X		X			
	Distance from vehicles	X					X
	Intersection corner radius		X				
	Cross-walk treatment		X	X			X
	Traffic calming feature			X			
	ADA curb ramps			X			X
	Lighting levels			X			
	Visual interest and amenities			X			
	Mid-block and intersection crossing delay	X					X
	Auto, transit, and bicycle impact						X
Bicycle	Auto volumes	X		X		X	
	Auto speeds	X	X	X	X	X	
	Percentage of heavy vehicles	X		X		X	
	Percentage of on-street parking	X		X	X	X	X
	Pavement rating	X		X			X
	Presence of bicycle lane or paved shoulder	X	X	X	X	X	X
	Width of bicycle lane	X		X	X		X
	Width of outside lane	X	X		X		X
	Bicycle lane blockage				X		
	Presence of physical barrier and buffers				X		
	Intersection crossing distance	X	X				
	Right turns on red	X	X	X		X	
	Right-turn lane length				X		
	Traffic calming features			X			
	Bicycle parking			X			
	Connection to on-street lanes		X	X			
	Line of sight, street slope, lighting			X			
	Residential development					X	
	Retail development			X			
	Street slope			X			
	Auto, transit, and pedestrian impact						X
Transit	Frequency of service	X					X
	Average transit travel speed	X					X
	Average excess wait time	X					
	Bus stop amenities	X					X
	Bus load factor	X					X
	Span of service						X
	Auto volume and speed	X					
	Sidewalk width and connection to stop	X					
	Outside lane, shoulder, bicycle lane width	X					
	Number of travel lanes						X
	Accessibility by bicycle						X
	Delay caused by automobiles						X

While the Garcia-Zuniga et al. [13] provides an extremely thorough and comprehensive comparison of features, one aspect lacking in the paper is a deeper discussion on how these features are handled and the fundamental differences in calculation approaches. All methods effectively determine a numeric score (e.g., 0-5 or 0-100), which can then be binned into a corresponding step function (e.g., LOS A-F) for evaluation. However, the scores themselves can be determined differently. The different methodological approaches can be categorized into three approach types:

- **Direct Classification** – Roadways/intersections are assigned a classification scale (e.g., 1-5) directly from a strict set of roadway feature criteria.
- **Weighted Average/Additive** – Each roadway feature is given a weighted score that contributes to the overall score either summed or averaged
- **Formulaic** – A set of calibrated modeling formulas are used to achieve a score based on input variables.

In all approaches, the score calculation is calibrated using some sort of weighting bias. For example, important features in weighted average/additive scores are simply given a greater weight than less important features. Formulas may also have weights in the form of constants to calibrate the functions to the expected or measured level of service. Although direct classification may not have explicit weights, the pre-defined bins effectively provide an implicit weight providing bias to the eventual score. The weights themselves are either:

- **Assumed** – Weights assigned *a priori* by creators as they see fit.
- **Empirical** – Weights determined *a posteriori* through measurements and surveys.

Empirical weights provide a more realistic and reliable "ground truth" but can require costly measurement and survey studies compared to simply assuming values. Furthermore, assumed values can also be aspirational, meaning that empirically measured values represent user perspectives at the time of measurement, not necessarily for future goals (e.g., fostering of a robust bicycling culture) or specific policy goals (e.g., safety over comfort). A summary comparison of MMLOS methodological approaches, and their pros/cons are shown in Table 2-2.

Table 2-2: Summary comparison of MMLOS methodological approaches

Method	Approach	Mode	Pros	Cons
HCM	• Formulaic • Empirical	• Pedestrian • Bicycle • Transit	• Evaluates intersection and links • Considers interaction of modes • Strong research background • Objectively measured inputs	• Complex and not easy to apply • Requires detailed data collection • Lacks individual features (e.g., buffer/barriers, traffic calming, etc.) • Not easily re-calibrated
CUSDG	• Additive • Assumed	• Pedestrian • Bicycle	• Easy to use • Detailed assessment	• Does not evaluate link segments • Locally subjective
PEQI/ BEQI[1]	• Additive • Empirical	• Pedestrian • Bicycle	• Evaluates intersection and links • Easy to apply • Requires minimal basic training	• Bicycle intersection assessment only considers three features
LTS	• Direct Classification • Assumed	• Bicycle	• Easy to apply • Evaluates intersection and links • Network level • Minimal field measurement	• Does not evaluate pedestrian and transit • Requires substantial GIS data
BCI	• Formulaic • Empirical	• Bicycle	• Easy to apply • Minimal field measurement	• Does not evaluate intersections • Does not evaluate pedestrian and transit
DI	• Average • Empirical	• Pedestrian • Bicycle • Transit	• New features easily added • Considers interaction of modes	• Requires technical knowledge • Requires a survey of stakeholders • Subjective scales of application
Walk/ Bike Score	• Formulaic(?)[2] • Empirical	• Pedestrian • Bicycle • Transit	• Easy to apply • No data collection • Evaluates intersection and links	• Not sensitive to infrastructure deficiencies (e.g., lack of bicycle lane or sidewalk) • Methodology not reproducible

Overall, although the HCM BLOS method does not include the most individual factors (e.g., street trees,

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land use, slope, etc.), it does rely almost entirely on 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.

2.1. HCM Bicycle Level of Service Methodology

To evaluate roadway LOS, the HCM defines three distinct components of roadways: intersections, links, and segments, as shown in Figure 2-2. An intersection is where two roadway sections intersect, a link is the linear section of roadway between intersections, and a segment is the contiguous combination of a link and an intersection.

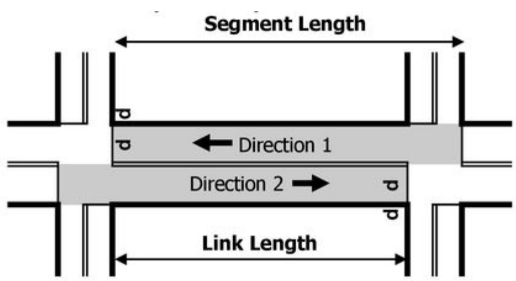


Figure 2-2: HCM link, intersection, and segment definition diagram

Bicycle LOS is determined in Chapter 17 of the Highway Capacity Manual 6th edition, as calculated using Equations (4), (5), and (6), calculated as:

Link LOS: $$I_{b,link} = 0.760 + F_w + F_v + F_s + F_p \quad (1)$$

Intersection LOS: $$I_{b,int} = 4.1324 + F_w + F_v \quad (2)$$

Segment LOS $$I_{b,seg} = 0.160\, I_{b,link} + 0.011 F_{bi} e^{I_{b,int}} + 0.035 \frac{N_{ap,s}}{(L/5280)} + 2.85 \quad (3)$$

Where:

F_w = cross-section adjustment factor,
F_v = motorized vehicle volume adjustment factor,
F_s = motorized vehicle speed adjustment factor,
F_p = pavement condition adjustment factor,
F_{bi} = boundary intersection control type = 1.0 if signalized, 0.0 if two-way STOP controlled,
$N_{ap,s}$ = number of access point approaches on the right side in the subject direction of travel, and
L = segment length, (ft).

The final numeric LOS score values are then converted to discrete letter-grade LOS designations from A-F based on Table 2-3.

Table 2-3: HCM Level of Service Designation Matrix

LOS	Segment-Based Bicycle LOS Score	Link-Based Bicycle LOS Score
A	≤2.00	≤1.50
B	>2.00–2.75	>1.50–2.50
C	>2.75–3.50	>2.50–3.50
D	>3.50–4.25	>3.50-4.50
E	>4.25–5.00	>4.50-5.50
F	>5.00	>5.50

The primary source of service quality reduction is through safety (i.e., exposure to automobile traffic) and delay caused by bicycle-vehicle conflict [14]. Two prominent sources of bicycle-vehicle conflict are when right-turning motorists encroach on a bicycle 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.

2.2. Application of HCM Methodology

A complete street project was designed and implemented in Berkeley, California. Several design and operation changes were implemented along a five-intersection section of Hearst Avenue along the north side of UC Berkeley campus. The changes include design changes to facilitate pedestrian and bicycle movement, including new separated bicycle lanes, painted bicycle lanes, and buffer areas, signal timing modifications and installation of new traffic signals.

The HCM methodology was applied to assess the LOS "before" and "after" the project changes for pedestrians and bicycles. The methodology applied using the latest version of the Highway Capacity Software (HCS). Table 2-4 and Table 2-5 show the results.

Table 2-4: Hearst Avenue Pedestrian LOS Designations

Intersection	Pedestrian															
	Before								After							
	EB		WB		NB		SB		EB		WB		NB		SB	
Shattuck	2.58	C	2.54	C	2.48	B	2.27	B	2.59	C	2.55	C	2.37	B	2.30	B
Oxford	3.02	C	2.34	B	2.53	C	2.47	B	3.02	C	2.34	B	2.29	B	2.19	B
Arch	1.75	B	1.84	B	2.35	B	2.55	C	1.73	B	2.01	B	2.09	B	2.30	B
Euclid	1.42	A	1.96	A	2.14	B	2.19	B	1.42	A	1.97	B	2.02	B	2.00	B
Le Roy									1.35	A	1.47	A	1.99	B	1.70	B
La Roma	2.21	B	2.08	B	2.03	B	2.37	B	2.21	C	1.92	B	1.85	B	2.37	B

Table 2-5: Hearst Avenue Bicycle LOS Designations

Intersection	Bicycle															
	Before								After							
	EB		WB		NB		SB		EB		WB		NB		SB	
Shattuck	2.86	C	3.02	C	1.62	B	2.02	B	3.11	C	3.27	C	1.40	A	1.81	B
Oxford	1.61	B	2.06	B	2.98	C	2.80	C	3.03	C	2.44	B	1.91	B	1.51	B
Arch	2.68	C	1.81	B			2.38	B	3.25	C	2.03	B			1.31	A
Euclid	2.46	B	1.91	B			2.31	B	2.90	C	1.91	B			2.31	B
Le Roy									2.86	C	1.89	B			2.31	B
La Roma	2.81	C	2.19	B	2.92	C	2.54	C	2.81	C	2.19	B	2.92	C	2.54	C

The results show that the HCS methodology is not sensitive to the design improvements at several of the intersections locations, especially the creation of a separation painted bicycle lane, with buffer space. There is a need to improve the HCM methodology to accurately access the impacts of design and operations improvements especially for pedestrian and bicycles.

2.2.1. Bikeway Classifications

Bikeway classification is not yet as consistent across jurisdictions or as well defined as is for roadway functional classification. There are a variety of context specific (e.g., bicycle boulevards) or unique design concepts (e.g., advisory bicycle lanes) that do not always fall cleanly into existing classifications. However, Caltrans currently uses a four-class system of bikeway classification, as shown in Table 2-6. The term "separated bicycle lanes" in this report refers to both Class IV bikeways (i.e., with vertical separation) and Class II buffered bicycle lanes (i.e., horizontal separation) if the buffer width is at least 3-ft.

Table 2-6: Bikeway Classifications

	CLASS I BICYCLE PATHS	CLASS III BICYCLE ROUTES	CLASS II BICYCLE LANES OR BUFFERED BICYCLE LANES	CLASS IV SEPARATED BIKEWAYS
DESCRIPTION	A completely separated facility for the exclusive use of bicycles and pedestrians with crossflow by motor vehicles minimized. Offer recreation or high-speed commute routes when motor vehicle and pedestrian conflicts are minimized. Typically provided along rivers, ocean fronts, canals, parks, etc.	Provides for shared use with pedestrian or motor vehicle traffic either to: (1) provide continuity to other bicycle facilities (typically Class II); or (2) designate preferred routes through high demand corridors. Established with bike route signs and shared roadway markings	Provides a striped lane for one-way bike travel on a street or highway. Buffered bike lanes are separated by a marked buffer between the bike lane and the traffic lane or parking lane.	Provides for exclusive use of bicycles (cannot be used by pedestrians or vehicular traffic) and includes a horizontal and vertical separation (e.g., flexible posts, on-street parking, grade separation) required between the separated bikeway and through vehicular traffic.
CONTEXT	Urban and Rural	Urban and Rural	Urban	Urban and Rural
POSTED SPEED LIMIT	*Any speed	*Any speed	50 mph or lower (considered buffer above 35 mph)	30 mph or higher
MOTOR VEHICLE TRAFFIC VOLUME	*Any volume	*Any volume	20,000 ADT or lower (consider buffer above 10,000 ADT)	Any volume, typically 6,000 ADT or greater
OTHER CONSIDERATIONS	See Caltrans Highway Design Manual Index 1003.1 for further guidance.	See Caltrans Highway Design Manual Index 1003.3 for further guidance.	See Caltrans Highway Design Manual Index 301.2 for further guidance.	See Design Information Bulletin 89 for further guidance.

SECTION 3. IMPROVEMENTS TO HCM METHODOLOGY FOR COMPLETE STREETS

In this project, several improvements to the existing HCM bicycle LOS methodology were developed and are presented in the following two sections. The first section includes several different revisions to the HCM Bicycle LOS methodology to account for protected bicycle lanes (i.e., separated bicycle lanes), bicyclists' exposure to automobile traffic, and additional sources of bicycle delay. The second section in this chapter develops and improved Pavement Quality Index (PQI) from the HCM to evaluate pavement quality specifically for bicycles.

3.1. Accounting for Separated Bicycle lanes, Traffic Exposure, and Delay in Bicycle LOS

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 (12). 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 often is where most bicycle-vehicle crashes occur. For example, approximately 75% of all bicycle-vehicle crashes occurred at intersections in Massachusetts between 2011-2014 (13, 14), and 62.4% occurred at intersections between 2014-2017 in Melbourne, Australia (15). Motorists speeding through intersections not only affects safety and comfort, but also operations 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:* $I_{b,seg} = 0.160 I_{b,link} + 0.011 F_{b,link} e^{I_{b,int}} + 0.035 \frac{N_{ap,s}}{L/5280} + 2.85$ (4)
- *Link:* $I_{b,link} = 0.760 + F_{wL} + F_v + F_s + F_p$ (5)
- *Intersection:* $I_{b,int} = 4.1324 + F_{wI} + F_v + F_s + F_{delay}$ (6)

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,
F_p = pavement condition adjustment factor,
F_{delay} is bicycle delay adjustment factor,
$F_{wL} = -0.005 W_e^2$ is cross-section adjustment factor for links, and
$F_{wI} = 0.0153 W_{cd} - 0.2144 W_t$ 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 it is important to note that bicycles also experience additional delay from 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 (16, 17). 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 inciting bikers to wait for the signals to change. In the worst case scenario, arrival on red means a bicyclist must wait two red phases before completing a left turn. This forces an unfortunate choice between substantial delay in a two-stage turn, or an intimidating and potentially dangerous single-stage left turn. This is just one example of various other difficult choices that can ultimately discourage less confident users from bicycling.

To date, studies have estimated bicycle-vehicle conflict delay and two-stage left turns, but these studies are primarily simulation based (17, 18). 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 a lower barrier of entry thus, is more 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" (19).

3.1.1. 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 (shown in Table 3) 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 [15]. Several common bicycle lane configurations compared to the standard bicycle lane with curbside parking is shown in Figure 3-1.

The configurations in Figure 3-1 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 level of service impact of each. The table 6 (from HCM 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 3-1 to account for separating features, while remaining as generalized as possible. Changes are shown in red.

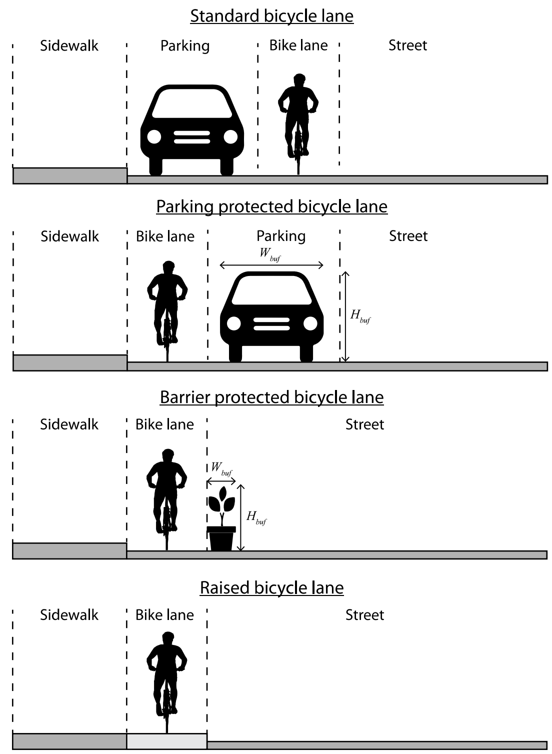


Figure 3-1. Example bicycle lane configurations

Table 3-1: Proposed revisions to effective cross-section width adjustment factor (HCM Exhibit 17-

21)

Condition	Variable when condition is satisfied	Variable when condition is not satisfied
$P_{pk} = 0.0$	$W_t = W_{ol} + W_{bl} + W_{os}^* + W_{buf}^*$	$W_t = W_{ol} + W_{bl} + W_{buf}^*$
$v_m > 160\ \boldsymbol{veh}/\boldsymbol{hr}$ 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 $P_{HV} > 50\%$	$P_{HVa} = 50\%$	$P_{HVa} = P_{HV}$
$S_R < 21\ \boldsymbol{mi}/\boldsymbol{hr}$	$S_{Ra} = 21\ mi/hr$	$S_{Ra} = S_R$
$v_m > 4N_{th}$	$v_{ma} = v_m$	$v_{ma} = 4N_{th}$
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.

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. This effective buffer width accounts for both 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. The proposed generalized function for effective buffer width is calculated as

$$W_{buf}^* = W_{max}\left(1 - e^{-(\beta_W W_{buf} - \beta_H H_{buf})}\right) \qquad \text{(if } \textit{not} \text{ parking protected)} \qquad (7)$$

where W_{buf}^* is the perceived effective buffer width and the β_W and β_H parameters are the rate of buffer benefit for width and height, or the amount of benefit that each additional unit of distance provides, respectively. For example, 6 inches of vertical buffer likely provides more added benefit compared to 6 inches of horizontal buffer [15–17]. This function also includes a maximum effective width, W_{max}. Intuitively, excessive buffer width and height will only provide diminishing returns where after a certain point, a taller barrier or a wider buffer will provide no additional benefit.

Another area of consideration is in the case of parking protected bicycle lanes where the parking lane is between the drive lane and the bicycle lane. In this case it is important to also consider the proportion of parked cars present because if there are no parked cars, then it provides no vertical separation. In the case of parking protected lanes, this effect can be approximated by introducing the proportion of parked cars, P_{pk}, to the vertical height as

$$W^*_{buf} = W_{max}\left(1 - e^{-(\beta_W W_{buf} - \beta_H H_{buf} \times P_{pk})}\right) \qquad \text{(if parking protected)} \qquad (8)$$

It is important to note that this maximum is not the actual physical width or height, but the maximum perceived *effective* width possible. Calibration is required to estimate the actual values for W_{max}, β_W, and β_H. The above formulation provides a convenient framework for estimating such parameters using conventional log-linear regression. However, literature suggests that vertical buffer is often perceived as approximately twice as beneficial as horizontal buffer [15–17]. As an initial assumption, this report will use values of $\beta_W = 0.5$ and $\beta_H = 1$ for the rate parameters, and W_{max}=12ft based on a typical width of a drive lane. Again, it should be stressed that these values require further research for calibration.

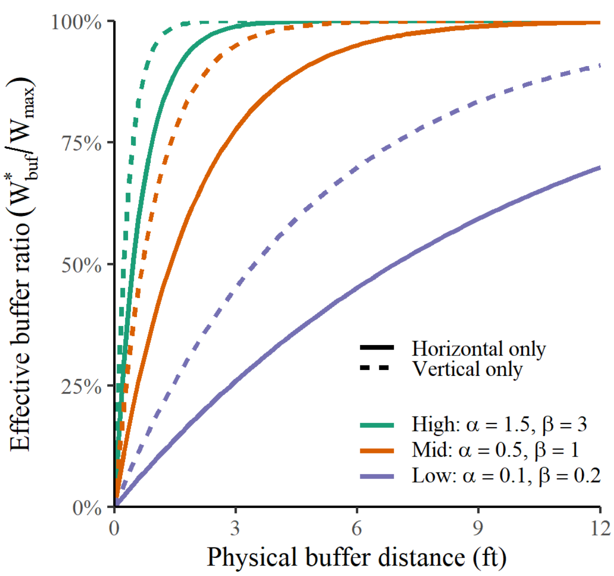


Figure 3-2: Diminishing effective buffer distance for horizontal and vertical buffers

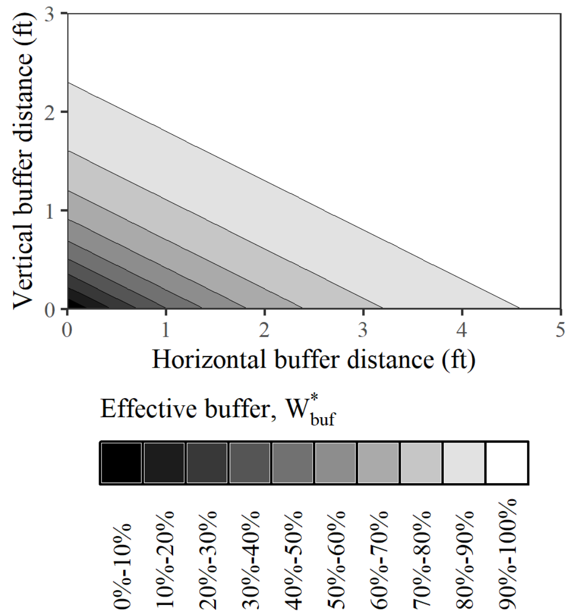


Figure 3-3: Combined effect of horizontal and vertical buffer

In addition to this effective buffer 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, as shown in Figure 3-4. Simply adjusting the constant from 2 to 1.8 eliminates the discontinuity.

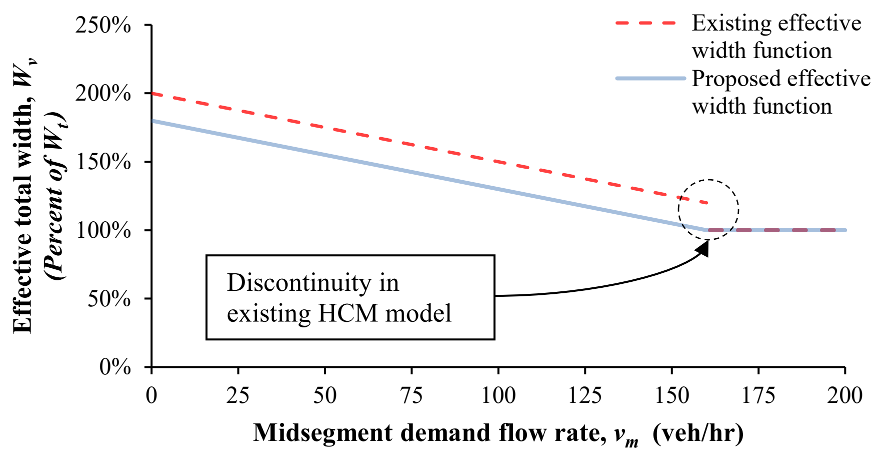


Figure 3-4: Effective total width functions

3.1.2. Motorized traffic speed exposure

The proposed revisions build upon existing HCM methodology[3] for pedestrian LOS at intersections, which have F_{delay} and F_s, as factors for delay and traffic speed, respectively, and are calculated as:

$$F_{delay} = 0.0401 ln(d_b) \quad (9)$$

$$F_s = \frac{\sqrt{n_{15,mj}} S_{85,mj}}{200} \quad (10)$$

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 85[th] 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.

3.1.3. Delay Penalty from Right-Turning Automobile Volume

In the current HCM, bicycle delay at intersections does not account for potential delay caused by right-turning motorists that cross over the bicycle lane. While the respective allocation of space to motorists and bicycles makes this situation unavoidable, it is analogous to having a through lane placed to the right of a left turn lane. This would force drivers to cross paths with each other and cause delay as the two lanes intersect, and their combined effective capacity is reduced.

[3]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.

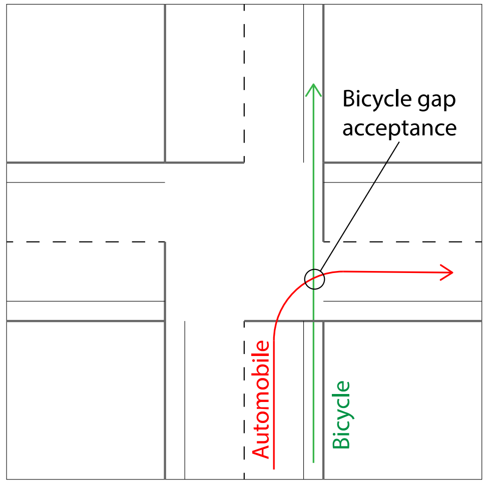


Figure 3-5: Right turn vehicle conflict with through moving bicycle

The same is true for bicyclists at intersections with a high volume of right-turning motorists that can impact the flow of bicyclists traveling in the bicycle lane. This delay can be caused at both red and green phases. At a red phase, this can cause motorists attempting a right-on-red to encroach or block the bicycle lane, reducing capacity of the bicycle lane. Conversely at a green phase, right turning motorist cross in front of a through moving bicyclists, thus reducing capacity or worse, potentially causing what is commonly referred to as "right-hook" collision. A common treatment for right-hook collisions is placing the bicycle lane to the left of a dedicated right-turn lane with an upstream merge zone (as shown in Figure 3-6). While such a treatment can mitigate right-hook collisions, it still poses a potential source of delay as they still must cross paths.

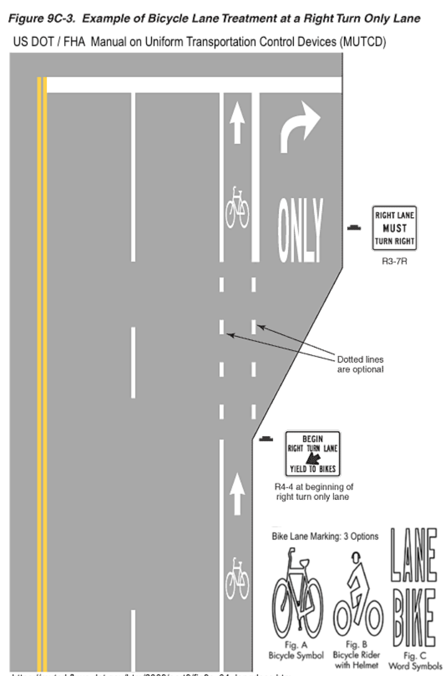


Figure 3-6: Right turn lane bicycle treatment

A proposed function reflects this by modeling the reduction in effective capacity as the two traffic streams cross paths, similar to if two uncontrolled traffic streams merge or cross paths. Precise bicycle lane capacity is largely undetermined in the industry with little research on the subject. The Highway Capacity Manual uses 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" [15, 18–20]. The saturation flow rate of a bicycle lane is calculated as

$$s_b = max\left[1500 \times \left\lfloor\frac{W_b}{2.5}\right\rfloor, 1500\right] \qquad (11)$$

where W_{bl} is bicycle lane width. When no bicycle 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 bicycle lane capacity by occupying its space. 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.

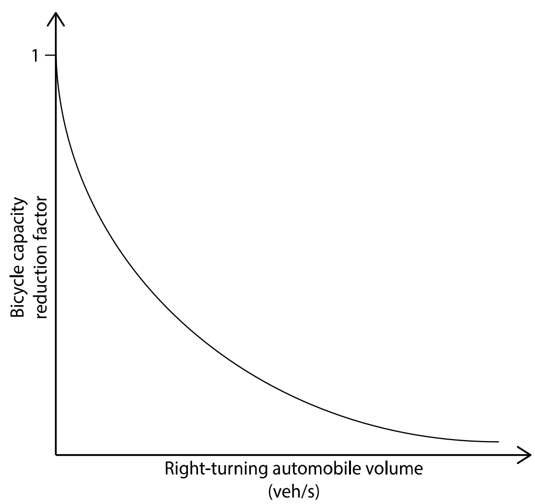


Figure 3-7: Right-turning vehicle impact on bicycle lane capacity

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

$$f_{RTV} = e^{-v_{RTV} t_c} \qquad (12)$$

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 will require 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:

$$c_{be} = s_b \times f_{RTV} \times \frac{g_b}{C} \tag{13}$$

Where:

c_{be} is capacity of the bicycle lane (bicycles/h),
g_b is effective green time for the bicycle lane (s),
s_b is the saturation flow rate of bicycles, and
C is cycle length (s).
The signalized intersection bicycle delay is computed with:

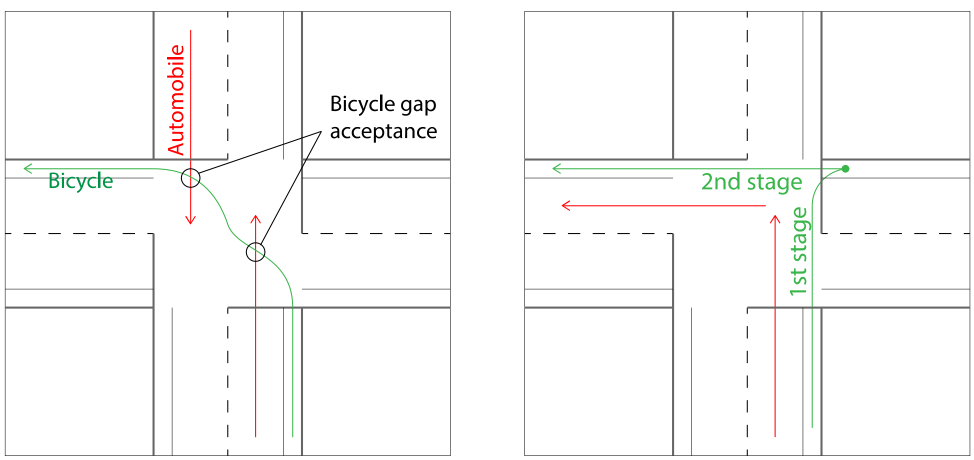
$$d_{bS} = \frac{0.5C\left(1 - \frac{g_b}{C}\right)^2}{1 - min\left[\frac{v_b}{c_{be}}, 1.0\right]\frac{g_b}{C}} \tag{14}$$

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.

3.1.4. Left-turning bicycle delay

At signalized intersections, bicycles typically perform a left turn using one of two maneuvers, as shown in Figure 3-8.



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

Figure 3-8: Left-turn bicycle conflict with through traffic

Single-phased permissive left leverages 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 is another common maneuver. This is typically performed at larger intersections with high volume and/or multiple traffic lanes where permissive left turns are 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" [22] 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:

$$d_b = d_{bS} + P_L[(1 - P_{L2})d_{bL1} + P_{L2}d_{bL2}] \tag{15}$$

Where:

d_b is overall average bicycle delay (s/bicycle),
d_{bS} is bicycle delay from signal (s/bicycle)[4],
d_{bL1} is bicycle delay for one-stage left turns (s/bicycle),
d_{bL2} is bicycle delay for two-stage left turns (s/bicycle),
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 level of service.

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

3.1.5. 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". 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 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, 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

$$t_{cb} = \frac{L}{S_b} + t_{sb} \tag{16}$$

[4] Signal delay in proposed methodology should include delay incurred by right-turning vehicles.

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.

$$N_b = max\left[\frac{2.5N_c}{W_{bl}}, 1.0\right] \tag{17}$$

Where:

N_b is spatial distribution of bicycles (bicycles),
N_{cb} is total number of bicycles in the crossing platoon,
W_{bl} is width of bicycle 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:

$$N_{cb} = \frac{v_b e^{v_b t_{cb}} + v_m e^{-v_m t_{cb}}}{(v_b+v_m)e^{(v_b-v_m)t_{cb}}} \tag{18}$$

where

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

The critical headway of the group is determined with:

$$t_{cb,G} = t_{cb} + 2(N_b - 1) \tag{19}$$

where

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

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.

$$P_b = 1 - e^{\frac{-t_{cb,G}\, v_m}{N_L}} \tag{20}$$

$$P_d = 1 - (1 - P_b)^{N_L} \tag{21}$$

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

$$d_{bg} = \frac{1}{v}\left(e^{v_m t_{cb,G}} - v_m t_{cb,G} - 1\right) \tag{22}$$

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:

$$d_{bgd} = \frac{d_{bg}}{P_d} \tag{23}$$

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 [23]. The headway is calculated as

$$h = \frac{\frac{1}{v_m} - \left(t_{cb,G} + \frac{1}{v_m}\right) e^{-v_m t_{cb,G}}}{1 - e^{-v_m t_{cb,G}}} \tag{24}$$

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

$$d_{bL1} = \sum_{i=0}^{n} h(i - 0.05)P(Y_i) + \left(P_d - \sum_{i-0}^{n} P(Y_i)\right) d_{bgd} \tag{25}$$

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 bicycles 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., $h(i-0.05)P(Y_i)$) represents expected delay when motorists yield, the second term (i.e., $P_d - \sum_{i-0}^{n} P(Y_i)$) represents expected delay waiting for adequate gap, and the third term (i.e., d_{bgd}) 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

$$d_R = \frac{C-g}{C}\left(\frac{C-g}{2}\right) + l + t_{sb} \tag{26}$$

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: $P(Y_i) = P_d M_y (1-M_y)^{i-1}$ (27a)
- Two-lanes: $P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j)\right]\left[\frac{2P_b(1-P_b)M_y + P_b{}^2 M_y{}^2}{P_d}\right]$ (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[5]: $P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j)\right] \times \left[\frac{P_b^4 M_y^4 + 4P_b^3(1-P_b)M_y^3 + 6P_b^2(1-P_b)^2 M_y^2 + 4P_b(1-P_b)^3 M_y}{P_d}\right]$ (20d)

where:

M_y is motorist yield rate (decimal),
i is crossing event ($i = 1$ to n), and
$P(Y_0) = 0$.

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

[5] An assumed correction in motorist yield probability formula was made from the current version shown in Chapter 19 of the Highway Capacity Manual. The cubed exponent is placed outside the parenthesis (i.e., $(1-P_b)^3$), not inside.

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:

$$d_{bL2G} = \frac{g_1}{2} + l_1 + t_{sb} \tag{28}$$

$$d_{bL2R} = \frac{C - g_1}{2} + g_1 + l_1 + 2t_{sb} \tag{29}$$

Where:

d_{bL2R} is left turn bicycle delay given arrival is during a red phase (s/bicycle),
d_{bL2G} is left turn bicycle delay given arrival is during a green phase (s/bicycle),
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:

$$d_{bL2} = \frac{g_1}{C} d_{bL2G} + \frac{C - g_1}{C} d_{bL2R} \tag{30}$$

Where:

d_{bL2} is bicycle delay for two-stage left turn (s/bicycle),
$\frac{g_1}{C}$ is the proportion of bicycles arriving during green, and
$\frac{C-g}{C}$ is the proportion of bicycles arriving during red or yellow.

Considerations for future traffic environments

With the advent of connected and autonomous vehicles (CAVs) and a potential future traffic environment of fully adopted CAVs, some special considerations should be made for the above formulations. A traffic environment dominated by CAVs enables radically new traffic patterns (e.g., platooning) and intersection coordination (e.g., coordinated gap clearance for continuous flow intersections). In these cases, many of the assumptions regarding gap distance and delay would no longer apply.

This new traffic system would present both challenges, and opportunities. For example, a stream of platooned vehicles at a TWSC would not have a probabilistic distribution of gaps and present a continuous barrier to bicyclists, but it could also create a predictable gap for bicyclists. In such a case, delay estimation would be closer to estimating control delay rather than probabilistic gap acceptance. Moreover, an intersection where coordinated flows of continuously moving traffic seamlessly intersect would also present a barrier to traditional bicycling operations. Again, such a case would necessitate further coordination with the CAV system to facilitate safe passage of non-motorized road users and potentially achieving a delay reduction compared to traditional signalized control delay. However, with CAV research still ongoing and since its capabilities are not fully realized in a naturalistic traffic environment, it is difficult to develop delay estimation models for such cases.

A more near-term caveat to the above delay function is dedicated bicycle signal phasing, particularly with separated bicycle lanes. Many cities are beginning to experiment with dedicated bicycle-specific signal-heads and phasing to provide temporal separation of bicycle and motorist traffic streams in addition to physical separation [24, 25]. In such a case, many of the above assumptions and formulations for delay no longer apply. Bicyclists would no longer need to wait for a gap in traffic or deal with right-turn conflicts. Instead, delay may be calculated directly as bicycle signal control delay for the intersection. However, this additional layer of traffic interaction will likely increase overall intersection delay for all modes due to the added complexity of handling traffic streams from bicycles, motorized vehicles, pedestrians, and possibly even transit. Nonetheless, the gain in LOS through improved safety is likely to outweigh the added delay. There is likely a design trade-off to be considered for each case as multi-modal traffic environments increase in complexity and volume.

3.1.6. Application of Proposed Methodology

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 bicycle lane buffers. A numeric demonstration is shown in Figure 3-9, showing the LOS compensating value as buffer width and height vary for a 5-ft bicycle lane and no outside shoulder.

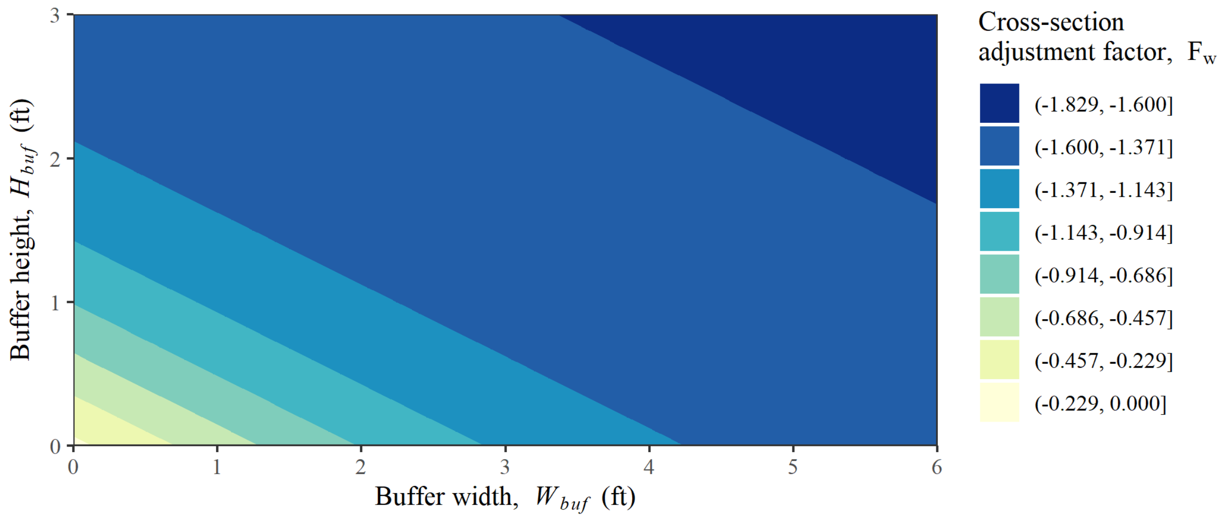
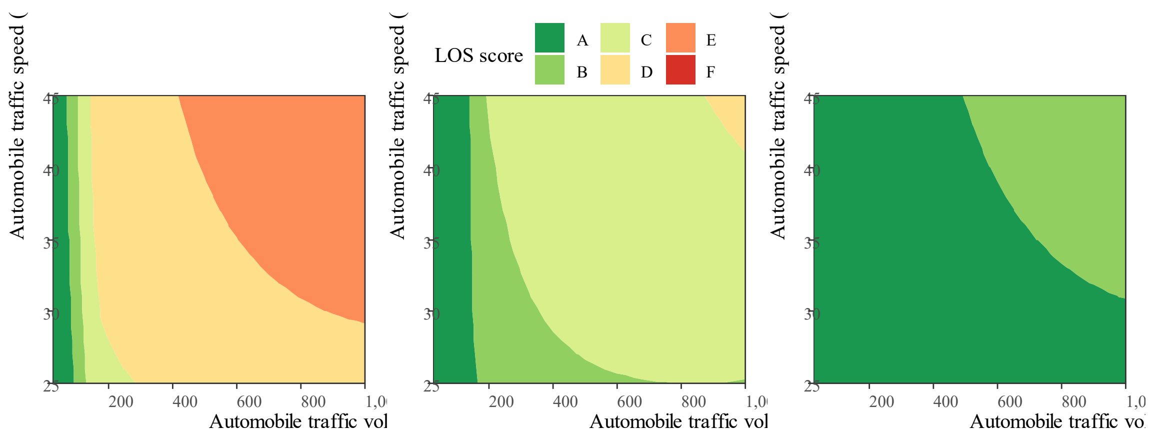


Figure 3-9: Cross-section factor adjustment for separated bicycle lane buffer size

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 [26]. 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 3-10 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 3-10: Bicycle LOS for links with proposed separated bicycle 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 is further study for field calibration and validation necessary, collateral effects from exogenous factors, such as intersection crash risk with lack complementary infrastructure also require further research (e.g., mixing zones and bicycle signals) [17, 27].

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 3-11, 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.

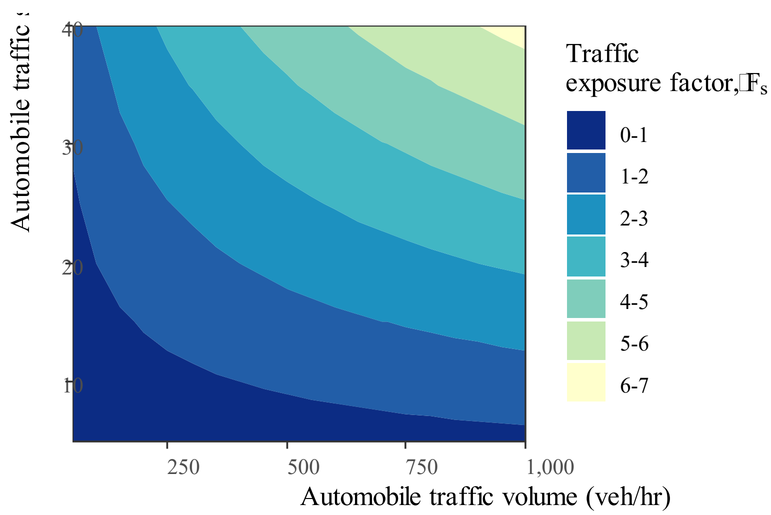


Figure 3-11: Traffic speed exposure for bicycle LOS at intersections

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. As right-turning motorists cross paths with bicyclists, this creates a conflict point where bicyclists and motorists must intersect, reducing the effective capacity of the bicycle lane as the space is occupied, similar to two lanes merging. This reduction in bicycle lane capacity thus increases bicycle delay experienced at signalized intersections.

The demonstration example in Figure 3-12 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 show the proposed bicycle delay model (solid blue line) gradually increases exponentially as the volume of right-turning vehicles increases. As an increasing number of right-turning motorists cross paths with bicyclists, delay gradually increases. Conversely, bicycle delay in the existing HCM model (dashed red line) remains constant, regardless of right-turning motorist volume, since it is entirely dependent on signal delay.

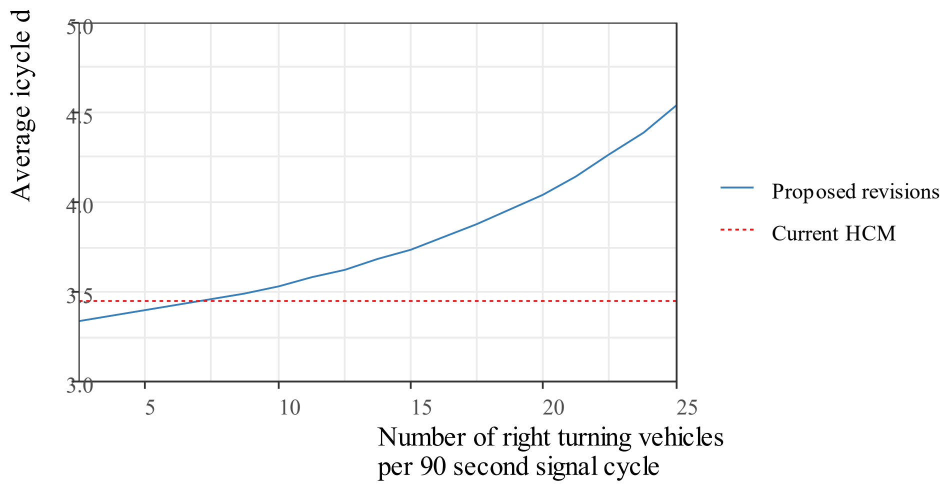


Figure 3-12: Bicycle delay incurred by right-turning automobiles

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. Moreover, there specific are instances where additional factors can further affect delay. For example, a pedestrian crossing phase causes right-turning vehicle be stopped, further blocking the bicycle lane.

Intersection left-turn bicycle delay

A numerical example for left-turn bicycle delay is demonstrated in Figure 3-13, showing that 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 3-13 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.

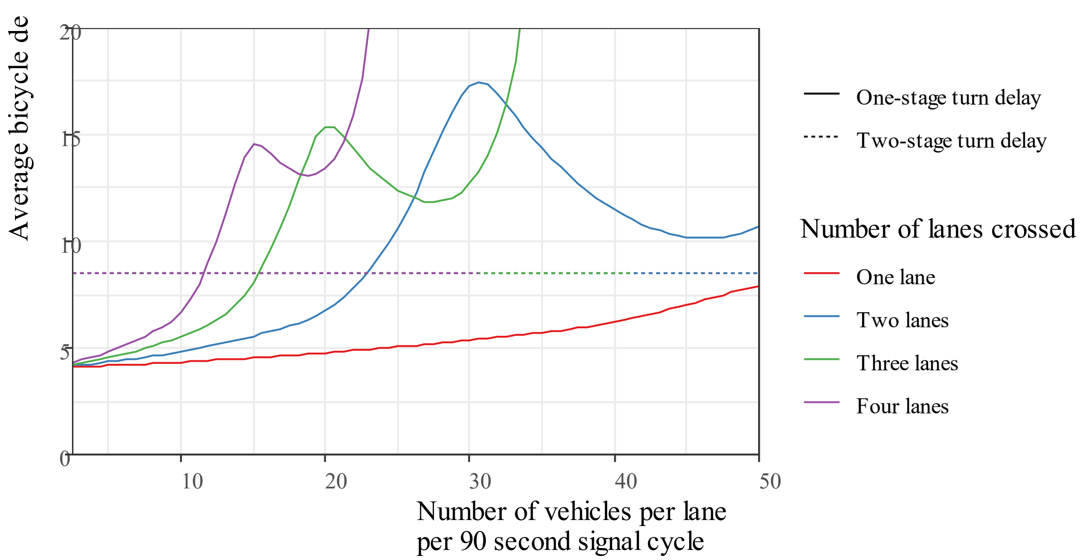
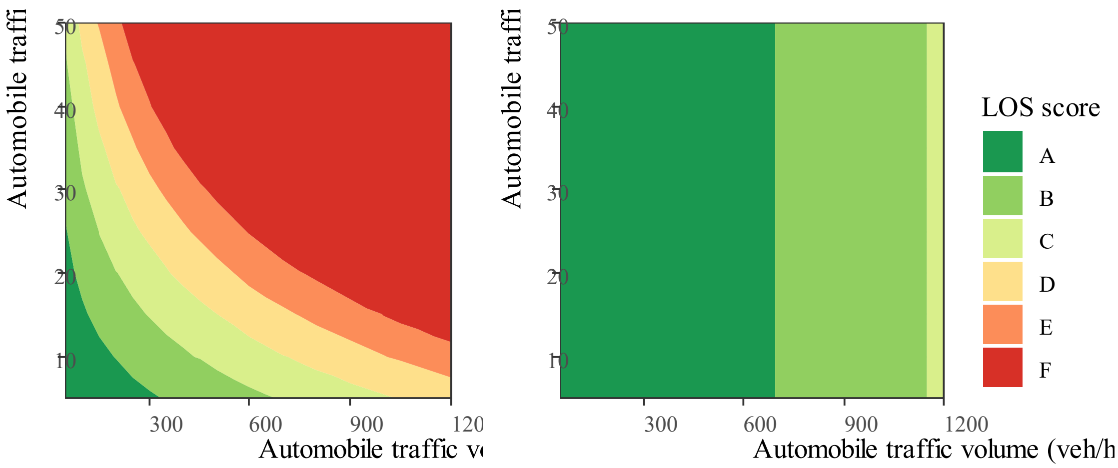


Figure 3-13: Left-turning bicycle delay

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 3-14. The proposed revisions (shown in Figure 3-14a) yields a far stricter LOS score compared to the current HCM methodology (shown in Figure 3-14b).



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

Figure 3-14: 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.

Overall Level of Service Results

To demonstrate the overall effect of the proposed LOS revisions, two case studies where Complete Streets improvements were recently built are used to evaluate the results. These two case studies are Hearst Avenue in Berkeley, CA, and Colorado Boulevard in Pasadena, CA. The two improvement projects provide a diversity of Complete Street improvements where Hearst Ave includes extensive bicycle improvements, such as standard bicycle lanes, buffered bicycle lanes, and parking protected bicycle lanes; whereas Colorado Ave mainly focused on pedestrian improvements and provides only shared-lane bicycle facilities. Figure 3-15 shows the extent of each project on a street map. The data for each project are obtained from the associated traffic studies and level of service analyses for each project [28–31]

Colorado Blvd, Pasadena, CA **Hearst Ave, Berkeley, CA**

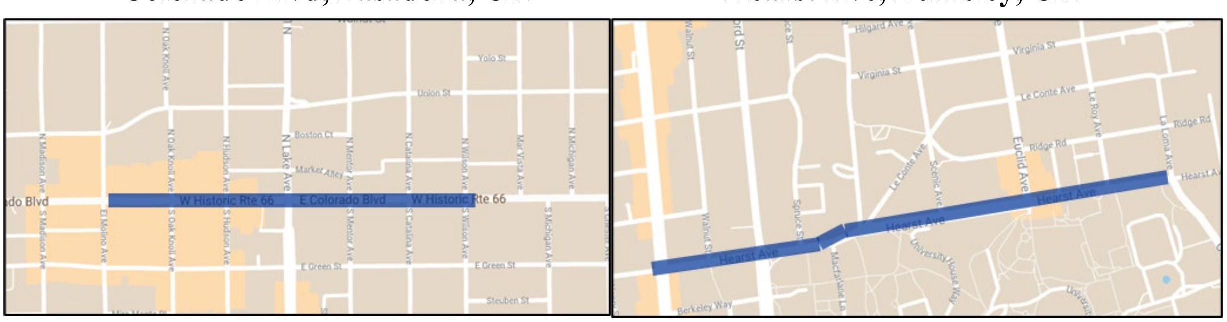


Figure 3-15: Street map of recent Complete Streets improvement projects along Hearst Avenue in Berkeley and Colorado Boulevard in Pasadena, California

The overall level of service results for intersections, links, and the combined segment are presented in Figure 3-16 for Hearst Ave and Colorado Blvd. The scatter plots compare the LOS values calculated using the existing HCM methodology on the horizontal axis with the LOS values calculated using the proposed revisions on the vertical axis. To summarize, points that appear above the diagonal reflect an increase in LOS values (i.e., a worse score) and points below the diagonal reflect a decrease in LOS values (i.e., improved scores). The different color of points shows the score for each of the LOS components: links, intersections and the combined segment (i.e., intersections and links)

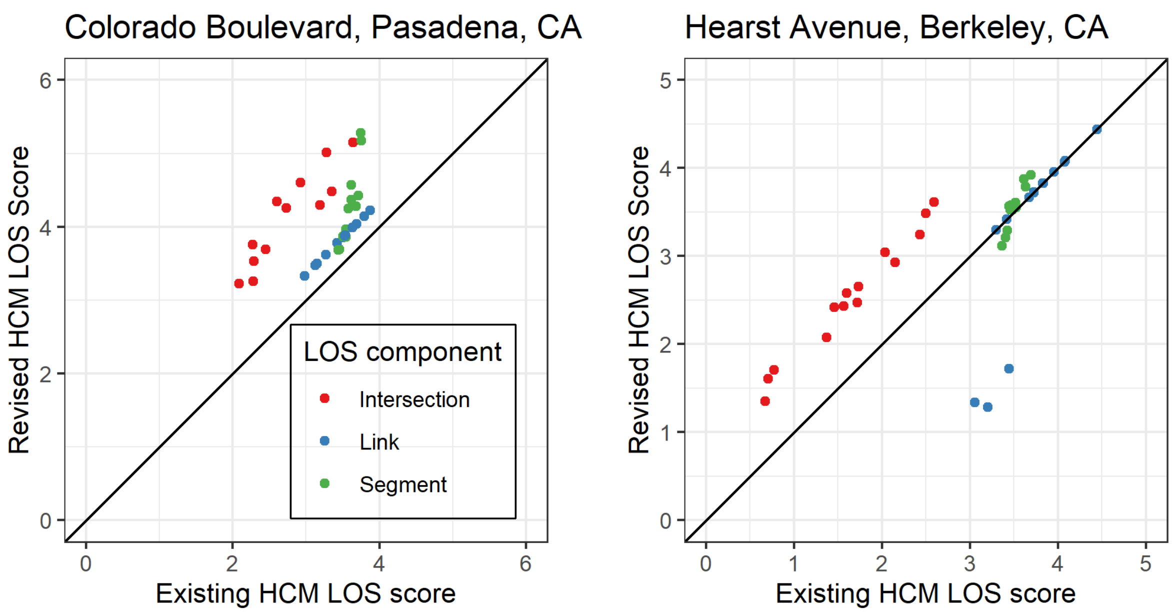


Figure 3-16: Comparison of proposed and existing HCM Bicycle LOS methodology for Hearst Ave in Berkeley and Colorado Blvd in Pasadena, CA

In the Colorado Blvd results, the LOS scores worsened overall. However, it is very important to point out that this does not mean the Complete Street improvements were a failure, it merely means that the proposed revisions provide a more conservative LOS score that accounts for previously unaccounted factors. In contrast, the Hearst Ave results yielded a relatively stable LOS score for segments, but when comparing LOS scores for links and intersections separate, the differences become more apparent. For Hearst Ave intersections, the LOS score worsened overall but for links the LOS score was substantially improved and helped soften the impact on the overall segment score. This improvement can be attributable to the separated bicycle lanes and other features previously not accounted for in the existing HCM methodology.

3.2. Updated Pavement Quality Index in the Bicycles HCM LOS

To better understand and evaluate bikeway-improvement for Complete Streets projects, there is a need to accurately represent conditions fundamental to the "rideability" of a bikeway through the Pavement Quality Index. In the following analysis, a bike-path is defined to be a path dedicated for the use of bicycles, with no limitation on its potential locations. Rideability on such bikeways can be broadly defined by factors such as comfort, speed, and difficulty – all of which are essential to the overall rider experience [32–34]. Thus, the lack of bicycle infrastructure is a major physical and perceived barrier to increasing bicycle ridership. Studies suggest a relationship between good biking infrastructure and overall biking mode share [32–36]. However, the existing pavement quality index F_p in the HCM methodology does not address this in its current framework [37]. shown in Table 3-2.

The pavement quality index F_p is a value from a scale of 0 to 5 [37], determined through the matrix given in Table 3-2. Each level is associated with a specific pavement description and a motorized vehicle ride quality and traffic speed [37]. There are three critical flaws in the current HCM Pavement Quality Index:

Table 3-2: Existing Pavement Quality Index in HCM

Pavement Quality 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 signs 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, and 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 are deep cracks exist.	Passable only at reduced speed and considerable rider discomfort.

- **No mention of bicycles.** The right-most column appears to only consider "Motorized Vehicle Ride Quality and Traffic Speed". While one can assume this is transferrable to bicycles, it is not perfectly convertible as bicyclists and motorists perceive quality at a different scale. Bicyclists are far more sensitive to debris, pavement defects, and pavement-aggregate roughness than an automobile would.
- **Lack of any explicit, quantitative, and objectively measured thresholds.** The lack of definition for the potentially ambiguous terms, such as what does or does not constitute a pothole, what is considered "new", or what is a "Good ride"? This allows for a wide range of interpretation and potentially biased subjectivity. For example, in order to qualify between a 3.0 and 4.0, it is stated that rigid pavement might exhibit "evidence of minor cracking" [37]. However, there is no clear delineation of what classifies as "minor" cracking, as opposed to more serious cracking. This ambiguity is evident in reports where the F_p value is noted as half steps, such as 3.5 and 4.5, showing a clear inability to clearly distinguish between the levels. This ambiguity is also coupled with potential for implicit bias due to each individual' level of biking experience and comfort. What one analyst determines to be an "acceptable ride" may be interpreted differently by another, rendering this pavement quality index to be subject to what is almost a singular survey point and reducing the quantitative nature of the HCM methodology.

- **No account for cross-classification**. The matrix presumes that all bikeways will cleanly fit onto the description and ride quality scale. However, this can become problematic as there can exist bikeways that straddle multiple categories. For example, a rider can describe an experience on bikeway with a "few joint fractures, faulting, or cracking" (2.0 to 3.0) as "ride quality not acceptable" (1.0 to 2.0) since these are not mutually exclusive. In this situation, there is no defined protocol for how to proceed. This lack of protocol is one of the various factors that contribute to the existing matrix' consistency and reproducibility of the matrix.

Due to this potentially subjective understanding of different pavement quality ratings, the existing HCM Pavement Quality Index fails to provide a consistent baseline for bikeway analysis that is robust across different jurisdictions, locations, and interpretations. More robust comparisons can better inform current and future users, policy-makers, and potential maintenance needs [33]. Furthermore, the current pavement rating descriptions are focused only on structural concerns, with descriptions targeting the existence of just "cracks", "patches", and "potholes." While the rating system is simple and straightforward, it is subjective and not tailored to bikeway specific challenges, such as debris, snow plowing, and pavement marking conditions. To better address conditions pertinent to the rideability of a bikeway, it is crucial to revise the existing HCM's Pavement Quality Index to include detailed, objective classifications.

Since rider comfort is a key factor of bikeway rideability, increasing the quality of bicycle lanes can help to grow bikeway usage [17, 38]. Through an intercept survey conducted in Portland, it was shown that 60% of the surveyed were "Interested, but Concerned" about commuting via bike, highlighting that a large proportion of the overall population is open to the idea but is "highly influenced by the quality of bicycle lanes available" [39, 40]. One of the ways to activate these individuals is to improve bike facilities. A study on nine bike facilities in five different cities highlights that improved bicycle treatments can increase riders from 21% to 171% [37]. Overall, data shows that cycling infrastructure is a "key facilitator", and conversely, a potential barrier, to encouraging cycling [41].

Overall, through this analysis, the goal is to help inform conditions of bikeways through a more robust pavement Quality index; this will allow for more accurate analysis of individual bikeways and more consistent analysis between different bikeways. The remainder of this paper will visit a comparison between the different Complete Streets evaluation method, to confirm the continued choice of using the HCM. Then, after analysis of key proposed revisions prompted by an in-depth literature synthesis of national and international practices, the proposed PQI matrix is presented. Finally, through a simulated sensitivity analysis, the crucial importance of an accurately and objectively rated PQI is demonstrated.

3.2.1. Sensitivity Analysis of HCM Pavement Rating Score

To demonstrate the relative impact of the pavement quality index on the HCM BLOS methodology, a sensitivity analysis was performed to highlight the changes in final BLOS designation in relation to isolated changes to the pavement quality index value. The equations from the 2016 HCM is utilized, as shown in the equations 30 - 32 below. The Bicycle LOS methodology is sourced from Chapter 18 and 19 of the 2016 HCM. The sensitivity analysis used two different methods. First, we assessed the difference in the Bicycle LOS on a set of assumed typical, urban values. Then, we will assess the difference on a greater varied set of intersection Levels of Service. Lastly, we will compare our findings with existing literature.

Link LOS: $$I_{b,link} = 0.760 + F_w + F_v + F_s + F_p \quad (30)$$

Intersection LOS: $$I_{b,int} = 4.1324 + F_w + F_v \quad (31)$$

Segment LOS: $$I_{b,seg} = 0.75\left[\frac{(F_c + I_{b,link}+1)^3 t_{R,b} + \left(I_{b,int}+1\right)^3 d_b}{(t_{R,b} + d_b)}\right]^{\frac{1}{3}} + 0.125 \quad (32)$$

where

F_w = cross-section adjustment factor;
F_v = motorized vehicle volume adjustement factor;
F_s = motorized vehicle speed adjustment factor;
F_p = pavement condition adjustment factor;
F_c = unsignalized conflicts factor;
$t_{R,b}$ = segment running time of through bikes (s);
d_b = bicycle control delay (s/bicycle).

Method 1: Using Assumed Typical, Urban Values

In order to ascertain the singular change due solely to change in pavement condition index, we assumed all other factors in Equation 30, 31 and 32 to be constant through all testing variations [42, 43]. The assumed values and simulated results are displayed in Table 3-3 and Table 3-4 below, respectively. Since the segment LOS is a combination of the Intersection LOS and the Link LOS, the analysis will focus on the segment LOS. As shown, the LOS values and designations can change due to a change in the pavement condition index.

Table 3-3: Sensitivity Analysis Assumed Variable Values

Description	Value	Units
Parking Occupancy	0.95	Percent
Midsegment Demand Flow Rate	250	Vehicles/Hour
Presence of Curb	1	Binary
Percentage Heavy Vehicle	0.05	Percent
Motorized Vehicle Running Speed	25	Miles/Hour
Number of Through Lanes	1	Count
Bicycle Control Delay	15	Seconds
Right Side Access Points (	0	Count
Length of Segment (L)	500	Feet
Signalized Intersection	1	Binary
Effective Width	12	Feet
Bike Speed	10	Miles/Hour

The segment LOS score jump per change in PQI rating varies and appears to decrease in magnitude with each jump depending on initial classification, as documented in "Change in Score" column of Table 10. For example, given the currently assumed values, a difference in pavement condition between 1 to 2 results in the greatest increase in segment LOS. Conversely, a change from 4 to 5 shows much less difference. In other words, the equation is more sensitive to changes on poorly rated pavements when evaluating segment LOS, with diminishing returns as pavement quality increases. Further research would be necessary to ascertain whether this relationship is reasonable.

Table 3-4: Sensitivity Analysis Results

PQI Rating	*Intersection LOS Score*	*Link LOS Score*	*Link LOS Grade*	*Segment LOS Score*	*Segment LOS Grade*	*Change in Score*
1	2.43	9.73	F	6.82	E	-
2	2.43	4.43	D	3.43	C	3.39
3	2.43	3.45	C	2.87	C	0.57
4	2.43	3.10	C	2.68	B	0.18
5	2.43	2.94	C	2.60	B	0.08

Nonetheless, these differences are substantial and can be the differentiating factor between different

LOS designations. Specifically, the difference between a 3.0 to a 4.0 in the pavement quality index can shift the Link LOS by about 0.35 and the Segment LOS by about 0.57, as shown in Table 10. In this case, this singular change resulted in the segment-based LOS designation to change from a C to a D, illustrating the delicate nature of the bicycle LOS structure. Given the subjective and ambiguous nature of the existing HCM pavement condition index, it is possible that analysts may misclassify existing bikeways and drastically affect the final segment LOS. Although this is one specific example, this result can be translated to other situations, thus reducing the robustness of the existing bicycle LOS methodology. We will further explore this idea in the next simulation.

Method 2: Using different Link LOS

The previous simulation (Model 1) provided only a static understanding of one specific scenario. In the following simulation, intersection LOS scores and pavement conditions are varied simultaneously. By varying the intersection LOS, it essentially simulates the different conditions that inform the intersection LOS in aggregate (e.g., effective width, left-turn volumes, through volumes, etc.).

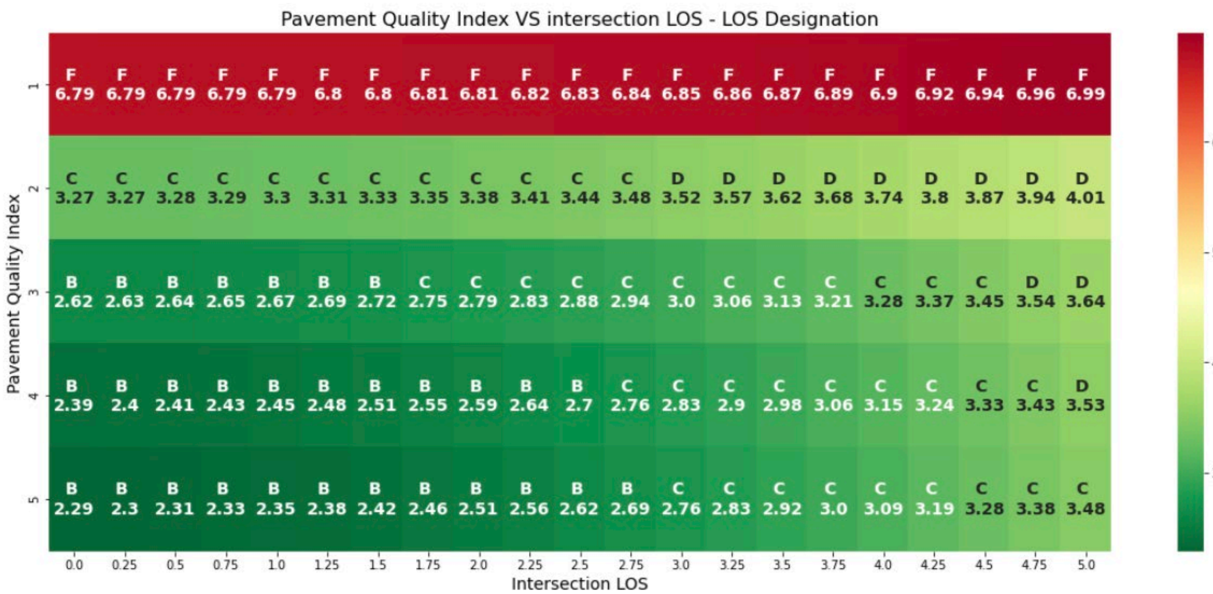


Figure 3-17: Sensitivity Analysis of Relationship between Intersection LOS and PQI– Heatmap

The results in Figure 17 are consistent with Table 10 showing the change from pavement quality 1 to 2 results in the biggest change in overall segment LOS. Similarly, the change from a pavement condition of 4 to 5 results in a smaller change in segment LOS. This shows that LOS is most sensitive when the magnitude of PQI score is lower and intersection LOS is high. Overall, across different intersection LOS scores the PQI score can indeed alter the outcome of the segment LOS, even at high LOS scores, highlighting the importance of accurate PQI scores.

Existing Pavement Quality Rating Literature

Previous literature highlights similar sentiment with changes in the Pavement Quality Index linked to various levels of change in the overall Bicycle LOS. In a study by Sprinkle Consulting, an increase in pavement condition of 1.0 resulted in a 0.16, or 4% increase, in Link LOS. A reduction of 1.0 and 2.0 in Link LOS is conversely associated with a 9% and 33% increase in bicycle LOS, respectively. Our analysis shows similar results in which changes in the PQI can be linked to overall change in bikeway evaluation. Although some literature suggests that the PQI is less influential than traffic speed (F_s) and volume (F_v) when comparing the relative impact of isolated changes by various factors, our analysis highlights that relatively small difference be still be a defining factor between segment LOS designations, as seen in Figure 3-17. In a similar user-intercept surveying effort on Pennsylvania Avenue and 15th Street in Washington, D.C, the data suggests pavement quality contributed to overall satisfaction but may be less influential than other factors. However, further analysis suggests that this effect may be due to the project's location on a separated bike facility, where the separation can mask the LOS experienced. In addition, since the overall objective is consistency and increased comparability between different projects, the pavement condition index remains a crucial factor necessary of further analysis.

3.2.2. Pavement Quality Evaluation for Bicycles

Upon analysis of the existing practice, it was noted that the current pavement condition rating lacks a rigid quantitative basis. In the following literature synthesis, a proposed updated matrix is developed that introduces key categories and provides explicit explanation for all potentially ambiguous terms.

Based on existing academic and industry literature reviewed for bicycle pavement quality, a pavement quality typology can be organized into three fundamental categories: *Functionality*, *Structural Integrity*, and *Maintenance*. The functionality of a bikeway is defined by its surface usability, in relevance to its measured skid resistance and roughness. Other surface usability metrics, such as the number of potholes and cracks, is evaluated in the Structural Integrity category. This category is similar to the metrics used in the existing matrix. However, the proposed index will define key terms such as a "pothole" and a "crack". Similarly, the Maintenance category will introduce evaluation of bikeway pavement color, where applicable, volume of debris, and frequency of snow plowing. All categories are crucial in maximizing comfort for riders through minimizing bumps, cracks, potholes, and surface debris that can impact the handlebar and saddle – two critical contact points between the user and the road.

The existing matrix encompasses various important features; the proposed matrix will encompass all such features and introduce quantitative methods to create a consistent framework for all. Within each category, the classifications are informed by existing literature and user insight but is general enough to be modified as new literature and user-inputs are introduced to the field. Regardless, the proposed matrix is important to ensure a consistent evaluation of bike ways, while considering the latest bikeway features (e.g., pavement color and plowing).

Functionality (Skid Resistance and Roughness):

Rider comfort is dependent on the comfort of the ride itself, as a function of skid and roughness [34, 44]. Skid resistance highlights the likelihood of the wheel slipping against the pavement material. Whether its determination is a result of the inherent pavement material or an outcome due to years of use, the skid resistance of a pavement can inform the safety of bikeway users [44]. Empirically, skid resistance can be measured by specific instruments such as the Grip Tester and the British Pendulum, as highlighted by the South Australian Bikeway Design Guide [45]. Based on the measured grip number, three different classifications for bikeways are used. To attain the best score of 3, the bikeway must have a grip number of at least 0.40. If the grip number is between 0.30 and 0.40, the bikeway is average 2. All grip numbers less than 0.30 is rated to have the worst score of 1. It is important to note that sometimes, given the use of different friction sealants in harsh weather conditions, skid numbers can be sensitive to and subject to variability depending on time since last application [46]. To mimic the average bicycle user experience, it is ideal to avoid measurements immediately after new friction sealant applications. Rather, the average experience can be better approximated when there is no longer a drastic change between consecutive skid number measurements over time.

Another key factor to analyze is the roughness of the bikeway, measured as the vertical displacement that is to occur on a trip down the designated bikeway length. Currently, the United States uses ASTM E950 to standardize test method for measuring surface profile using "accelerometer-established inertial profiling reference". However, since the ASTM standard does not include guidance for reasonable threshold values when evaluating bikeways, the proposed matrix references the National Association of Australian State Road Authorities (NAASRA) Roughness Meter (NRM), which measures in counts per km (ct/km) since there are specific tolerances referenced in the Guide to Bikeway Pavement Design Construction and Maintenance for South Australia. NAASRA units can be translated to other metrics such as length over distance, as would be produced by the ASTM E950, and the International Roughness Index (IRI), in meters/kilometer. One NAASRA count is equivalated to about 15.2mm of vertical displacement per kilometer. The conversion between the NAASRA count and IRI is as follows in Equation 33.

$$\mathrm{NRM}\ \left(\frac{\mathrm{ct}}{\mathrm{km}}\right) = 26.5 * \mathrm{IRI} - 1.27 \tag{33}$$

Similar to ASTM E950, the NAASRA count and IRI require their own specific testing environment and methods, involving variations of laser profiling, walking profilers, and more. To score a 3 on bikeway pavement roughness, an equivalent of maximum 75 counts/km is allowed. When converted to vertical displacement in the imperial system, this is a maximum of 3.44 inches per 100 feet. The next guided threshold is equivalent to 100 counts/km. The range to secure a 2 is between 3.44 and 4.57 inches per 100 feet, adapted from the 75 and 100 counts/km range. Anything greater than 4.57 inches per 100 feet is considered a score of 1. Future studies can be conducted to fine-tune the proposed framework.

Structural integrity (Pothole, Cracks):

As the current practice acknowledges, potholes and cracks are fundamental factors to rider comfort [34, 44, 45, 47, 48]. In a previous study, with over 160 open-ended responses to the question "What would you do to improve the cycle track?", the key terms "pavement", "bumpy", "potholes", and "repaved" appeared 21, 21, 20, and 16 times, respectively [49]. Although the survey suggests these factors are overshadowed by others during before-and-after improvement quality assessments, it is still important to address this subject. One crucial revision in the proposed matrix is the definition of each term. These definitions, and a discussion of the proposed quantification of structural integrity deformations are described below.

Potholes are defined as a crevice of depth of greater than 1 inch and a surface area of greater than 155 square-inches [50]. The threshold is informed by a study on pothole severity. With a clear measurable definition of a pothole number of structural deformations and overall condition can be empirically determined. To receive the highest score of 3, the link of interest must have at most 1 pothole. If the link has between 1 and 3 potholes, it is considered average quality, 2. A link with greater than 3 potholes is noted with the lowest score of 1.

Cracks are categorized with guidance with the National Asphalt Pavement Association [48]. It is specifically noted that "Cracks which are less than 1/4 inches wide are considered low severity". Similarly, medium, and high severity conditions are defined as cracks ¼ to ½ inches in width and cracks greater than ½ inch, respectively. To evaluate the link of interest, the most severe classification of all cracks in the segment is utilized. If the critical crack can be classified as a "low severity" crack (< ¼ in. wide), the link should receive the best score of 3. However, if the critical crack is "medium severity" of between ½ in. and ¼ in., the link is average quality of 2. Links with critical cracks of greater than ½ in. is of the lowest quality of 1. This process streamlines the current process of estimating the difference between what are a "few potholes", "large potholes", and a surface with "75% distress."

Maintenance (Pavement Color, Debris, Snow Plowing):

Maintenance and upkeep of bikeways are crucial to the rideability of corridors. The condition of pavement color, where applicable, allows for continued focus on biker visibility. As highlighted by a study produced by the City of Portland Office of Transportation, planners and engineers were able to analyze the impact of the combined use of blue paint, adjusted signage, and restriping of existing bike facilities on behavior of motorist and bicyclist through collection of empirical collision rates and surveys by users. The results show that 49% of motorist and 76% of cyclists feel safer given the changes. In addition, the percentage of motorists who slows/stops for bicyclists increased from 71% to 87%. In this proposed matrix, the threshold distances are motivated by the AASHTO A Policy on Geometric Design of Highways and Streets Stopping Sight Distances (SSD). The SSD is a standard calculation to derive the time needed for a user to perceive and react to a need for stopping and is calculated as shown in Equation 34.

$$\text{SSD} = 1.47Vt + 1.075\frac{V^2}{a} \tag{34}$$

where

SSD = stopping sight distance, ft;
V = design speed, mph;
t = brake reaction time, s;
a = deceleration rate, ft/s^2.

For an user cruising at 10 mph, derived from the average biking speed of 13mph according to analysis by the SFMTA, with a 2.5 second perception reaction time and deceleration rate of 11.2 ft/s^2 as sourced from AASHTO, the SSD is about 50 feet. This analysis motivates the use of 50 feet as the threshold for poor quality indication. To emphasize visibility, colored pavement fully visible from further away, such as 100 feet and 150 feet away, are more desirable. The corresponding speeds are 18 mph and 25 mph, respectively, with the same assumed perception time and deceleration rate. Although these speeds are less realistic for bikers, it is important to design the facility to also be visible to vehicles that might operate at higher speeds. The values may be adjusted in the future upon additional research. NACTO guidance highlights that the longevity of different treatments (i.e., paint, thermoplastic, Durable Liquid Pavement, etc.) differ and will depend on usage and road treatments.

Another factor that is important to consider is the quantity of debris. Bikeways are often blocked by debris, such as broken glass, and trash, which can block portions of usable bike space. The quantification of debris on a certain square footage highlights the association between rideability and available space. A typical American urban street segment (e.g., city block) is about 400 feet; a typical American bikeway is about 5 feet wide. Thus, the area of a bikeway on a typical link is about 2,000 square feet. Per 2,000 square feet, less than 2 lb. of debris is considered best quality of 3, while accumulated debris weight between 2 to 5 lb. is considered average of 2. If an area of 2,000 sq. ft has greater than 5 lb. of debris, this will result in the lowest score of 1. This value can be further adjusted based on further studies and empirical data.

Obstructions in bike lane can also be environmental. Where applicable, snow plowing is an important consideration. Without adequate consideration for bikeway snowplowing, or worse, the use of the bikeways for snow storage, bikeways can be left unusable for months at a time. This reduces the feasibility of biking despite Complete Streets efforts. Snow clearance on bikeways provides legitimacy to bicycling as a mode of transportation, but also important reliability. If bikeways are unreliable, potential bicyclists will be forced to choose and invest in another transportation mode. The inclusion of snow plowing standards allows for a wider application of this proposed matrix.

Through a review of case studies from within the United States, namely Minneapolis, MN, and outside the United States, including Montreal, Canada; Calgary, Canada; Amsterdam, Netherlands; and more, this index adopts the standard used in Järvenpää, Finland. Specifically, a score of 3 is reserved for bikeways that are "plowed within 4 hours of 1 inch of snow accumulation", where "plowing is done before 7AM" if the snow was overnight, and where de-icing treatments are applied before 7AM [51]. A score of 2 is given if the average bikeway would be plowed within "4 hours of 2 inches of snow accumulation", where plowing is still done before 7AM if the snow was from overnight, and where de-icing treatment is only applied on an as needed basis. If the bikeway fits neither these 2 standards, it is given a score of 1.

3.2.3. Proposed Bicycle Pavement Quality Index

The proposed PQI incorporates a revised point system. Each characteristic is evaluated on a 3-point scale, which is then summed and divided by a factor depending on applicability. For example, where neither pavement color nor snow plowing is not applicable, the sum will be divided by 3. If pavement color or snow plowing is applicable, the sum will be divided by 3.6. If both pavement color and snow plowing are applicable, the sum will be divided by 4.2 This allows the PQI to follow the existing F_p scale and be seamlessly integrated into the existing bicycle LOS. Each 3-point scale employs mutually exclusive and quantitative classifications to minimize the possibility that bikeways that fit multiple categories. By breaking down the existing single 5-point evaluation scale into specific criteria that each have a 3-point scale, the framework motivates greater detail during the evaluation. With the objective of each Complete Streets project being to attain the highest bicycle LOS possible, the inclusion of a more comprehensive list of important bikeway elements will encourage planners and engineers to consider key elements more carefully during the design process. Inclusion of pavement, and thus ride quality, into evaluation brings awareness for key bikeway-specific design elements. Based on the literature discusses, a proposed bicycle pavement quality index has been synthesized in the Table 3-5.

Table 3-5: Proposed Pavement Condition Index Matrix

Category/Criteria	1 (Bad)	2 (Average)	3 (Good)
Functionality			
Skid Resistance*:* Grip Number Determined by instruments such Grip Tester and the British Pendulum Tester.	< 0.30	0.30 to 0.40	> 0.40
Roughness: Vertical Displacement on a Specified Point on Test Vehicle Over a Distance	> 4.57 in per 100 ft	3.44 in to 4.57 in per 100 ft	< 3.44 in per 100 ft
Structural			
Potholes: Number of Potholes	> 3 potholes per block	1 – 3 potholes per block	≤ 1 pothole per block
Cracks: Width of Most Severe Crack	>1/2 in wide	¼ to ½ in wide	< ¼ in wide
Maintenance			
Pavement color: State of Painted Pavement Color by Visibility From Distance, where Applicable	Not fully visible from 50 ft	Fully visible from 50 ft	Fully visible from 150 ft
Debris: Volume per Area of Trash, Glass, etc.	> 5 lb. per 2000 sq. ft	2 to 5 lb. per 2000 sq. ft	< 2 lb. per 2000 sq. ft
Snow Plowing: Description of Plowing Guidelines, where Applicable	Study block is not plowed to standards of other two categories	• Plowed within four hours of 2 inch of snow accumulation. • Plowing is done before 7AM if snowed overnight. • De-icing treatments are applied as needed.	• Plowed within 4 hours of 1 inch of snow accumulation • Plowing is done before 7AM if snowed overnight. • De-icing treatments are applied before 7AM

SECTION 4. SIGNAL CONTROL STRATEGIES FOR COMPLETE STREETS

Traffic signals is the predominant form of control for urban arterial streets and grid networks. Traffic signals operate under specific timing plans (cycle length, and green times) to provide the right of way to conflicting traffic movements. Optimization of signal timing plans is a highly cost-effective measure to reduce delays and stops and cut fuel consumption and air pollutant emissions. Traditionally timing plans are improved for vehicle movements with the rest of the road users' requirements acting as constraints in the optimization process, e.g., allocate the green time to the arterial through traffic subject to the minimum green time for pedestrian crossing.

We developed and tested signal control strategies that can be effective in addressing objectives of complete streets, i.e., facilitating the movement of busses, pedestrians, and bicyclists. These strategies are based on both conventional approaches and emerging technologies. The following strategies have been tested in real-world test sites:

- Arterial timing optimization without private vehicles
- Transit signal priority at signalized intersections
- Bicycle detection and priority

4.1. Arterial Optimization for Buses Without Private Vehicles

Market Street is a major corridor in the Central Business District of San Francisco, California. In January 2020, it was converted to bus only route banning private vehicles, as part of the Better Market Street initiative. The Market Street corridor is 1.4 miles long with 14 signalized intersections. There are 20 different bus routes. Five bus routes operate along the entire length of the corridor with an average headway of about 10.8 minutes and an average travel time of about 14.4 minutes.

The combination of its central location with the new ban on private vehicle highlights the selected Market street corridor as an ideal case study for arterial optimization strategies aimed at improving active transportation, rather than private vehicles.

4.1.1. Methodology

There are limited studies and approaches for "non-vehicle" timing signal optimization. In this study we applied the following methods: SYNCRO software and Time-Space diagram, as implemented in Microsoft Excel by the San Francisco Metropolitan Transportation Authority (SFMTA).

SYNCHRO: SYNCHRO is an existing industry standard signal timing optimization for signalized intersections and arterials. SYNCHRO optimized the signal timing plans to minimize the delay in the arterial network. Data requirements include the intersection geometrics (number of lanes and configuration per intersection approach), distance between intersections, existing timing plans (cycle length, green times ns offsets), and average midblock speeds. SYNCHRO cannot model bus movements and dwell times at bus stops.

We obtained the required data from SFMTA and applied SYNCHRO to optimize the signal settings for both all-vehicles network scenario and bus-only network scenario. The all-vehicles scenario provided the cycle length and green times that required for the intersections to operate as undersaturated (volume/capacity ratio <1.0). The bus only scenario was modeled in SYNCHRO by using 1% traffic volumes (for bus speeds) and average speeds of 10 and 25 mph to account for the lower bus speeds and dwell times at bus stops.

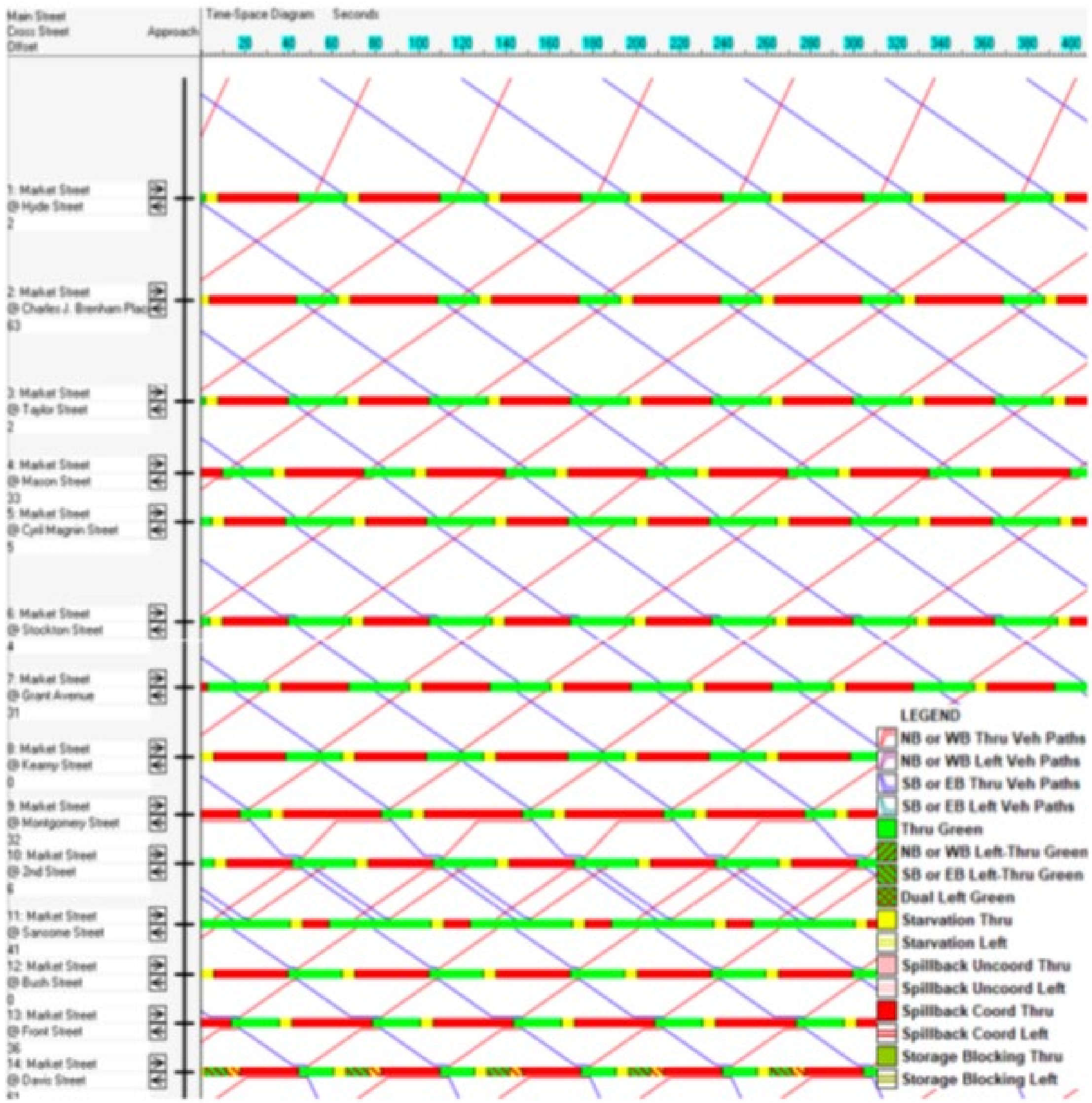


Figure 4-1: Market Street Arterial in SYNCHRO

Microsoft Excel (SFMTA): This is a spreadsheet implemented by SFMTA staff that essentially automates the time-space diagram approach. It uses field collected data on average dwell times per bus stop and block lengths. The spreadsheet calculates the arrival time of buses based on the average travel time, dwell time, and signal delay from prior intersections. By summing the accrued differences between arrival time at intersection and wait until intersection turns green, the total delay is calculated. The signal offsets are then adjusted to minimize the total signal delay. Spreadsheets were developed for different peak periods (AM, Midday, PM), travel direction, (direction (Outbound, Inbound), and bus stop location (curb, center).

4.1.2. Results

Under bus-only network scenario for 25MPH, the optimal cycle length was found to be at 65 seconds which reduced the overall network intersection delay by approximately 35%, as seen in Figure 4-2. The eastbound Market Street approach delay was reduced 65% and the westbound was reduced by a whopping 77%. Similar to the 25MPH analysis, the optimal cycle length for 10MPH bus-only network scenario was also found to be 65 seconds. When comparing with the existing cycle length results, the optimal 65 seconds cycle length reduced the traffic delay by approximately 34% with eastbound reduction of 71 % and westbound reduction of 70%, as seen in Figure 4-3.

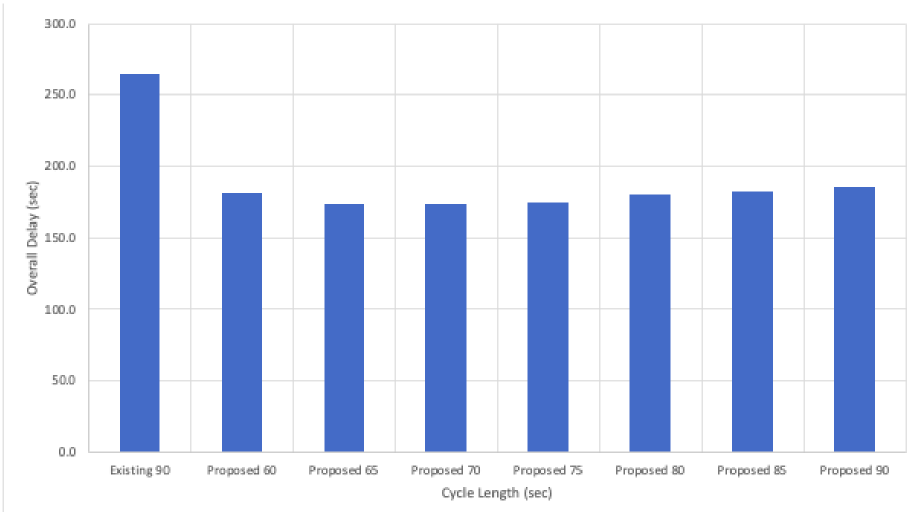


Figure 4-2: Summary of delay for different cycle lengths for bus-only network under 25mph

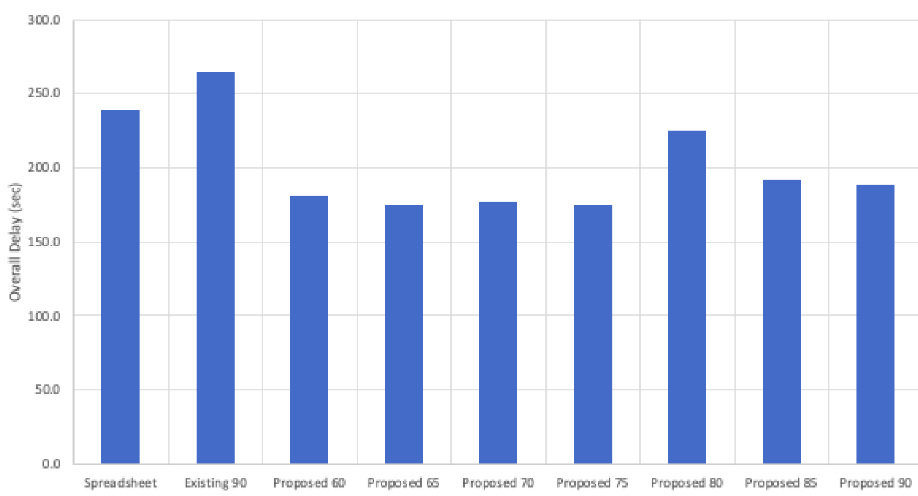


Figure 4-3: Summary of delay for different cycle lengths for bus-only network under 10mph

In comparison with the spreadsheet results which focuses on the most critical delay value from each intersection (for both center and curb-side bus stops), the optimal 65 seconds cycle length reduced the overall intersection delay by approximately 27%. The eastbound Market Street approach was reduced by approximately 67% and the westbound was reduced by about 71%.

Table 4-1: Summary of delays for bus-only scenario under 10mph using MS Excel

Int #	Intersection Name	Delay (seconds)				
		EB (curb-side)	**EB** (center)	**WB** (curb-side)	**WB** (center)	**Overall**
1	Market Street / 8th Street I Hyde Street	0	0	0	0	0
2	Market Street / 7th Street I Charles J. Brenham Place	53.4	0	0	0	0
3	Market Street / 6th Street I Golden Gate Avenue / Taylor Street	0	0	21.3	8 . 8	21.3
4	Market Street / Turk Street I Mason Street	22.5	0	34.6	33.4	34.6
5	Market Street / 5th Street I Cyril Magnin Street	0	36.6	0	0	0
6	Market Street / 4th Street I Ellis Street / Stockton Street	53.3	45.9	56.9	44.1	56.9
7	Market Street/ O'Farrell Street I Grant Avenue	15.1	0	36.9	0	36.9
8	Market Street / 3rd Street/ Kearny Street / Geary Street	0	22.1	0	0	0
9	Market Street/ Montgomery Street/ New Montgomery Street	37.9	0	0	21.6	0
10	Market Street / 2nd Street	6	44.8	42.8	0	42.8
11	Market Street / Sutter Street / Sansome Street	13.1	0	0	0	0
12	Market Street / 1st Street / Bush Street	0	18.9	0	18.9	0
13	Market Street / Fremont Street / Front Street	13	0	0	14.3	0
14	Market Street / Davis Street / Beale Street / Pine Street	0	49	47.1	0	47.1
Total		214.2	217.2	239.6	141.1	239.6

4.1.3. Discussion

Both SYNCHRO and Microsoft Excel approaches predict significant improvements in traffic performance. Using total intersection delay as the prime performance metric, signal timing optimization can reduce intersection delay from 34% to 36%. The Microsoft Spreadsheet method appears promising as an optimization tool but requires further testing and sensitivity analysis and test its accuracy and robustness.

4.2. Transit Signal Priority (TSP) at Signalized Intersections

Measures to provide priority to transit vehicles in urban networks are based on facility design and/or on traffic control. Strategies based on facility design usually consist of exclusive lanes for transit on arterials, as well as street designs that facilitate transit movements (e.g., bus bays and bus bulbs to facilitate safe loading, and reduce conflicts with other vehicles and on-street parking management to ensure the availability of adequate curb space for buses).

TSP measures that rely on traffic control can be passive or active. Passive strategies adjust the signal settings on arterials to provide progression to the busses considering the slower bus speed and the midblock dwell times. Active strategies may hold the green until the bus clears the intersection (phase extension) or advance the start of the green for the phase serving the buses (phase advance) as highlighted in Figure 4-4. TSP is granted subject to the safety constraints for pedestrians and vehicles, and the schedule adherence and occupancy of the transit vehicle.

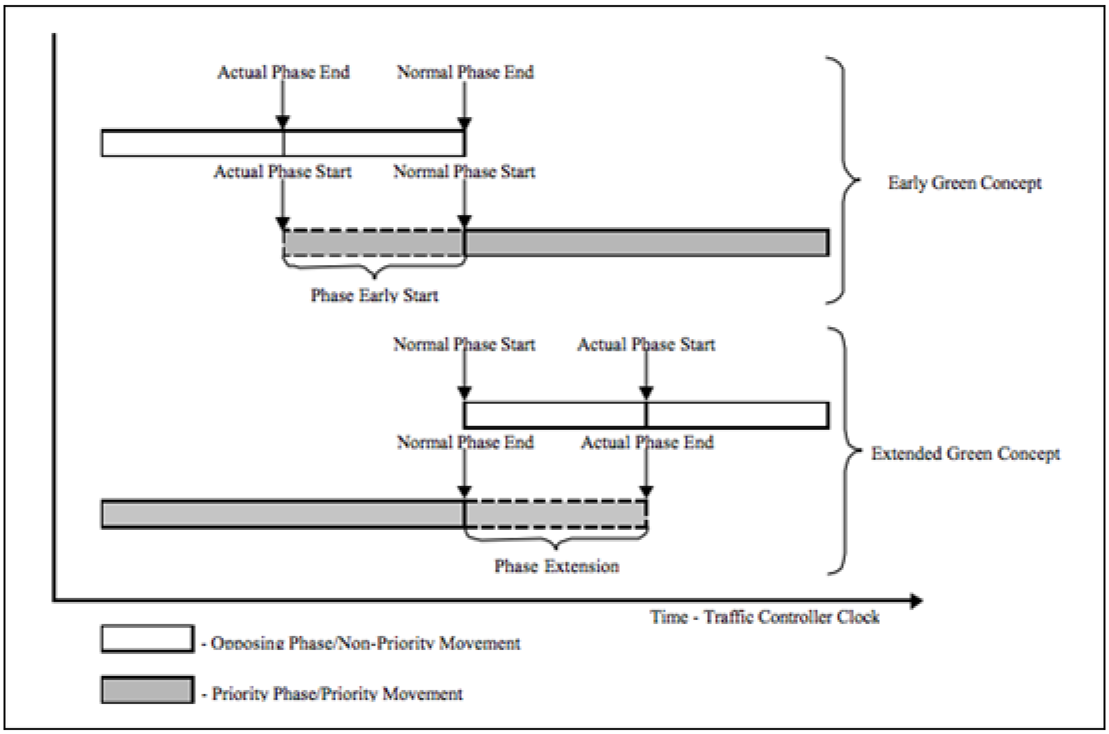


Figure 4-4: Early Green and Extended Green TSP Concepts

TSP was implemented on Geary Street, a major transit corridor in San Francisco. Geary corridor is primarily served by the 38 and 38R (express) transit on a bus-only lane, with headways of between 4-5 minutes for the 38R and 8 minutes for the 38. During the afternoon peak hours, Geary Street westbound serves about 800-900 vehicles per hour.

The Geary Corridor extends over 0.9 miles, covers 11 signalized intersections, and utilizes 1 of its 3 lanes as a transit-only lane. The total demand for buses in the typical afternoon 4-7pm is about a cumulative 90 transit vehicles. The traffic signal timing cards were provided by the SFMTA. The vehicle counts were the results from a traffic study conducted by Fehr and Peers, from 2006 and 2010 post-adjustment volumes.

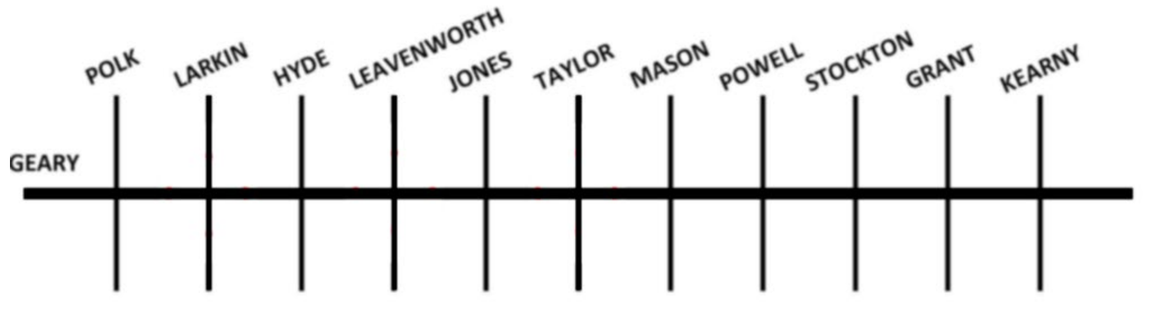


Figure 4-5: Geary Street Test Network

The Geary Corridor was analyzed by SYNCHRO and VISSIM. VISSIM is an advanced microsimulation software that simulates the movements and interaction of individual vehicles and signal operations strategies including TSP. Figure 4-6 shows a screenshot of the simulation of transit signal priority along Geary street using the VISSIM model.

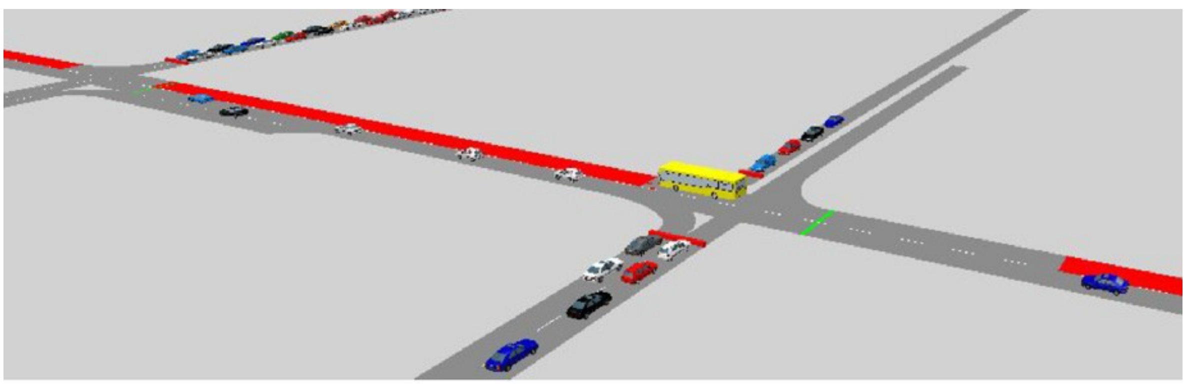


Figure 4-6: VISSIM Simulation of transit Signal Priority, Geary Street, San Francisco

SYNCHRO was applied to optimize the signal timing plans at the corridor. The optimized plans were inputted into the VISSIM model and several TSP scenarios were simulated. Table 4-2 shows the scenarios tested consisting of different cycle lenghts and intersctions with TSP in the corridor. Both early greens and green extensions were simulated, with total allowable fluctuation of up to 15 seconds.

The existing corridor features a 60 second cycle for all 11 intersections except Geary/Kearny, which utilizes a 90 second cycle length. According to the SYNCHRO Analysis, the total delay for the Geary Corridor can be minimized by using a proposed 60 second cycle length, as seen in Figure 4-7. The breakdown is clear in Table 11; the total control delay is reduced by 30.2 seconds, a 20% reduction from the existing configuration.

Table 4-2: TSP Scenarios Tested on Geary Street Corridor

Scenario		Cycle length	Intersections with TSP
1	Baseline (60)	60 sec	
2	4TSP (60)	60 sec	Larkin, Leavenworth, Mason, Stockton
3	5TSP (60)		Hyde, Leavenworth, Mason, Stockton, Grant
4	All TSP (60)		All 11 intersections
5	No TSP (90)	90 sec	
6	5TSP (90)		Hyde, Leavenworth, Mason, Stockton, Grant
7	All TSP (90)		All 11 intersections

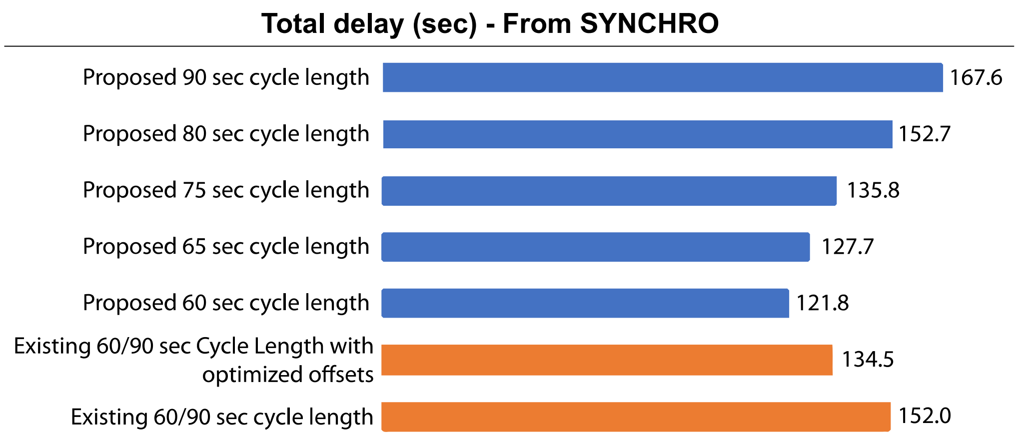


Figure 4-7: Comparison of Total Control Delay of Different Cycle Lengths on Geary Corridor

Table 4-3: Summary of Control Delays for Existing vs Optimal Scenario

		Control Delay (seconds)	
Int. #	*Intersection Name*	Existing 60/90 sec Cycle Length*	Optimal 60sec Cycle Length
1	Geary Street / Kearny Street	16.0	14.9
2	Geary Street / Grant Avenue	12.5	16.0
3	Geary Street / Stockton Street	18.3	10.0
4	Geary Street / Powell Street	12.8	8.9
5	Geary Street / Mason Street	12.4	8.9
6	Geary Street / Taylor Street	12.0	9.9
7	Geary Street / Jones Street	13.4	11.5
8	Geary Street / Leavenworth Street	14.4	10.6
9	Geary Street / Hyde Street	10.2	10.2
10	Geary Street / Larkin Street	14.7	10.9
11	Geary Street / Polk Street	15.3	10.0
	Total	152.0	121.8

*Kearny Street intersection 90 sec, other intersections 60 sec cycle length

Figure 4-8 and Figure 4-9 show the VISSIM predicted total travel time and stopped intersection delay per vehicle for each scenario tested at the Geary corridor. Under the cycle system length of 60 sec and TSP in all intersections, the total travel time is reduced 9% and 2% decrease for the 38 and 38R respectively.

The travel time for cars was slightly increased by 0.18 minutes in this scenario but since the primary focus is bus operations, this can be understood as a reasonable tradeoff. The change is more drastically understood when comparing change in stop delay per vehicle. Using the optimal 60 second all TSP scenario, the stop delay is reduced by for the 38 and 38R by about 40 and 30 seconds, respectively. Similarly, the stop delay per vehicle was also reduced in this scenario by 52% and 31%, for the 38 and the 38R respectively. There is a small increase in travel time and delay for the autos as expected given the priority for busses, but the LOS remained the same.

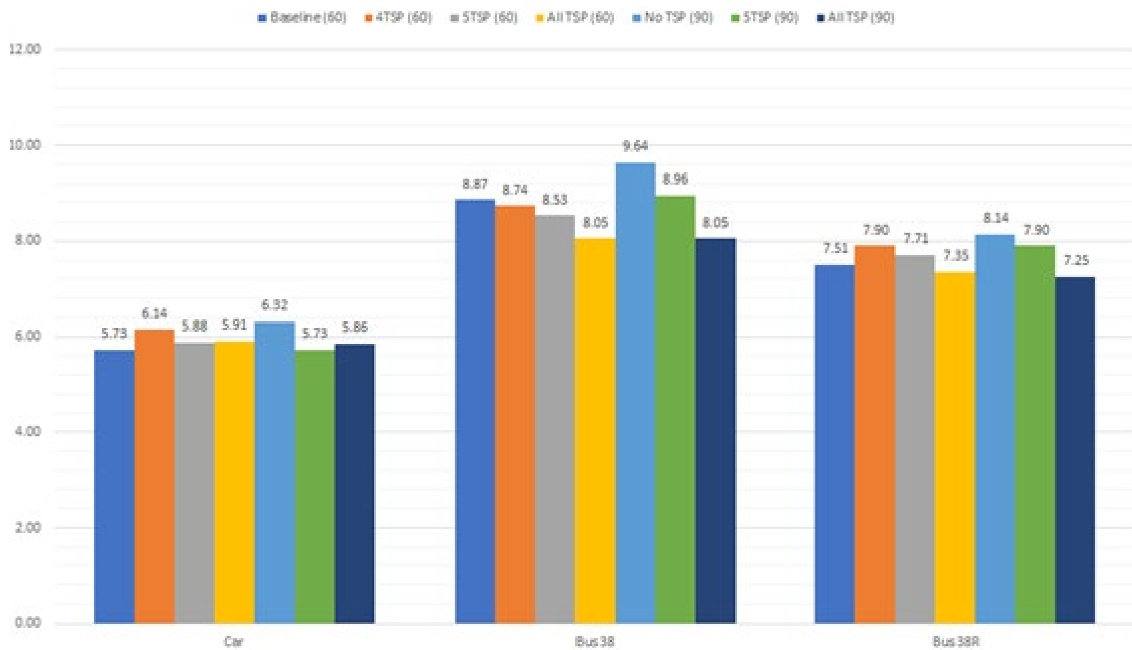


Figure 4-8: Total Travel Time (min) .vs Cycle Length on Geary Corridor

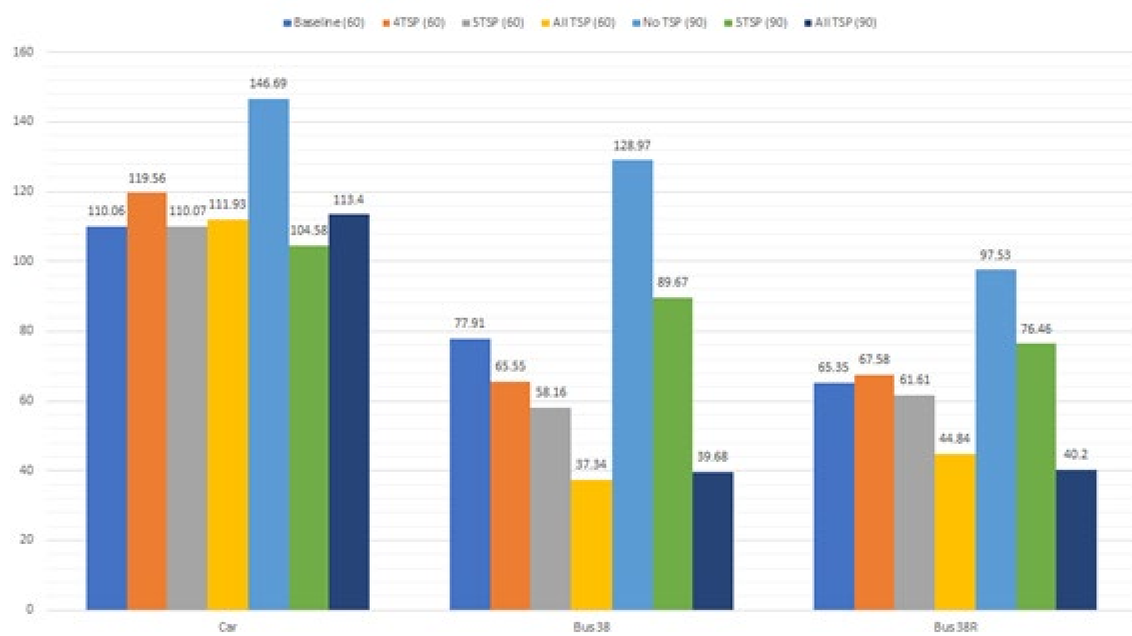


Figure 4-9: Stop Delay per Vehicle vs. Cycle Lengths on Geary Corridor

SECTION 5. SURVEY-BASED CALIBRATION OF PROPSOED BLOS AND PQI METHODOLOGIES

In the absence of observed sensor data, a survey was conducted to calibrate and validate the proposed effective buffer width model and Pavement Quality Index (PQI) described in Sections 3.1 and 3.2, respectively. This section describes design, collection, and analysis results of the bicycle level of service and pavement quality calibration survey. The purpose of this survey is twofold:

- *to calibrate the "effective buffer model" with empirical parameters, and*
- *to determine appropriate scoring weights for the pavement quality rating index.*

The survey is intended to collect both qualitative and quantitative data that can be used to quantitatively calibrate the models, but also help explain the result using qualitative responses.

The following two subsections describe the survey methodology and the results.

5.1. Methodology

The survey was a web-based survey using Google Forms and consisted of five question areas. Within these five areas may include multiple related questions.

5.1.1. Rank-ordered questions

Most of the questions utilize a rank-ordered system in which the respondent must rank their choices in order from least to greatest. The reasoning for using a rank-ordered survey is twofold.

First is to minimize respondent bias as much as possible. For example, when asked to rate from 1 to 5 the importance of pavement structural integrity, functionality, and maintenance; a respondent that wants to promote bicycle infrastructure overall and may simply respond with 5 for all choices. The benefit of rank-ordered question is it forces the respondent to definitively decide between each choice rather than making an arbitrary choice.

The second reason is that rank-ordered questions yield an ordinal response variable that can be estimated using ordinal logistic regression, or more specifically a proportional odds logistic regression model (POLR). Estimating a POLR model is useful in that it yields fitted coefficients for known independent variables. This becomes very useful in this case for estimating the empirically perceived benefit importance of horizontal buffer width versus vertical buffer height hypothesized in Equations (7) and (8). It is anecdotally known that a vertical separation is preferrable to only a horizontal buffer, but this methodology enables a quantitative value to be estimated.

Rank-ordered questions do have some drawbacks. First is that it they are much more cognitively taxing than multiple choice or a linear Likert scale. Ranking questions effectively forces the respondent to compare every possible pair of choices and rank them in order, thus it is as if there are multiple questions in one. This can lead to a low response rate if the survey is too long. For this reason, the survey was kept to only five questions. The second drawback to rank-ordered questions is that relative importance cannot be determined. Ranked results only determines that one choice is more than another, but not by how much. Despite these limitations, the goal of coefficient estimation and minimizing bias far outweighed the drawbacks.

In the case of the bike lane buffer type, the actual vertical and horizontal buffer dimensions are not given to the survey respondent. They are instead shown visually in an image and the actual numeric dimensions are known to the researcher. This enables coefficients to be estimated for each variable, respectively. Providing an image rather than a text description also helps ensure consistency across respondents rather than relying on their imagined bicycling experience and preferences.

5.1.2. Proportional odds log ratio

In an ordered logit model, it is assumed that the response variable is ordered, such as "worst", "better", or "best". As with most regression models, a generalized linear model of the form is used

$$y^* = x^T\beta + \varepsilon$$

where y is the unobserved dependent response, analogous to the utility function (i.e., the perceived benefit), x is the vector of independent variables (e.g., buffer width and height), β is the coefficient to be estimated, and ε is the error. The model is iteratively re-weights the estimated coefficients for each ranked pair

$$y = \begin{cases} 0 & \text{if } y^* \leq \mu_1, \\ 1 & \text{if } \mu_1 \leq y^* \leq \mu_2, \\ 2 & \text{if } \mu_2 \leq y^* \leq \mu_3, \\ \vdots & \\ N & \text{if } \mu_N < y^* \end{cases}$$

where μ_i is the imposed boundary (i.e., from rank 1 to 2, or 2 to 3). The result is regression model with a vector of estimated coefficients and a unique intercept for each rank pair.

5.1.3. Survey questions

The questions of the survey are as follows:

---

1) **PAVEMENT RATING CRITERIA:**
   a) RANK: Structural Integrity, Functionality, Maintenance
   b) OPEN RESPONSE: Are there other pavement features missing that you think are especially important to you? (leave blank otherwise)
2) **PAVEMENT STRIPING VISIBILITY:**
   a) RANK: Ellery, Embarcadero, Hampshire, Broadway, Potrero, Meridian

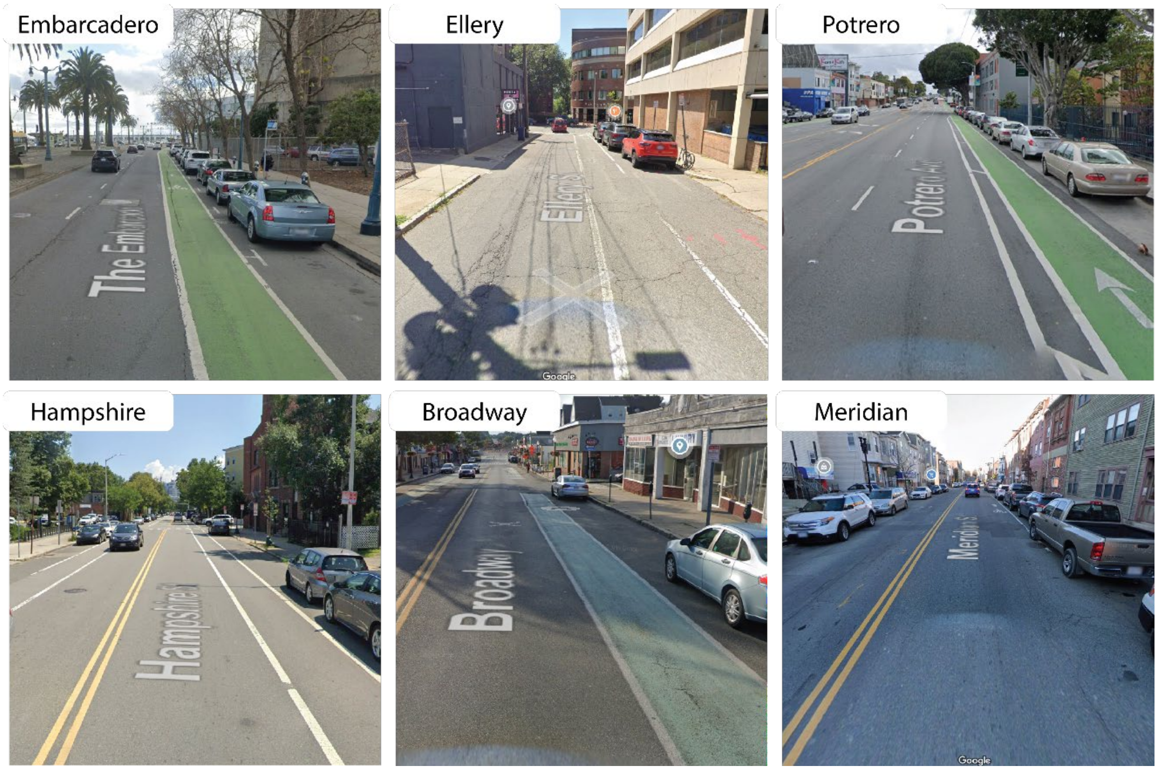


Figure 5-1: Supporting image for survey question #2 on ranked choice bike lane visibility

3) **DEBRIS IMPORTANCE:**
   a) RANK: Non-puncture hazards, Particulate debris, Precipitation Snow/Ice/Puddles, Slip hazards, Puncture hazards
4) **DEBRIS MEASUREMENT PREFERENCE:**
   a) CHOICE FOR EACH HAZARD: Area, Volume, Weight, Depth
      i) Non-puncture hazards
      ii) Puncture hazards
      iii) Slip hazards
      iv) Particulate debris
      v) Precipitation Snow/Ice
   b) OPEN RESPONSE: Do you have another suggested measurement? or a specific refinement? (leave blank otherwise)
5) **BUFFER TYPE**:
   a) RANK: Post protected, Buffered, Raised, Standard, Parking protected, Curb protected

Figure 5-2: Supporting image on survey question #5 for ranked choice buffered bike lane type

b) CHOICE: "If road space wasn't a problem, how much horizontal distance you would put between the bike lane and car lanes before it doesn't make you feel any safer or comfortable? For reference, we'll measure in "car widths", where 1 car width is about 9ft (~2.7m) and 5 car widths is 45 ft"

6) **DEMOGRAPHICS:**

a) NUMBER: "What is your age? (type a number in years)"

b) CHOICE: "What is your gender?"

c) CHOICE: "Do you consider yourself a cyclist?"

i) COMMUTER: "Commuting even if only pre-pandemic"

ii) RECREATIONAL: "for fitness"

iii) RECREATIONAL-SOCIAL: "as casual activity with family/friends"

iv) SOCIAL: "Wouldn't go on my own, but don't mind biking"

v) NONCYCLIST: "You couldn't get me on a bike"

d) How often do you bike?

i) DAILY: "Almost daily"

ii) WEEKLY: "at least once a week if possible"

iii) MONTHLY: "More than once a month but not most days"

iv) YEARLY: "A few times a year but less than once a month"

v) RARELY: "Rarely, if ever"

5.2. Results

The current number of survey responses is 77 (N=77) with 64% women, 31% male, 1% non-binary, and 4% preferred not to say. While the survey was predominantly women, the age distribution was surprisingly wide for a bicycle infrastructure related survey with a mean age of 43, a standard deviation of 15 and a range of 15 to 85 years. The results of this are displayed in Figure 5-3.

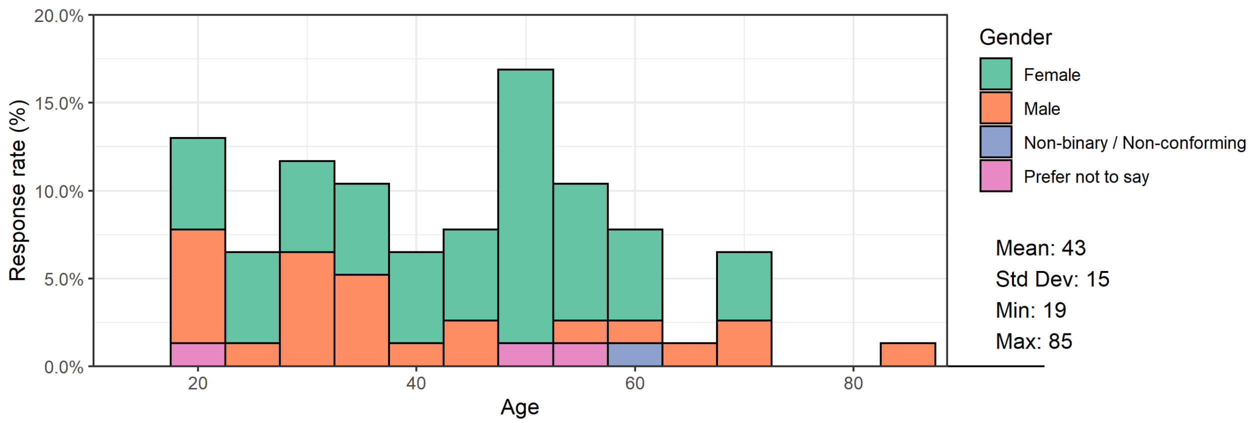


Figure 5-3: Age and gender distribution of survey respondents

An important factor in bicyclist infrastructure is the relative bicyclist type and confidence level. For example, a novice bicyclist may be less favorable of shared lanes whereas a confident bicyclist may prefer it. Many studies utilize the Geller [39] typology of:

1) **Strong and Fearless:** People willing to bicycle with limited or no bicycle-specific infrastructure
2) **Enthused and Confident:** People willing to bicycle with some bicycle-specific infrastructure
3) **Interested but Concerned:** People willing to bicycle with high-quality bicycle infrastructure
4) **No Way, No How:** People unwilling to bicycle even if high-quality bicycle infrastructure is in place

However, this typology is an oversimplification and does not account for a variety of other factors, such as bicycling purpose, frequency, age, or ability. Two questions were targeted at addressing this: *bicycling frequency,* and self-identification of *bicyclist type*. A proportional contingency table of responses for these two categories is presented in Figure 5-4.

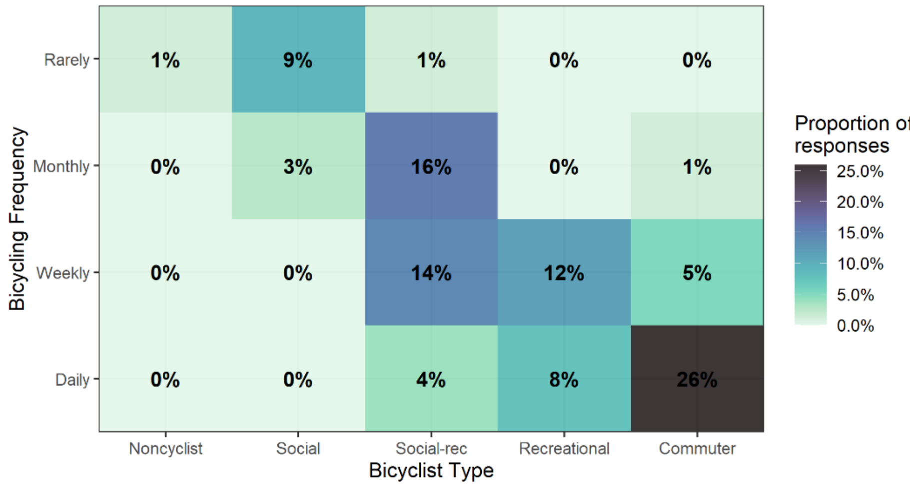


Figure 5-4: Contingency table of bicyclist type and bicycling frequency

5.2.1. Pavement Quality Index

This section presents the results of the pavement quality related questions for general criteria, pavement striping visibility, and debris. The overall average ranking score for each question is summarized in Table 5-1.

Table 5-1: Average ranking scores for pavement criteria, bike lane visibility, and debris type

CRITERIA RANK		VISIBILITY RANK		DEBRIS RANK	
CHOICE	AVERAGE RANK	CHOICE	AVERAGE RANK	CHOICE	AVERAGE RANK
STRUCTURAL INTEGRITY	2.27	POTRERO (Solid green lane)	5.82	PUNCTURE HAZARDS	4.51
MAINTENANCE	1.96	EMBARCADERO (Solid green lane)	4.91	SLIP HAZARDS	3.40
FUNCTIONALITY	1.77	BROADWAY (Solid green lane)	3.95	PRECIPITATION	2.77
		HAMPSHIRE	3.17	PARTICLES	2.38
		ELLERY	2.04	NON-PUNCTURE	1.94
		MERIDIAN	1.12		

General Criteria Importance

When stratified by bicyclist type, the results in Figure 5-5 are consistent with the overall average. This means that the overall average provides a value consistent across different bicyclist types. However, the large standard errors (shown as the black "I" bars) means the differences are not statistically significant. This indicates that the respondents ranked choices were not consistent with each other. The statistical insignificance means that for now, the criteria have relatively equal importance.

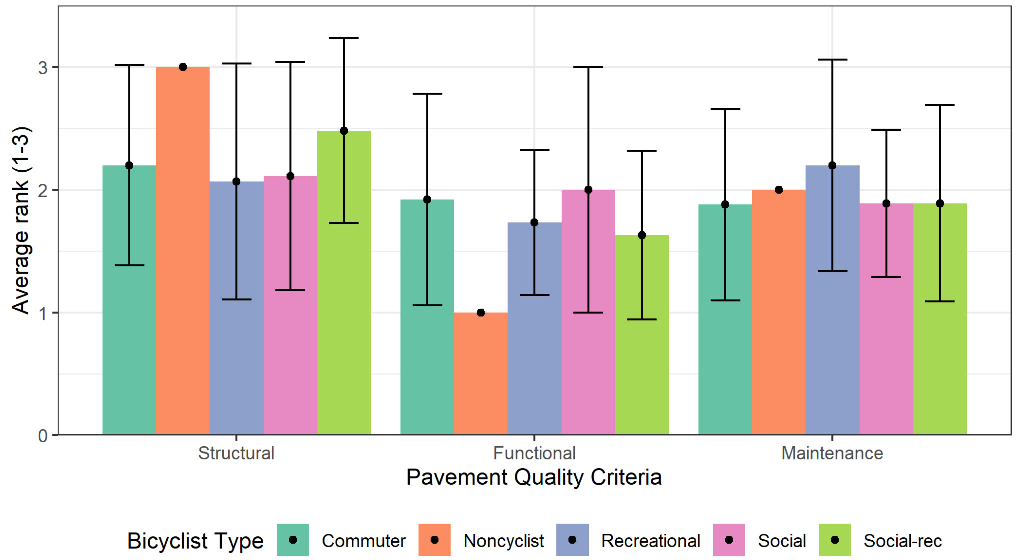


Figure 5-5: Pavement criteria rank by bicyclist type

Pavement Striping Visibility

In contrast to the overall pavement criteria ranking, the pavement striping ranking yielded a much more consistent result across respondents. Figure 5-6 shows a very consistent ordered preference among respondents with the solid green painted lanes being most preferred.

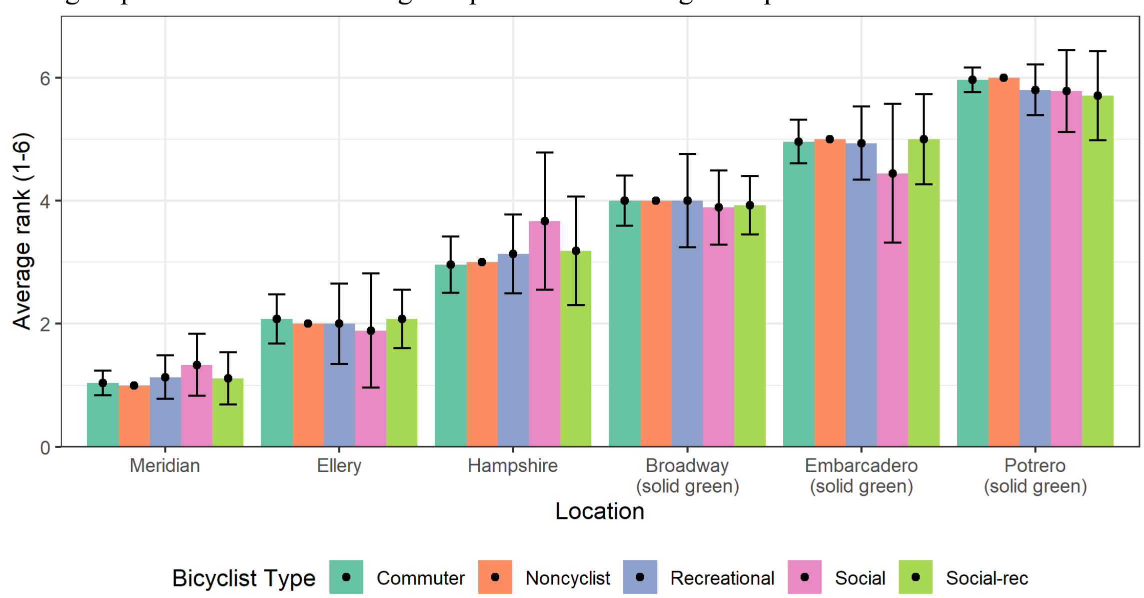


Figure 5-6: Average ranking of bike lane pavement paint visibility by bicyclist type

Debris

The debris ranking in Figure 5-7 was less ordered than the visibility ranking, but still provided useful insight. For example, puncture hazards and slip hazards unsurprisingly appear as being of greatest importance to bicyclists. This makes intuitive sense as these present a safety hazard, not just a comfort issue.

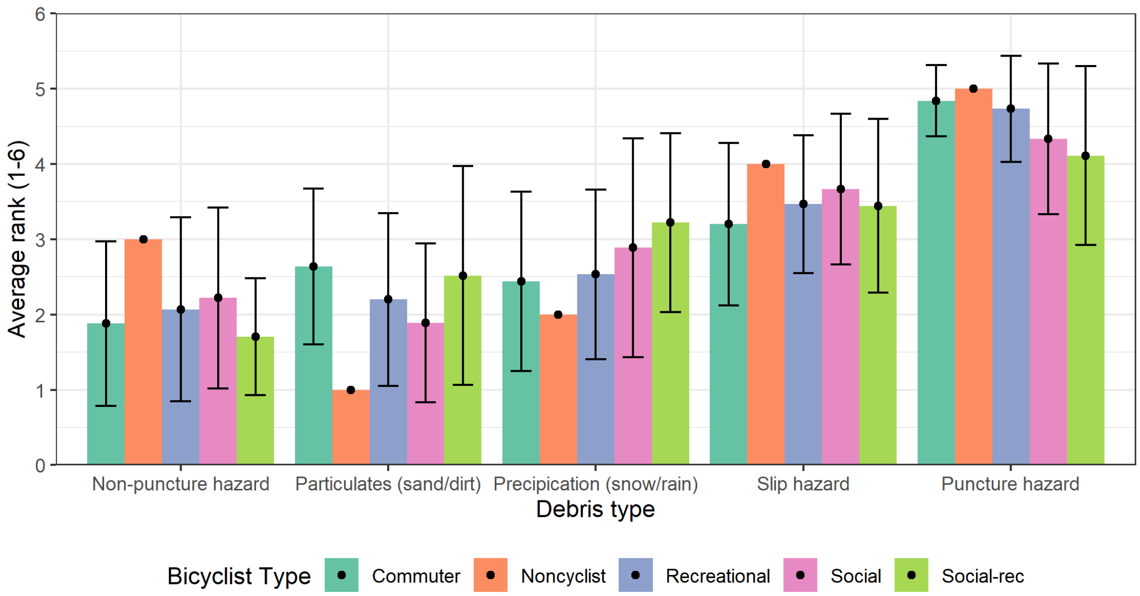


Figure 5-7: Average ranking of debris type by bicyclist type

It is recommended that BLOS methodologies and municipalities prioritize those types of hazards above general cleanliness of bike lanes. Regarding the actual measurement of such hazards, users were asked which type of measurement they believe to be most appropriate for each debris type. Results are presented in Figure 5-8 and Table 5-2.

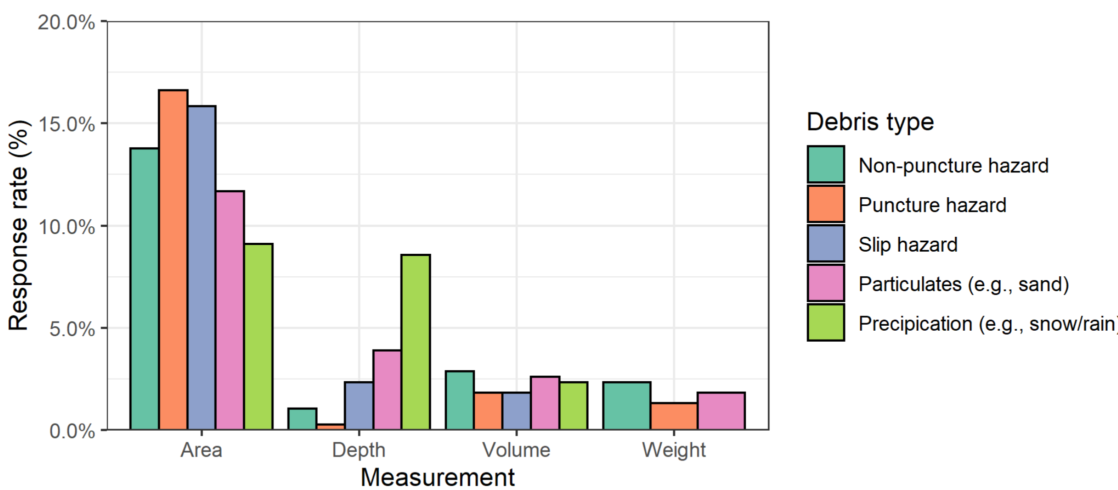


Figure 5-8: Proportion of responses for preferred measurement type by debris type

Table 5-2: Table of responses for preferred measurement type by debris type

DEBRIS TYPE	AREA	VOLUME	WEIGHT	DEPTH

NON-PUNCTURE HAZARDS	54 (14%)	11 (3%)	9 (2%)	4 (1%)
PUNCTURE HAZARDS	65 (17%)	7 (2%)	5 (1%)	1 (0%)
SLIP HAZARDS	62 (16%)	7 (2%)	0 (0%)	9 (2%)
PARTICULATES	46 (12%)	10 (3%)	7 (2%)	15 (4%)
PRECIPITATION	36 (9%)	9 (2%)	0 (0%)	33 (8%)

While street maintenance is often evaluated based on volume or weight of debris collected, debris measurement by area is the clear preference among respondents. This makes intuitive sense from a user's perspective. As more of the narrow bike lane is obstructed by debris the greater the impact, regardless of weight or volume. The once noticeable exception is with precipitation where nearly half of the respondents chose depth as a measurement. In this case, depth does make sense, particularly when the precipitation is snow. It may be recommended to use area for most debris types, with the exception of snow accumulation.

5.2.2. Separated bikeway preference

When evaluating the different bike lane buffer types (results presented in Figure 5-9), the "curb protected" image (6-inch-high curb with 3-ft horizontal buffer) was the most preferred, followed by parking protected, post-protected, raised curb, buffered (paint only), and last the standard bike lane. Unsurprisingly the standard bike lane was least preferred, which correlated with the hypothesized benefit of vertical and horizontal buffer separating bicycles from vehicles.

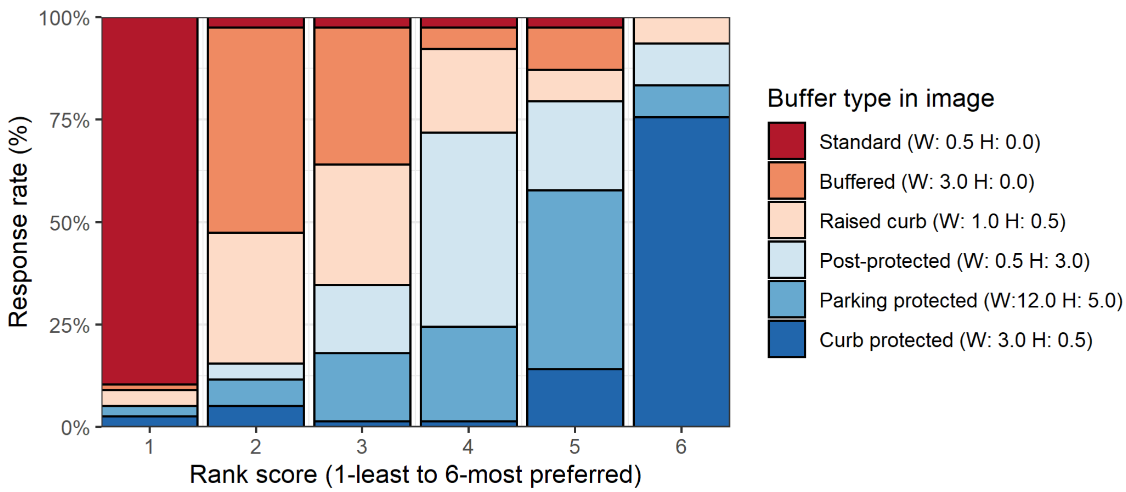


Figure 5-9: Bar chart of ranked bike lane buffer type

Shown in Figure 5-10 there is a general trend of buffer preference increasing with buffer width and height. The one major exception being the parking protected case, which offers the greatest buffer distance but is not the most preferred choice. The reason for this is not entirely clear, but possible causal factors might be a fear of "dooring" (where an automobile occupant opens a door, hitting a bicyclist) or lack of visibility.

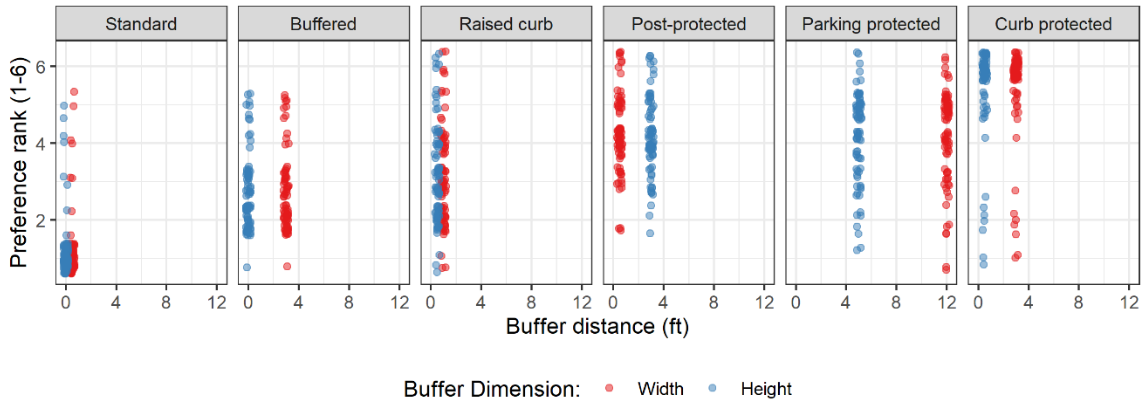


Figure 5-10: "Jitter" plot of rank versus buffer distance by buffer type

Another visualization perspective in Figure 5-11 compares the moving average ranking against vertical buffer and horizontal buffer independently. For clarity, the figure is plotted on a logarithmic scale, which reveals an interesting trend. Vertical buffer provides an immediate preference, even when the vertical width is small, while the horizontal buffer gradually increases with distance and both yields diminishing preferences.

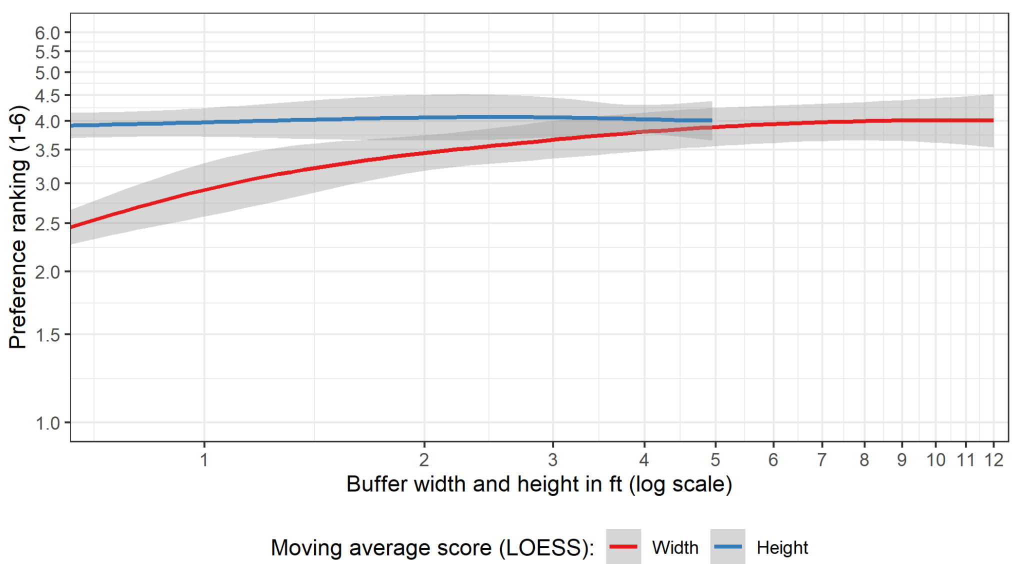


Figure 5-11: Moving average score for buffer width and height

These findings correspond with the hypothesized model formulated in Equations (7) and (8). To recall, the function is

$$W^*_{buf} = W_{max}\left(1 - e^{-(\beta_W W_{buf} - \beta_H H_{buf})}\right) \qquad \text{(if } \textit{not} \text{ parking protected)}$$

where W_{buf} and H_{buf} are the field measured buffer width and height. The remaining three terms, W_{max}, β_W, and β_H are empirically measured calibration constants. W_{max} is the maximum effective buffer possible, and β_W and β_H are the corresponding bicyclist preference coefficients.

The first parameters, W_{max}, the model assumes there is a maximum effective buffer achievable in which the vertical and horizontal buffers approach with diminishing returns in the logarithmic exponential function. To determine the maximum, the survey asked respondents for this directly in question 5b. The results are presented in Figure X with an overall average preferred buffer of 18.47 feet, or about two parked car widths.

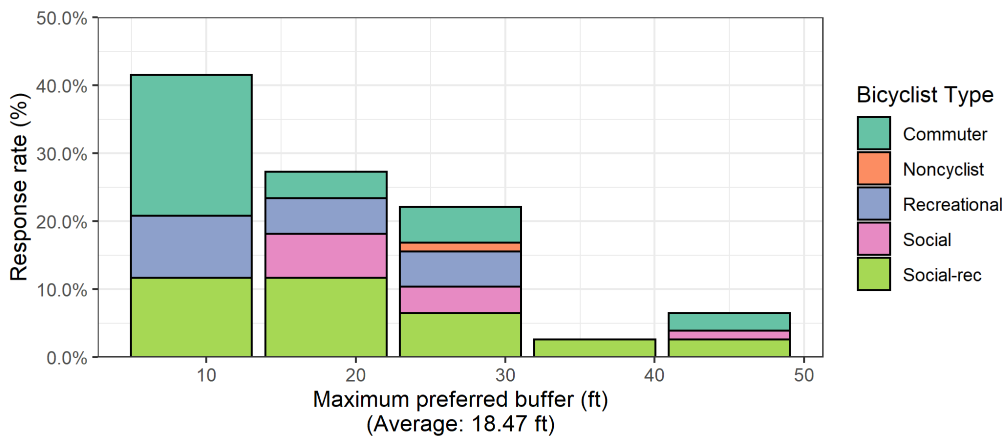


Figure 5-12: Distribution of maximum preferred buffer by bicyclist type

The remaining coefficient parameters in the model are the then estimated by fitting a rank-ordered logit model.

Logistic regression results

For research purposes, several models were estimated to explore potential confounding factors. These models include:

- Simple model with only width and height factors
- Full model with width, height, bicyclist type, bicycling frequency, gender, and age
- Conditional model with width and height by bicycling frequency
- Conditional model with width and height by bicyclist type

In the simple model in Table 5-3, only buffer height and width are considered factors in the model. The regression results show that height is a significant factor (with 99% confidence) in ranked preference but width is not. A potential confounding factor is the parking protected case where it was not the most preferred, despite having the greatest horizontal buffer. In any case, the estimated coefficients for width and height, β_W and β_H, are 0.013 and 0.290. This means that a vertical buffer contributes to perceived benefit at a rate 22 times more than horizontal buffer. This, of course, is within a logarithmic scale and provides diminishing returns. Nonetheless, height is substantially more important to bicyclists than a horizontal buffer.

Table 5-3: Regression Model 1: Simple width and height model

TERM	*ESTIMATE*	*STD ERROR*	*t-STATISTIC*	*P-VALUE*	
Width	0.013	0.027	0.457	0.648	
Height	0.290	0.063	4.640	4.55E-06	***
Intercepts:					
1/2	-1.215	0.137	-8.852	1.82E-17	***
2/3	-0.211	0.121	-1.745	0.082	*
3/4	0.580	0.127	4.583	5.90E-06	***
4/5	1.353	0.141	9.626	4.03E-20	***
5/6	2.292	0.164	13.963	2.98E-37	***

For a broader analysis, all demographic variables are included in the regression model presented in Table 5-4. In this model, none of the demographic variables were significant contributors to the model on their own. The width and height coefficients also remained relatively unchanged.

Full model

Table 5-4: Regression model 2: Fully demographic variable model

TERM	*ESTIMATE*	*STD ERROR*	*t-STATISTIC*	*P-VALUE*	
Width	0.012	0.027	0.450	0.653	
Height	0.291	0.063	4.649	4.38E-06	***
Age	0.001	0.006	0.099	0.921	
Bicyclist type:					
Non-cyclist	0.156	0.905	0.172	0.863	
Recreational	0.035	0.279	0.127	0.899	
Social	0.070	0.531	0.133	0.895	
Social-recreational	-0.015	0.281	-0.054	0.957	
Bicycling Frequency:					
Monthly	0.016	0.334	0.049	0.961	
Rarely	-0.014	0.553	-0.026	0.979	
Weekly	0.016	0.251	0.065	0.948	
Gender:					
Male	-0.010	0.202	-0.051	0.960	
Non-binary / Non-conforming	-0.054	0.746	-0.073	0.942	
Prefer not to say	0.023	0.468	0.049	0.961	
Intercepts:					
1/2	-1.174	0.335	-3.502	5.08E-04	***
2/3	-0.170	0.329	-0.517	0.605	
3/4	0.621	0.332	1.870	0.062	*
4/5	1.395	0.338	4.123	4.45E-05	***
5/6	2.334	0.349	6.682	6.91E-11	***

A more robust model is to consider the conditional dependency that bicyclist frequency and type has on the height and width coefficients. Results presented in Table 5-5 and Table 5-6 show bicycle type and frequency have and interacting effect on the height parameter. This means that depending on the category of bicyclist, a vertical buffer may be more or less important. However, overall a similar trend to the simple case is seen where height is generally much more important than width.

Conditional model: Bicycling frequency

Table 5-5: Regression model 3: Conditional bicycling frequency

TERM	*ESTIMATE*	*STD ERROR*	*t-STATISTIC*	*P-VALUE*	
Width by Bicycling Frequency:					
Width | Daily	0.043	0.043	1.006	0.315	
Width | Monthly	-0.048	0.063	-0.765	0.445	
Width | Rarely	-0.122	0.082	-1.492	0.136	
Width | Weekly	0.054	0.048	1.128	0.260	
Height by Bicycling Frequency:					
Height | Daily	0.199	0.094	2.122	0.034	**
Height | Monthly	0.384	0.137	2.812	0.005	***
Height | Rarely	0.623	0.179	3.487	0.001	***
Height | Weekly	0.246	0.104	2.360	0.019	**
Intercepts:					
1|2	-1.228	0.138	-8.929	1.04E-17	***
2|3	-0.221	0.121	-1.819	0.070	*
3|4	0.576	0.127	4.539	7.24E-06	***
4|5	1.358	0.141	9.622	4.37E-20	***
5|6	2.313	0.165	13.986	2.81E-37	***

Table 5-6: Regression model 4: Conditional bicyclist type

TERM	ESTIMATE	STD ERROR	t-STATISTIC	P-VALUE	
Width by Bicyclist Type:					
Width | Commuter	0.028	0.046	0.600	0.549	
Width | Non-Cyclist	0.306	0.288	1.060	0.289	
Width | Recreational	0.073	0.062	1.186	0.236	
Width | Social	-0.217	0.085	-2.555	0.011	**
Width | Social-Recreational	0.023	0.045	0.497	0.619	
Height by Bicyclist Type:					
Height | Commuter	0.251	0.101	2.470	0.014	**
Height | Non-Cyclist	0.192	0.495	0.387	0.699	
Height | Recreational	0.242	0.131	1.853	0.065	*
Height | Social	0.788	0.189	4.162	3.77E-05	***
Height | Social-Recreational	0.237	0.099	2.387	0.017	**
Intercepts:					
1|2	-1.230	0.138	-8.920	1.13E-17	***
2|3	-0.222	0.122	-1.823	0.069	*
3|4	0.575	0.127	4.524	7.75E-06	***
4|5	1.363	0.142	9.616	4.66E-20	
5|6	2.330	0.167	13.992	2.81E-37	

Empirically fit model

Combining the estimated parameters W_{max}, β_W, and β_H, into the effective buffer function from Equation (7), it can be visualized as separate components in Figure 5-13.

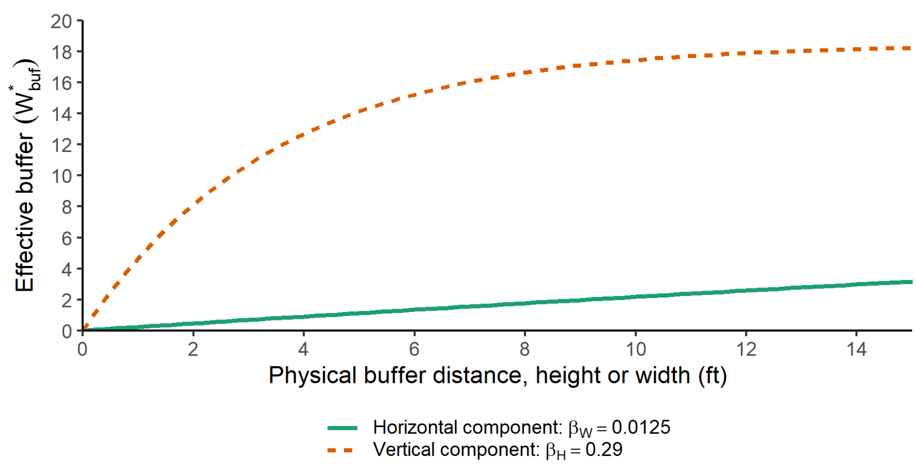


Figure 5-13: Functional form of width and height variables in effective buffer model

It is clear the horizontal buffer provides a small contribution to the effective buffer and is almost linear, which makes intuitive sense since it is effectively converting combined vertical-horizontal into an effective horizontal buffer. However, the vertical buffer provides a huge amount of benefit initially before gradually decreasing. The combined effect of the two buffers contribution to effective buffer is shown in Figure 5-14.

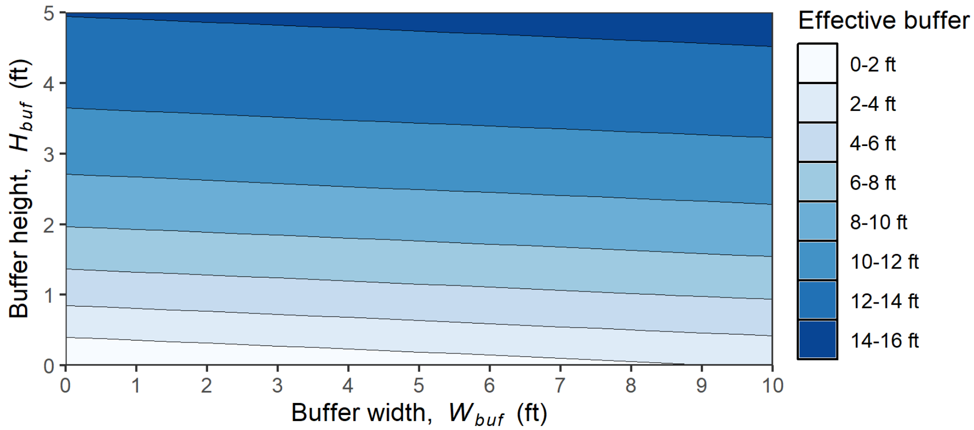


Figure 5-14: Combined functional form for width and height in effective buffer model

This combined effect then translates to an improvement in BLOS score. Figure 5-15 shows the BLOS cross sectional factor as horizontal and vertical buffer vary. A larger LOS value in the HCM is a worse score, thus the larger the negative value means the greater the LOS score improvement.

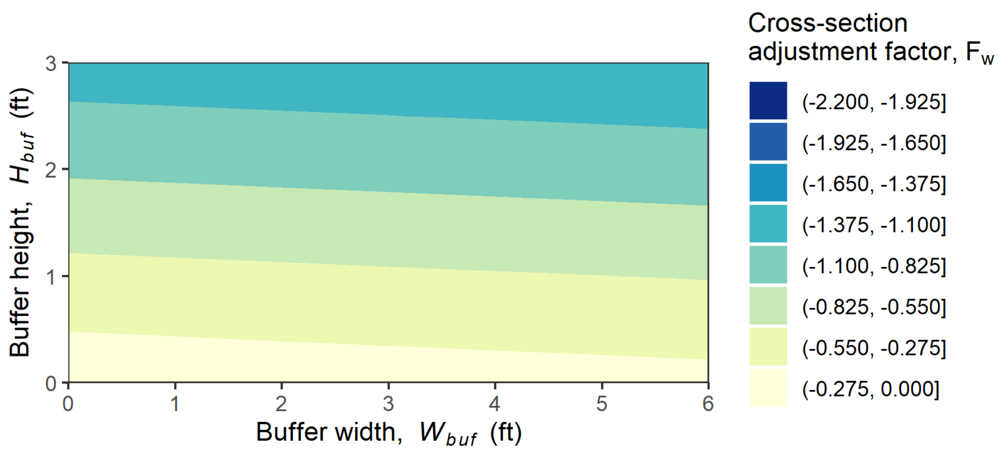


Figure 5-15: Combined effect of width and height on BLOS cross sectional adjustment factor

5.3. Discussion

While the survey sample size was only 77 respondents, the results provide both vital quantitative empirical estimates as well as useful qualitative insights. Key findings include:

- Equal weighted pavement quality criteria
- Safety related debris are most important
- Debris should be measured by area, unless snow
- Solid green lanes are most preferred
- Maximum effective buffer is approximately two car widths (18 ft)
- Height buffer is much more important to bicyclists and horizontal buffer

The pavement quality criteria (structural, functional, maintenance) are of relatively equal ranked importance. There was no clear agreement among respondents and no criteria was significantly different than the other. It is difficult to explain this outcome, but it is possible that the question was not entirely clear, causing respondents to have varied opinions. For example, a respondent may rank "structural" as most important from an infrastructure perspective, but "maintenance" might be more important from a user's perspective. In contrast to criteria, most respondents ranked the bike lane visibility images in a similar order with each other. The most faded bike lanes being the worst ranked and the bright lines the highest rank. A clear trend is that the solid green lane is most visible/preferred overall, even if faded.

Regarding debris types, it was clear that safety-related debris are most important with puncture and slip hazards as ranked most important to bicyclists. This makes intuitive sense and is an important consideration for LOS guidelines when evaluating bike lane maintenance. All debris are not equal, cleanliness of bike lanes must include type of debris. For example, broken glass is much more critical than sand in the bike lane. When evaluating debris in bike lanes, respondents consistently chose "area" as the most appropriate measurement for evaluating debris in bike lanes, with the one exception being precipitation (i.e., snow). This makes intuitive sense as debris effectively reduces the usable bike lane area. Snow differs in that the impact of snow depends upon snow depth. For example, a light dusting that covers the entire bike lane is less critical than 6 inches of snow covering the same area.

The effective buffer function was able to be calibrated from the survey data with a maximum effective buffer of 18 feet (approximately two car widths), and coefficients for width and height of 0.013 and 0.290, respectively. This means that height is substantially more important to bicyclists than horizontal buffer alone. However, these results are an oversimplification. It is likely that these results will vary depending on bicyclist type and bicycling frequency (e.g., confidence and experience). The survey results are also very limited in extent with only six facilities shown and only 77 respondents. This yielded a modest overall goodness of fit with a pseudo-Nagelkerke R^2 of 0.11, which is reasonable considering the psychological context and limited sample size but is still low. Moreover, only height was found to be a significant factor which may be due to the confounding factor of the parking-protected case. One respondent noted that despite the greater vertical and horizontal buffer provided by parking protected lanes, they dislike them due to fear of "dooring". Despite the limited scope of this survey, the results provide crucial design and policy recommendations. Height of buffer is much more preferred to width separation only, but with diminishing returns and with contextual limitations (e.g., parking protected).

SECTION 6. DISCUSSION

The following subsections summarize the research findings from the development of improved methodology and applications of control strategies and outlines next steps in the ongoing research project.

6.1. Research Findings

6.1.1. Improving HCM Bicycle LOS Methodology

A. Accounting for Protected lanes, Traffic Exposure, and Delay in Bicycle LOS

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 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 [4], 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. Further study is needed to address these calibration and validation issues.

B. Improved Pavement Quality Index

The proposed synthesized Pavement Quality Index scoring matrix aims to fill in the qualitative gaps that exist in the current HCM Pavement Quality Index, applied in the calculation of bicycle LOS.

With the existing subjective quality index, it is difficult to eliminate bias and guarantee objective, reproducible results between evaluators. Given the impact that the Pavement Quality Index score has on segment LOS it is crucial that the matrix is modified to offer a more robust, rigid baseline to encourage empirical analysis. The key elements highlighted are direct functionality, structural integrity, and maintenance factors. Each category is fundamental to the bicyclist experience and can be an indicator of use and accessibility of bike paths. The proposed data-driven matrix is not only a tool for more consistent and objective bikeway comparison, but also a reminder of important factors to consider during people-centric design.

While this current proposed framework provides a substantially expanded pavement quality scoring matrix, it can be continually modified to include additional considerations such as modified cut-offs, weight factors and new sub-categories. The proposed cut-offs between different classifications are a result of literature reviews and researcher judgement. However, the basic framework can be easily modified as additional literature is published with new findings. For example, the cut-offs between different classifications could be refined through user survey (e.g., field survey of bicyclists) or expert survey (e.g., survey of prominent researchers and practitioners). Furthermore, empirical weight of relative importance for each element in the framework could also be determined through surveys.

C. Survey Calibration Results

Results from the survey calibration yield the following key results:

- PQI criteria Structural, Maintenance, and Functionality are of relatively equal weight
- Safety related debris are most important (e.g., puncture and slip hazards)
- Debris should be measured by area, unless snow (e.g., percent of bicycle lane covered)
- Solid green lanes are most preferred and most visible to users
- Maximum effective buffer is approximately 18 ft (about two car widths)
- Height buffer (β_H=0.290) is much more important to bicyclists and width buffer (β_W=0.013)
- Despite having greatest vertical and horizontal buffer, parking-protected lanes were not most preferred.

Although these results are limited and simplistic, they provide clear and critical instruction for the design and evaluation of bicycle facilities.

6.1.2. Development and Testing Signal Control Strategies

Arterial Optimization for Without Private Vehicles

A novel approach was used to optimize the signal settings along Market Street a major corridor in downtown San Francisco for buses without private vehicles. The method is based on SYNCHRO software and a practical method implemented in Microsoft Excel. The results indicate that the optimization resulted in significant reductions in intersection delays for busses without adverse impacts on the cross streets.

Transit Signal Priority

We implemented several TSP scenarios on Geary corridor, a major arterial in San Francisco served by the two transit lines on the transit-only lane. Findings indicate that FSP provides significant benefits to the busses intersection delay without significant adverse impacts to private vehicles.

6.1.3. Ongoing Work

The following research activities will be performed during the remaining time of performance in the project:

Application and Testing of Methodologies

The developed improvements for the estimating the bicycle level of service will be tested in real world test sites to determine if they are improving the accuracy and robustness of the HCM methodology.

Two test sites have been selected with actual implementation of complete streets approach:

- Hearst Avenue, Berkeley, CA
- Colorado Blvd, an arterial with eight signalized intersections in Pasadena, CA

Dissemination of the improved methodology: Currently, the proposed methodology 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/MMLOS with a user guide and simple tutorial. Additional forms of dissemination will be discussed.

Emerging Technology: Testing of Bicycle Detection and Priority at Intersections

Emerging technologies include the connectivity V2X between the infrastructure (intersection-I) and the user (vehicle, pedestrian, bicyclist X) to provide real-time dynamic green to each user class based on real- time information. The California connected vehicles (CV) test bed in Palo Alto [10] provides the opportunity for testing control strategies for complete streets. The test bed consists of 11 signalized intersections along the El Camino Real arterial. Recently, the Multi Modal Intelligent Traffic Signal System (MMITSS) [11] originally developed by the University of Arizona for FHWA was tested at a test bed signalized intersection for transit signal priority.

Development and testing of a bicycle signal priority system at a signalized intersection at a corridor was planned for 2020. Currently a bicycle sensor has been purchased and installed at the intersection of El Camino Real and Stanford Avenue, located close to Stanford University Campus. It was expected that sensor operator will complete sensor installation by end of October 2020, with field testing of bicycle priority in the early spring of 2021 but data collection was impacted due to COVID-19 with ongoing delays.

Calibration of proposed BLOS and PQI methodology using web-survey

A web-based survey has been designed and disseminated throughout local and national traffic safety and bicycle advocacy organizations. These data are used to calibrate and validate the proposed BLOS methodological improvements for separated bike lanes and pavement quality ratings based on bicyclist preference. The experimental design of the survey utilized a rank-ordered approach to minimize respondent bias as well as to estimate quantitative parameters for the effective buffer model using an ordered logistic regression, also called a Proportional Odds Log Ratio (POLR) regression model. At current date, a total of 77 survey respondents have participated and results have been analyzed and are presented in Section 5.

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