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Accessible Bus Stop Design in the Presence of Bike Lanes

Principal Investigator (s)
Eleni Christofa
Chengbo Ai
Peter Furth

University of Massachusetts Amherst
Northeastern University

Research and Technology Transfer Section
MassDOT Office of Transportation Planning

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16. Abstract
Floating bus stops are used to facilitate transit operations and enhance accessibility by allowing in-lane stops. A bike channel separates the platform from the sidewalk, preventing conflicts between buses and bicycles but potentially causing conflicts between bicyclists and bus riders. The objectives of this research are to: 1) investigate bus rider and bicyclist behavior and interactions at floating bus stops, and 2) propose design improvements and guidance to enhance accessibility and mitigate conflicts between bus rider of all abilities and bicyclists. This study utilized multiple methods including focus groups, professional community outreach, and a field study. Community and professional outreach contributed to an understanding of challenges associated with floating bus stops especially for transit riders with visual, hearing, and mobility impairments and assisted with a summary of lessons learned from other cities that have a history of implementing floating bus stops. LiDAR and video cameras were employed at five bus stops in the Greater Boston area to capture trajectory data for both bicyclists and bus riders, along with bus stop inventory data. All of this information was used to develop design recommendations that improve safety and accessibility for all users, as well as a step-by-step system-wide procedure for assessing existing floating bus stops and suggesting improvements. Recommendations include various types of infrastructural interventions (e.g., platform width, bike lane deflection, fencing, and signage) that are effective in increasing separation between bicyclists and transit users, managing bicyclist speeds, and facilitating wayfinding.

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Accessible Bus Stop Design in the Presence of Bike Lanes

Final Report

Prepared By:

Eleni Christofa, Ph.D.
Principal Investigator

Chengbo Ai, Ph.D.
Co-Principal Investigator

Peter Furth, Ph.D.
Co-Principal Investigator

Yu-Min Yang
Graduate Research Assistant

Dewan Tanvir Ahammed
Graduate Research Assistant

Nathan David Obeng-Amoako
Graduate Research Assistant

Prepared For:

Massachusetts Department of
Transportation Office of
Transportation Planning
Ten Park Plaza,
Suite 4150 Boston,
MA 02116

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Disclaimer

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Executive Summary

This study of Accessible Bus Stop Design in the Presence of Bike Lanes was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Introduction

The ongoing and increased rate of implementation of shared and dedicated bike lanes, raised cycle tracks, and other bike infrastructure that is adjacent to MBTA bus stops has a direct impact on transit riders' experience and safety. This is critical considering that MBTA's service area includes 8,000 bus stops in 51 communities. The recent introduction of floating bus stops, which incorporate a bike lane behind a bus stop, requires transit riders to cross an active bike lane to access the bus boarding area, increasing the likelihood of bicyclist-rider conflicts and introducing accessibility concerns.

Floating bus stops are also referred to as curbside bus stops or bus islands and often include a raised platform that allows people to get on and off the bus. One goal of these bus stops is to prevent conflicts between bicyclists and buses. There are three types of floating bus stops as seen in Figure 1:

1) full-width floating bus stop that includes a platform with a width of 8 feet or wider,
2) a partial-width floating bus stop with a platform that is less than 8 feet wide, and
3) the no platform floating bus stop, also known as a constrained bus stop based on the MassDOT Separated Bike Lane Planning & Design Guide.

Besides the platform width or presence of a platform, partial-width and no platform floating bus stops also differ in the location of the bus stop shelter on the sidewalk versus the platform for full-width floating bus stops.

The goal of this project is to provide a better understanding of the impacts of floating bus stops on transit user safety (e.g., conflicts between bicycles traveling on adjacent bike lanes and transit riders), and accessibility and the exploration of design elements that will support an accessible, equitable, and safe travel experience for all riders. The objectives of this project are:

1) investigate bus rider and bicyclist behavior and interactions at floating bus stops, and

2) propose design improvements and guidance to enhance accessibility and mitigate conflicts between bus riders of all abilities and bicyclists.

The goal of this project is to develop guidelines for floating bus stop design that municipalities can implement when designing bus stops in their jurisdictions.

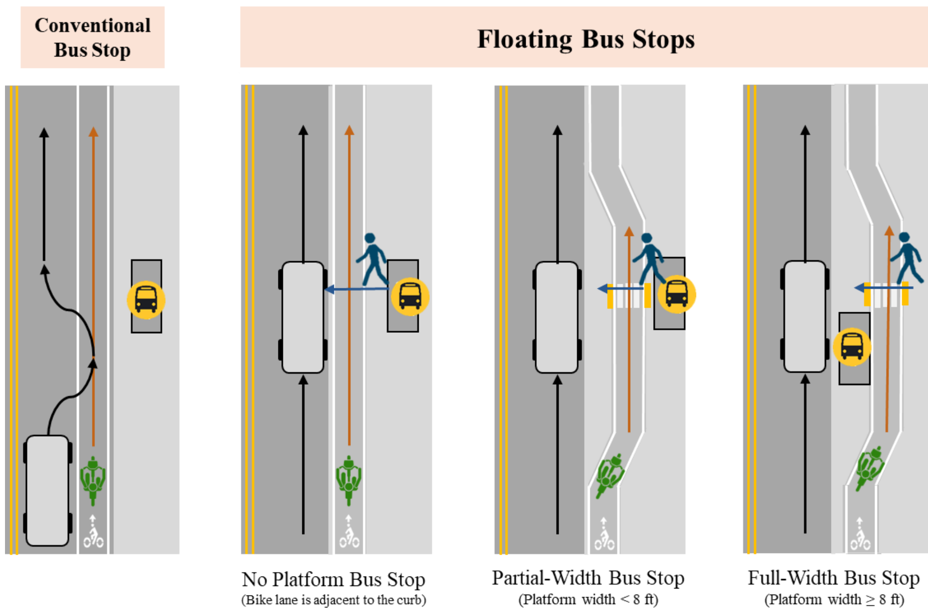

Figure 1: Conventional and floating bus stops

Research Methodology

The research methodology consists of an inventory of floating bus stops, literature review, user and professional community input, a field study, and recommendations. The floating bus stop inventory was created through manual observations and field visits to summarize design characteristics of 56 floating bus stops in the MBTA's service area. Light Detection and Radar (LiDAR) scans of five floating bus stops in the Greater Boston area were also used to supplement this inventory with additional element dimensions. The inventory was followed by a comprehensive review of agency reports and guidebooks related to bicycle and transit infrastructure design to understand the state-of-practice on floating bus stop design. Focus groups with transit riders from the disability community allowed for a better understanding of their challenges with navigating floating bus stops. Professional community input was received through an email that was sent to the Association of Pedestrian and Bicycle Professionals listserv and interviews with city officials and representatives of engineering and planning firms that have that have worked with cities that are at the forefront of integrating bus stops and bicycle infrastructure and developing design guidelines for those in the United States and internationally. Professional input furthered our understanding of guidelines, practices and lessons learned regarding the design of bus stops next to bike lanes. A field study conducted with the use of LiDAR and video cameras at five floating bus stops enabled trajectory data collection of bicyclists, transit riders, and other pedestrians. This study also facilitated manual observations through the video recordings to further study bicyclists and transit rider behaviors, including their interactions around floating bus stops. Lastly, recommendations for a methodology that can be used by transit agencies to assess all their floating bus stops for improved safety and accessibility, including data collection recommendations, are provided.

Results

Floating Bus Stops Inventory

An inventory of 56 floating bus stops was created, and its analysis revealed that most floating bus stops in the Greater Boston area are full-width bus stops (45%), followed by partial-width bus stops (32%) and no platform bus stops (23%). Eighty-three percent of partial-width platform bus stops and 69% of the no platform bus stops feature no bus stop shelter. The inventory also revealed that bus stop signs are rarely adjacent to the shelters (in only 4% of the cases), while fencing is present in only 38% of the full-width and 22% of the partial-width platform bus stops. Tactile pavement, used for wayfinding and to indicate crosswalks across bike lanes, was very common for full-width platform bus stops (80%). The partial-width bus stops have the highest percentage of both signs and markings near crosswalks (61%), and the no platform bus stops have the highest percentage of having signs only (46%). Finally, this inventory effort concluded that LiDAR scans that were used to obtained detailed dimensions of five floating bus stops in the MBTA service area, are advantageous compared to aerial image and field observations as they allow for measuring detailed dimensions of infrastructure elements, especially in the presence of vertical fixtures. Similar horizontal measurements were obtained through Google Maps and LiDAR scans.

Literature Review

A comprehensive search of the literature revealed that there are no research studies focusing on floating bus stop design and its impact on safety and accessibility, which is indicative of the lack of bicyclist and transit rider behavioral analysis performed at floating bus stops. As a result, the literature review focused on guidebooks related to transit and bicycle infrastructure design revealing that even though bicyclists are expected to yield to pedestrians who are accessing the boarding island, additional elements are needed to ensure safety and accessibility at floating bus stops such as “Bikes Yield to Pedestrians” signs and yield line markings at crosswalks, contrasting materials, or green color treatments that enhance the visibility of various elements and indicate function change. Additional guidelines include maximum slopes for platform access ramps and the installation of detectable warning strips at the edge of the sidewalk and the curb of the boarding area. International guidelines recommend wider platforms compared to the U.S. ones. In the absence of a platform, they recommend a minimum bike lane width plus 2.7 ft to allow for ramp deployment for wheelchair users. Overall, while some commonalities were found across guidebooks in the U.S. and abroad, no prevailing industry standard has been established for ensuring safe and accessible operations of floating bus stops.

Professional Community Input

Professional community input revealed many ongoing efforts by various cities and organizations to develop floating bus stop guidelines with an emphasis on how to make these bus stops safer and more accessible. Recommendations provided through the listserv focused primarily on the implementation of floating bus stops in Montgomery County, MD and Austin, TX and included the use of **audible messages** and **channelization for crosswalk wayfinding** (i.e., providing elements for wayfinding and path guidance such as fences, planters, etc.) as well as speed management strategies, such as **changes in grade** and **bollards in the middle of two-way cycle tracks**. For constrained spaces, recommendations included **narrower bike lanes and shelters**, as well as **merging bicyclists into shared-use paths with pedestrians**.

Input from the city interviews with Amsterdam, Montreal, Toronto, and professionals involved in various floating bus stop designs in Montgomery County, MD; Austin, TX; and British Columbia, Canada included design strategies for wayfinding and speed management in addition to platform-width guidelines. Platform widths vary from 7-7.8 ft for the interviewed cities, with a minimum of 5-6 ft decided upon the need to accommodate ramp implementation for wheelchair users. Wayfinding for visually impaired individuals is achieved with the use of **tactile pavement** (i.e., truncated domes) along the bike lane and at crosswalks as well as other locations connecting to the crosswalk for guiding riders to the bus boarding area; different materials can be used to differentiate between crosswalks and boarding locations. Speed management strategies used in the interviewed cites include **raising and narrowing bike lanes** and implementing **contrasting color pavement materials.** Installation of speed bumps is not allowed in Montreal while the use of shared use paths is never considered in Amsterdam. **Regulations** related to yielding to blind pedestrians are in place in Amsterdam and Montreal, while Toronto prohibits cars from passing a bus closer than 6.6 ft when it is actively boarding and alighting passengers. Lastly, **signalization of crosswalks** is being considered in Montgomery County to improve safety.

Community Outreach

Focus group participants identified challenges associated with floating bus stops especially for visually, hearing, and mobility impaired riders and provided design recommendations. The full-width platform bus stop was considered comfortable to navigate and the preferred floating bus stop type, though still in need of improvements. Partial-width platforms that have the bus stop shelter on the sidewalk were considered high-risk as they encourage crossing of the bike lane when a bus is arriving for those transit riders waiting at the shelter – this increases crash risk and makes it harder for the bus driver to see transit riders. Fencing was considered helpful for crosswalk wayfinding and improving situational awareness for pedestrians and bicyclists. Recommendations included bicycle speed management strategies (e.g**., bike lane elevation change or deflection, pavement surface or color change, signage, and lower speed limits**) in addition to wayfinding treatments such as **tactile pavement** and **pavement surface change** or **warning strips** at the edge of the bike lane. Additional recommendations include visibility of crosswalks, pedestrian-activated flashlights, shelter placement close to the bus stop sign, and audible messages at bus stops inform the riders of the type of bus stop they are aligning to.

Behavioral Analysis

Statistical analysis of the trajectory data revealed that:

- Horizontal curves on the separated bike line (i.e., adding bike lane deflection/deviation) around the bus stop location do not significantly reduce bicyclist speeds, other than for those traveling faster than 15 mph, even though only by small amounts (~1 mph) for those higher-speed riders. It should, however, be noted that due to the LiDAR sensor installation on a temporary tripod, limiting the installation height, it was not possible to obtain bicyclist speeds the straight part far in advance of the horizontal curve. This might have affected the findings of this statistical analysis.

- Fencing does not significantly reduce bicyclist speeds at the bus stop area, even for those traveling at higher speeds, but it does encourage crosswalk use, limits the duration of pedestrians walking along the bike lane and restricts potential for bicyclists to veer off to the sidewalk.

- Full-width platform bus stops were found to have a significantly higher percentage of pedestrians standing on the bike lane compared to both partial-width and no platform bus stops. While this seems counterintuitive since full-width platform bus stops offer space for transit users to wait at, it could be due to site-specific characteristics of the full-width bus stops under study and should be further explored.

- The proportion of pedestrians walking along the bike lane is significantly higher at bus stops with fences compared to those without indicating that fences do not prevent transit riders from walking along the bike lane. However, the duration of walking along the bike lane is significantly lower, which could be because fences act as a reminder the pedestrians should step out of the bike lane.

- Full-width and partial-width platforms present a statistically higher number of pedestrian crossings of the bike lane more than twice, compared to no platform bus stops. This indicates that even when full-width bus stops are present, many transit riders choose to wait for the bus on the sidewalk rather than the platform.

- High percentages of pedestrians traveling along the bike lane could be attributed to bus stop layouts, pedestrians' incentive to reduce their walking distance, and low bicyclist traffic. However, the likelihood of conflict with bicyclists was found to be low; even at the Massachusetts Avenue opposite Christian Science Center bus stop, that featured the higher bicyclist and pedestrian volumes among all studied bus stops, there were only seven bicycle-pedestrian interaction cases in 12 hours.

- Wide crosswalks encourage crosswalk use but can also result in longer crossing times as people walk diagonally across the width of the crosswalk to shorten their path of travel – this may also generate additional interactions between pedestrians and bicyclists.

Overall, further exploration is recommended to ensure that the results are not specific to these five floating bus stops.

Recommendations

Bus stop design recommendations were developed based on findings from the literature review, a synthesis of input from the professional community via a professional organization emailing list and interviews and from bus passengers through focus groups, in addition to the behavioral analysis. These recommendations are related to:

- Separation between bicyclists and pedestrians:
    - Full-width platform bus stops should be implemented when possible.
    - Fencing is helpful for physically separating passengers from bicycles, managing platform access, and encouraging crosswalk use, in addition to improving situational awareness of transit riders and bicyclists. Different pavement materials can also increase situational awareness.
    - Construct platforms with widths that present sufficient space for ramp implementation and navigation of mobility-assisting devices.

    - Narrow or divert bike lanes to convert partial-width bus stops to full-width platform bus stops

    - Relocate shelters from the sidewalk to the platform at partial-width platform bus stops by using narrower shelters.

- Bicyclist Speed Management:

    - Deflect bike lane and change its elevation to help get bicyclists' attention possibly resulting in lower speeds and higher yielding to crossing pedestrians rates

    - Narrow bike lanes.

    - Create channelization for bicyclists with flexposts and built-in ramps.

    - Implement regulations and signage/markings to manage bicyclist speeds and yielding/stopping behavior.

    - Control crossings through signals at the crossing or by incorporating them in the main signal of a signalized intersection.

- Wayfinding:

    - Align crosswalk and with boarding areas, equipped with tactile pavement, to facilitate wayfinding. The presence of fences can also contribute to wayfinding.

    - Implement detectable surfaces to differentiate sidewalk, crosswalk entrance, bike lane, platform, and boarding area.

    - Place bus stop sign poles close to the shelter or bus door.

    - Set octagon-shaped flexpost or secondary bus stop sign pole on the sidewalk to mark the crosswalk and provide bus route information to visually impaired passengers without their needing to cross the bike lane multiple times.

    - Introduce audible announcements on board of buses to assist alighting passengers with knowing they are stepping off into or have to cross a bike lane.

In addition, bus operators should be trained to look for and identify transit riders interested in boarding across the bike lane that might have opted to stay close to the shelter or secondary post, rather than next to the bus stop sign. Bus operators should also be trained to align the bus parallel to the platform to improve accessibility and safety. Lastly, two-way bike lanes or counterflow bike lanes should be avoided at floating bus stops as they introduce additional challenges for visually impaired riders' crossings.

A step-by-step assessment procedure was also developed that provides a series of questions for assessing existing bus stop conditions and providing recommendations for improved safety and accessibility. In addition, recommendations related to the data collection process point to attention to the LiDAR sensor selection and configuration so that a desirable accuracy level can be achieved, and the overlapping of multiple sensors to cover a wider area and eliminate occlusion issues.

Conclusions

This research study used multiple methods, including community engagement, professional input, and a field study to provide floating bus stop recommendations that ideally include (see Figure 2):

1) A "SLOW" stencil with colored pavement on the bike lane section approaching the bus stop area.
2) Vertical and horizontal deflection for the bike lane when approaching the bus stop area.
3) A "YIELD TO PEDS" pavement marking before each crosswalk.
4) Yield markings before crosswalks.
5) An "In Street Crossing" sign or a "Bicycle Yield to Peds" sign on the sidewalk side of each crosswalk.
6) Fences with openings only at crosswalks.
7) Crosswalks that are aligned with boarding areas and equipped with tactile pavement.
8) Platforms that are at least 8 feet wide.
9) Shelters/benches that are located on the platform.
10) A bus stop sign pole near the shelter/bench and boarding area.
11) A secondary bus stop sign pole at the sidewalk side of a crosswalk to indicate the crosswalk location for visual impaired riders and provide bus route information.

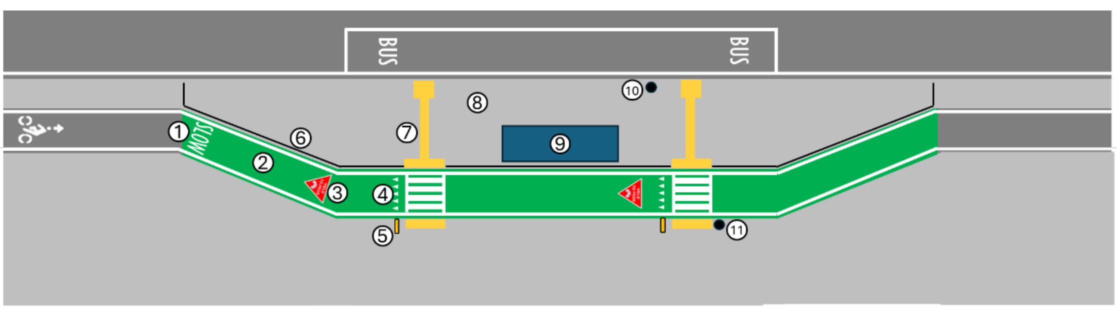

Figure 2: Ideal floating bus stop elements

Overall, this research contributes to the body of literature by:

1) Providing a clear understanding of the challenges encountered by visually, hearing, and mobility-impaired transit riders at floating bus stops,

2) Summarizing best practices across the world on the integration of separated bike lanes and bus stop infrastructure and

3) Analyzing bicyclist and transit rider behavior at various types of floating bus stops to further understand bicyclist-transit rider interactions and inform design guidelines and

4) Developing design guidelines and policy recommendations that improve the safety and accessibility of floating bus stops.

Future work should focus on improved LiDAR data filtering process, mode classification algorithm improvements, longer-term data collection at more bus stops, implementation of alternative sensing technologies to improve accuracy, and surveys that in combination with can be used to analyze correlations between bicyclist perceptions and behaviors.

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List of Acronyms

Acronym	Expansion
ADA	Americans with Disabilities Act
AC Transit	Alameda Contra-Costa County Transit
BRT	Bus Rapid Transit
FHWA	Federal Highway Administration
LiDAR	Light Detection and Ranging
MDOT	Maryland Department of Transportation
MassDOT	Massachusetts Department of Transportation
MBTA	Massachusetts Bay Transportation Authority
NACTO	National Association of City Transportation Officials
RTAG	Riders' Transportation Access Group
RRFB	Rapid Rectangular Flashing Beacons
TDI	Tactile Directional Indicators
US	United States

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1.0 Introduction

The Massachusetts Bay Transportation Authority (MBTA) operates 8,000 bus stops in 51 communities in eastern Massachusetts. Bus stop design and construction requires careful utilization of available sidewalk and road space so that all users, i.e., pedestrians, transit users, bicyclists, and motorists are efficiently and safely accommodated in often space-constrained locations. Recent improvements in multimodal policy and design guidelines have led to a marked increase in dedicated bike infrastructure, which are often located adjacent to MBTA's bus stops, having a direct impact on transit riders' experience and safety. While these design improvements have generally resulted in safer or more reliable biking and bus experiences, very little research or guidance exists for designing bus stops that are neighboring bike lanes. More specifically, there is a need to develop design guidelines that meet accessibility needs and provide a high-quality customer experience for transit riders, while simultaneously providing space for safe biking along bus corridors. Ultimately, the goal of this research project is to provide a consistent approach for municipalities to pursue bus stops within the sidewalk space.

1.1 Floating Bus Stops

This research project focuses on improving the design of floating bus stops. The MBTA's service area currently consists of at least 56 floating bus stops, making the need for the development of design guidelines for these types of bus stops a necessity. Floating bus stops are separated from the sidewalk with a bike channel; see Figure 1.1. Because the boarding and alighting area is separated from the rest of the sidewalk area by the bike lane, it is referred to as a floating bus stop [1]. Floating bus stops are also referred to as curbside bus stops or bus islands and often include a raised platform that allows people to get on and off the bus.

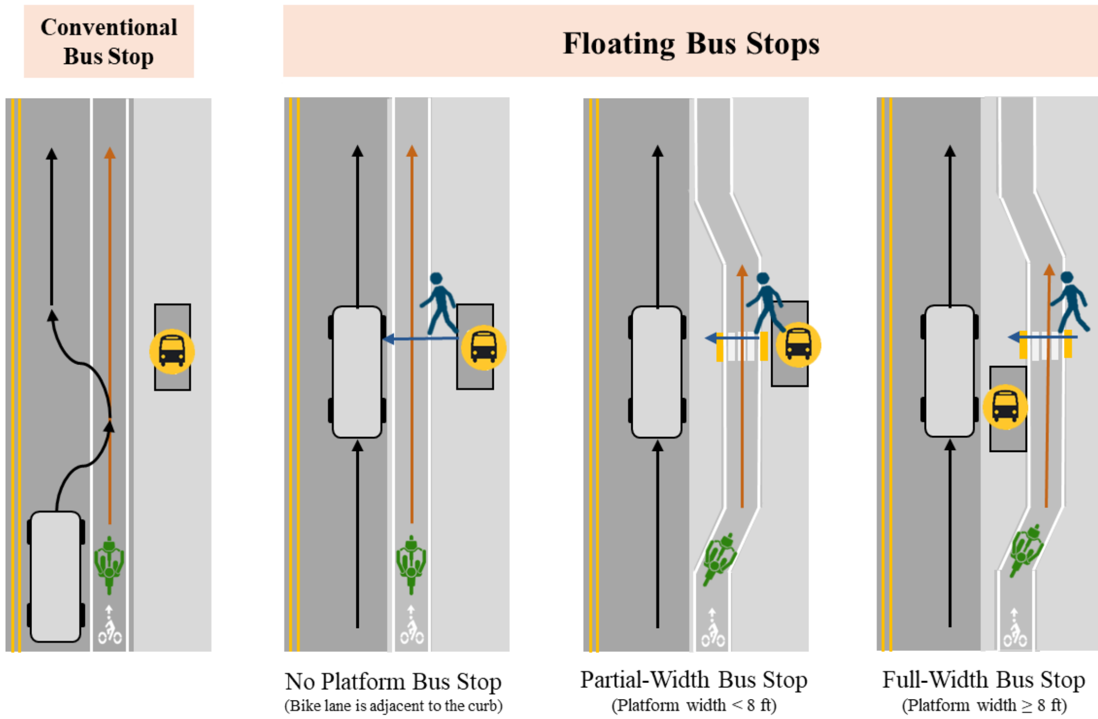


Figure 1.1: Conventional and floating bus stops

Floating bus stops are most often utilized when separated bike lanes are provided along a street, but they can also be used alongside other bike lane configurations to avoid bus-bike conflicts during boarding and alighting of transit passengers, especially when bicyclist volumes are high [1]. These bus stops are common in situations where there is insufficient space for a bus to pull over to the curb or when conflicts over space with other modes of transportation must be avoided.

There are three types of floating bus stops based on the presence of a platform next to the bike lane and the width of that platform, as shown in Figure 1.1:

1) full-width floating bus stops that include a platform with a width of 8 feet or wider,

2) partial-width floating bus stops with a platform that is less than 8 feet wide, and

3) no platform floating bus stops, also known as constrained bus stops based on the Massachusetts Department of Transportation Separated Bike Lane Planning & Design Guide [3].

When space constraints prevent the installation of a full-width floating bus stop and passenger boarding and alighting demand is relatively low, a part of the boarding and alighting area can be designated for shared use with the neighboring bike lane, i.e., no platform floating bus stops. In this configuration, the bike lane gradually rises to match the height of the sidewalk and maintains the elevation for the duration of the bus stopping zone. In some cases, terminating the bike lane and incorporating a dedicated bike ramp to assist a smooth transition to a shared-use path at the transit stop may be useful [1]. Another key difference between the full-width platform and the other two designs is the location of the bus shelter, which for the partial-width and no platform bus stops is on the opposite side of the bike lane compared to where the bus stops.

1.2 Research Problem Statement

Floating bus stops are beneficial in that they eliminate conflicts between transit vehicles and bicycles at stops [1], [2]. However, they introduce conflicts between transit riders and bicyclists as riders have to cross the bike lane to reach the bus stop for waiting and boarding as well as when alighting from a bus. This is particularly challenging for individuals with low or no vision and those with hearing impairments. When a platform is present, navigating the platform while boarding and alighting or even waiting for the bus introduce challenges for users of wheeled mobility devices, due to space constrains limiting their mobility and complicating their boarding and alighting processes.

There is a pressing need for a better understanding of the impacts of bicycle infrastructure on transit user safety (e.g., conflicts between bicyclists traveling on adjacent bike lanes and transit riders), on bus stop accessibility and the exploration of mitigation plans and designs that will ensure an accessible, equitable, and safe travel experience for all riders. The objectives of this project are to:

1) investigate bus rider and bicyclist behavior and interactions at floating bus stops, and

2) propose design improvements and guidance to enhance accessibility and mitigate conflicts between bus riders of all abilities and bicyclists.

1.3 Research Approach

To achieve the research objectives, a multitude of methods was engaged. First, an inventory of floating bus stops in the MBTA service region was created starting with a database maintained by the MBTA and supplemented with information that was collected via aerial imagery and field visit observations. Specific design characteristics of five floating bus stops were also obtained using a Light Detection and Ranging (LiDAR) sensor.

Next, a thorough review of the state of practice was performed to develop an in-depth understanding of design guidelines and learn from existing implementations, whether successful or not. The review of the literature was supplemented with focus groups with individuals from relevant communities as well as with professionals from the transportation engineering and planning communities through email responses to and interviews. Interviews with professionals and emailing outreach to professional groups were pursued to complement knowledge obtained through guidebooks and deepen our understanding of the state of practice. Focus groups with individuals representing the visually impaired, hearing impaired, and mobility-impaired communities were performed to understand specific challenges associated with these types of bus stops as experienced by those individuals.

A field study was also completed to obtain information on transit rider and bicyclist behavior at five bus stops in the Greater Boston area. A LiDAR sensor and a video camera were used to collect data from these five floating bus stops and the data was used to analyze the behavior of bicyclists and transit riders as well as their interactions. In addition to manual observations through the video recordings, nine research questions were formulated and tested using statistical methods to understand the impacts of different designs on bicyclist and transit rider behavior and, ultimately, on their safety.

Findings from the inventory, literature review, email responses, interviews, focus groups, and behavioral analysis were used to develop design recommendations for floating bus stops as they pertain to both bicycle and transit infrastructure. A step-by-step process for system-wide bus stop assessment was also developed to guide inventory and overall assessment of floating bus stops within MBTA’s and other transit agencies’ networks to support safety improvements for all users.

1.4 Report Organization

The rest of the report is structured as follows:

- Chapter 2 discusses this project's methodology, including the data collection process for the floating bus stop inventory creation, the literature review, the community outreach efforts, both user and professional (i.e., focus groups, email responses, and interviews), as well as the data collection methods and the analysis plan for the behavioral analysis.
- Chapter 3 presents the findings of the inventory, literature review, community outreach, and behavioral analysis.
- Chapter 4 summarizes the practical outcomes derived from the analysis findings, including design recommendations and the step-by-step process for system-wide bus stop assessment.
- Finally, Chapter 5 presents a summary of this study’s findings and proposes future work.

2.0 Research Methodology

The research methodology includes six parts: 1) an inventory of floating bus stops in the Greater Boston area; 2) a comprehensive literature review of agency reports, and guidebooks from the United States and internationally; 3) community outreach through focus groups with transit riders representing the visually, hearing, and mobility impaired communities; 4) interviews with city officials and representatives of engineering and planning firms as well as email responses through a professional listserv; 5) behavioral analysis at five selected floating bus stops in the Greater Boston area, and 6) recommendations on floating bus stop design and methods for a network-wide assessment of the safety and accessibility of floating bus stops.

2.1 Floating Bus Stop Inventory

The research team collected the inventory information for all floating bus stops in the Greater Boston area by using both the online street view services from Google Maps, Bing Maps, and Apple Maps and through field visit observations. The information collected focused on addressing the following questions below:

1. *Platform width? Measure and record the platform width. If there are no platforms at the bus stop, record 0.*

2. *Number of boarding areas? Record the number of boarding areas. Record 0 if there are no boarding areas at the bus stop.*

3. *Size of the boarding areas? Measure the length and width of the boarding areas and record the value. Record 0 if the value of the previous question is 0.*

4. *Is there a shelter? Yes, if there was a shelter at the bus stop, No otherwise.*

5. *Where is the shelter? P if the shelter is located on the platform, S if the shelter is located on the sidewalk, N if the previous question recorded No.*

6. *Brick pavement? Yes, if there is brick pavement in front of the shelter, No otherwise.*

7. *Where is the bus stop sign? P if the bus stop sign is located on the platform, S if the bus stop sign is located on the sidewalk, and N if there is no bus stop sign.*

8. *Is the bus stop sign adjacent to the shelter? Yes, if the bus stop sign is adjacent to the shelter; No, otherwise.*

9. *Is there a fence? Yes, if there is a fence on the platform; No, otherwise.*

10. *What is the number of openings in the fence? Record the number of openings in the fence.*

11. *Is there a bench? Yes, if there is a bench on the platform or sidewalk; No, otherwise.*
12. *Audio announcement? Yes, if the bus stop has audio announcements; No, otherwise.*
13. *Bike lane width? Measure and record the bike lane width.*
14. *Green pavement for the bike lane? Yes, if the bike lane is green-colored; No, otherwise.*
15. *Direction of the bike lane? One, if there is a one-way bike line, and two, if there is a two-way bike lane,*
16. *Number of crosswalks? Record the number of crosswalks at the bus stop. Record 0 if there are no crosswalks at the bus stop.*
17. *Tactile pavements? Yes, if there is tactile pavement at the two ends of the crosswalk; No, otherwise.*
18. *Number of yield signs? Record the number of yielding signs on the bike lane at the bus stop location. Record 0 if there are no yield signs.*
19. *Number of yield markings? Record the number of yield markings on the bike lane at the bus stop location. Record 0 if there are no yield markings.*
20. *Number of pedestrian warning signs? Record the number of pedestrian warning signs on the bike lane at the bus stop location. Record 0 if there are no pedestrian warning signs.*
21. *Tree obstructions? Yes, if there are trees on the sidewalk that could potentially be blocking pedestrians' right-of-way; No, otherwise.*
22. *Bike racks? Yes, if there are bike racks at the bus stop providing legal parking space for bicycles; No, otherwise.*

In addition to the comprehensive inventory using publicly available data, e.g., Google Maps and Streetview imagery, and field observations, the research team collected detailed terrestrial LiDAR scan data using the Riegl VZ-2000 scanner for the five study sites identified in the following section. Besides the abovementioned information, the point cloud data derived from the terrestrial LiDAR scan can provide detailed geometry with more accurate measurements, such as the platform's width, bike lane's width, etc. Figure2.1 shows a picture of when the LiDAR was scanning the testing site at Broadway at Horizon Way Street and the corresponding point cloud data.

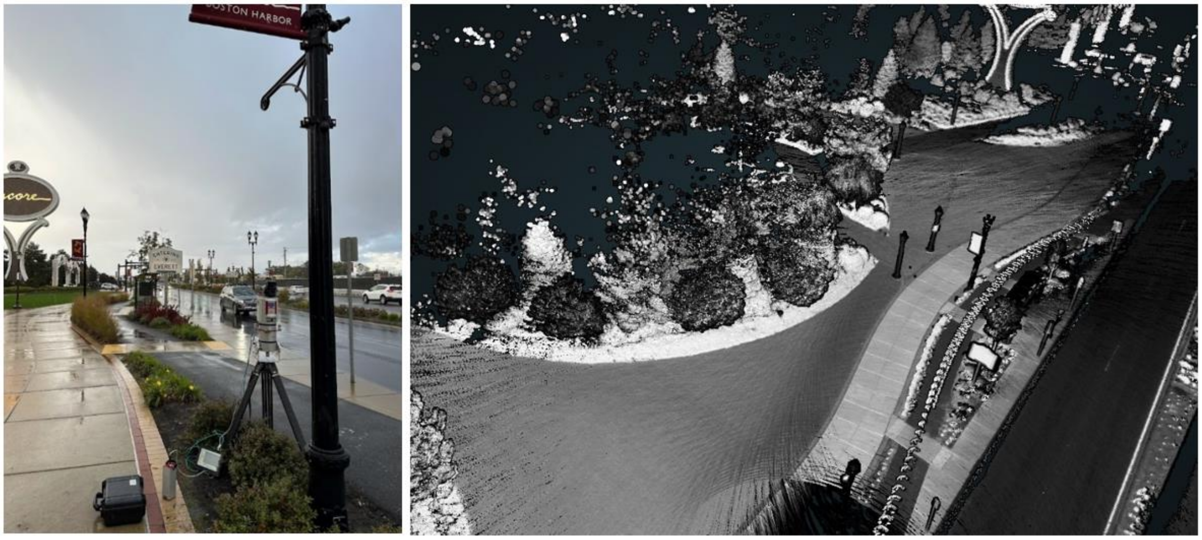


Figure 2.1: LiDAR scanning set up and corresponding cloud point data (Broadway at Horizon Way Street.)

2.2 Literature Review

To understand the design of floating bus stops, this study started by reviewing all current guidelines. Keywords such as Floating Bus Stop, Accessible Bus Stop, Constrained Bus Stop, Boarding Island Stop, Shared Cycle Track Bus Stop, Bus Islands, Bus Stop Bypass, and Bus Stop Design Guidelines were used to search for relevant publications on Google search engine. Related guidebooks from outside the United States identified through this process or professional community outreach were also reviewed, restricted to those written in English.

2.3 Professional Community Input

2.3.1 Professional Organization

The research team sought feedback from the professional community through questions that were posted on the Association of Pedestrian and Bicycle Professionals listserv. More specifically, the email that was sent out to the members of this listserv read:

I'm on a team doing research for MassDOT and the MBTA about designing bus stops where there's a protected bike lane or shared use path going behind the bus stop – so-called "floating bus stops". How to make them safe and accessible to all, including blind and low vision passengers, people who use wheelchairs, seniors, etc. Looking for input on any or all of these topics.

Legal/Policy

1. Do you have any laws or policies requiring bikes to stop when a bus is stopped? Or do you apply a bicycle speed limit where bikes are riding through or behind a bus stop?

Right-of-Way Design

2. Do you favor (or not) fencing / railings that separate the bus stop area from the bike path, with one or two openings for people crossing the bike path to get to/from the stop?

3. Do you use any treatments for slowing cyclists or drawing their attention to the bus stop crossing, beyond marking a crosswalk (e.g., speed tables, bollards, color)?

4. Where space is limited, do you use treatments aimed at enlarging the bus stop depth, such as shrinking the bike path, merging the bike path and sidewalk, or channeling bikes into a bike lane in the street?

Stop Furniture

5. Where space is limited, do you ever use narrow shelters, or provide only a bench andnot a shelter, as a way of keeping the waiting area adjacent to the curb instead of on the other side of the bike path?

Wayfinding for Low Vision

What treatments do you use to help blind and low-vision travelers find the bus stop (which may be rather distant from the sidewalk) and to find the landing area / bus stop pole?

Five responses were received in the duration of one week from individuals representing both cities and private transportation engineering, planning, and design firms in the United States and Canada.

2.3.2 City Interviews

The research team pursued interviews with city officials and representatives of engineering and planning firms that have worked with cities that are at the forefront of integrating bus stops and bicycle infrastructure and developing design guidelines for those in the United States and internationally. These cities and professional organizations were chosen based on the extent of the guidelines they developed specifically for floating bus stops. They were identified by the literature review and the researchers' prior knowledge of the state of practice. The cities interviewed include Amsterdam, Netherlands; Montreal, Toronto, and British Columbia, Canada; Montgomery County, MD; and Austin, TX.

2.4 Community Outreach

Focus groups were conducted to obtain information about individuals' experiences and general concerns about these bus stop types and whether they had experienced them while using the transit system. Participants were asked to share any recommendations they might have on the specific designs or changes that need to be made to make them accessible for all. The specific questions posed to the participants are presented in section 2.4.2.

A total of three focus group discussions took place on June 21, August 8, and August 10, 2023 via Zoom. The structure and questions prepared for the focus group discussions were evaluated by both the Northeastern and University of Massachusetts Amherst Internal Review Boards and deemed to be exempt human factors research. No financial incentive was provided to participants who volunteered their time.

2.4.1 Recruitment

The recruitment process was targeted to ensure that visually impaired, hearing impaired, and individuals with mobility impairments were represented in the focus group participant list. Participant recruitment was facilitated via MBTA's Department of System-Wide Accessibility, which advertised the focus group through an email to the Massachusetts Commission for the Blind and during the June Riders' Transportation Access Group (RTAG) Meeting.

The recruitment process resulted in 12 participants for the June 21, 5 for the August 8, and 4 for the August 10 focus groups. Based on the information disclosed voluntarily to the research team, 12 participating individuals were visually impaired, 2 were hearing impaired, and 2 were wheelchair users. Representatives of MBTA and, in the case of the June 21 focus group, a representative of RTAG, were present as non-participating observers.

2.4.2 Structure

Focus groups included brief presentations by the research team followed by discussion with the participants using questions posed by the research team as prompts. Focus groups lasted for three hours. The participants were asked to raise their hand using the zoom feature if they were able to and unmute only when it was their turn to share their throughs. The last two focus group discussions also included a captioner and an interpreter to accommodate participants with hearing impairments.

The first focus group that took place on June 21, 2023, started with a description of the three types of bus stops using videos, one from the Netherlands describing practices related to bus stops located next to bike lanes, and the other videos showing bus stop conditions, i.e., busses stopping at bus stops, and bus riders boarding and alighting for three bus stops in the Boston area. The descriptions of the videos were followed by these questions:

1. When waiting for a bus, do you stand at the curb, or do you wait in the shelter or on the bench until the bus is close, and only then move close to the curb?
    a. Also, particularly for bus users who are blind or visually impaired
    b. Also, particularly for people with mobility impairments
2. For the 3 different designs (platform widths): When you're getting off the bus, how do you ensure that you won't collide with a bicycle? Can you describe your experience in those situations?
    a. Also, particularly for bus users who are blind or visually impaired
    b. Also, particularly for people with mobility impairments (possibly related to ramp use)
3. For the 2 designs (partial width platform, no platform) in which the bike path lies between the waiting area and the curb: When you're getting on the bus, how do you ensure that you won't collide with a bicycle? Can you describe your experience in those situations?
    a. Also, particularly for bus users who are blind or visually impaired
    b. Also, particularly for people with mobility impairments (possibly related to ramp use)
4. For full-width platform stops, when you arrive at the stop (on foot) and want to cross the bike path to get to the platform, how do you ensure that you won't collide with a bicycle? Can you describe your experience in those situations?
    a. Also, particularly for bus users who are blind or visually impaired: How do you locate the bus stop, and avoid conflicts with bikes while locating it?
6. Some bus stops have a fence between the bike path and the platform. Do you think a fence works to reduce the collision risk and related anxiety? Are there negative aspects of a fence?
    a. Also, particularly for bus users who are blind or visually impaired
    b. Also, particularly for people with mobility impairments
7. What have you noticed about how bikes behave at bus stops like this? For example, do they stop when a pedestrian is crossing the marked crosswalk? Is there anything about a bus stop's design that makes cyclists behave better or worse?

Upon receiving feedback from the MBTA team, the structure and the specific questions posed during the second and third focus groups were slightly revised as follows:

1. The PI of the project presented the agenda and some housekeeping elements regarding participation in this focus group.
2. An image of a floating bus stop was used to describe the basic elements that would be the focus of the discussion, e.g., bike lane, platform, crosswalks, and fence.
3. Each type of bus stop was presented starting with the full-width platform, continuing with the partial-width platform, and lastly, the no platform. For each bus stop type, first, an image of a real-world bus stop was presented and described in detail, then a rendering of that type of bus stop was shown, and finally, questions were posed to the participants. These questions slightly varied by bus stop type as follows:
    a. Full-width bus stop:

        i. What are the design elements that make you feel safe or unsafe in this bus stop design?
        ii. Does the railing work to guide you to the crossings?
        iii. What is your experience with bicyclists at this type of bus stop?
    b. Partial width bus stop:
        i. What are the design elements that make you feel safe or unsafe in this bus stop design?
        ii. Where do you wait for the bus (shelter on the curb side, or on the platform)?
        iii. What is your experience with bicyclists at these types of bus stops?
    c. No platform bus stop:
        i. What are the design elements that make you feel safe or unsafe in this bus stop design?
        ii. What is your experience with bicyclists at this type of bus stop?
4. Next, participants were asked:
    a. What other treatments do you think would be helpful in improving safety at these types of bus stops?
5. At the end, they were asked to share any other recommendations or thoughts they might not have had the opportunity to share by that point.

The PowerPoint slide deck used during the last two focus groups is provided in the Appendix.

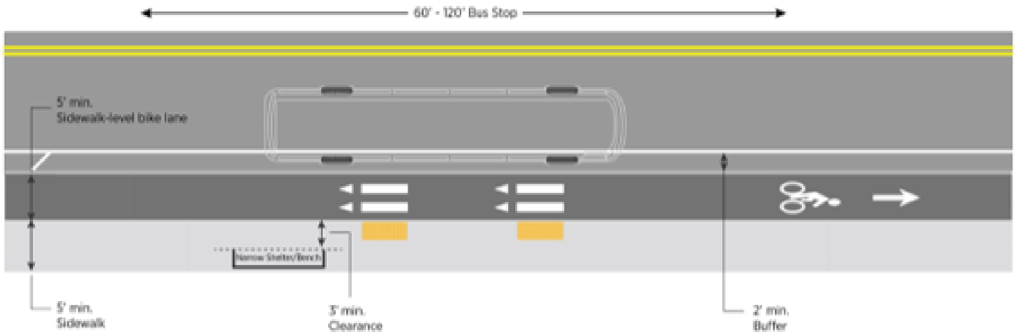
Additional comments were received via emails from individuals who could not participate in one of the focus groups due to scheduling conflicts or were present during one of the focus groups but preferred communicating their concerns via email. Those comments are also included in the discussion of the findings in Chapter 3.

2.5 Behavioral Analysis

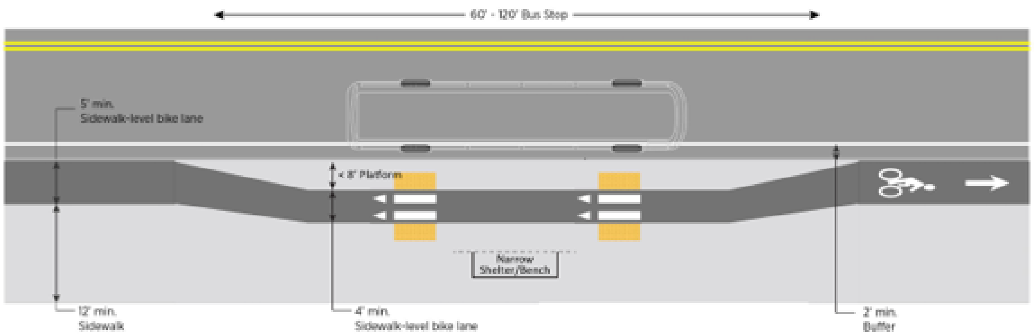
A behavioral analysis was conducted using data form advanced technologies, namely LiDAR and 360º video recordings at five selected floating bus stops. Data were collected for durations varying from 4 to 12 hours in October and November 2023 to obtain detailed trajectories of bicyclists and bus riders. These trajectories allowed for the study of their interactions and the characterization of potential conflicts that arise at floating bus stops. In addition to automated creation and analysis of trajectories, this part of the study also utilized data obtained through manual review of the videos to make observations of conflicts and user behavior.

2.5.1 Study sites

A total of five floating bus stops were selected for field data collection in this study, with the main criteria of ensuring diversity by having representation of the three types of floating bus stops (i.e., no platform, full-platform, and partial-platform bus stops; see Figure 2.2) and each study bus stop having at 1east 100 boardings and alighting bus riders and at least 400 bicycle trips per day. The average number of bus riders (boardings and alightings) for the five bus stops ranges from 110 to 410 passengers per day, while the number of bicycle trips ranges from 440 to 1,140 trips per day.

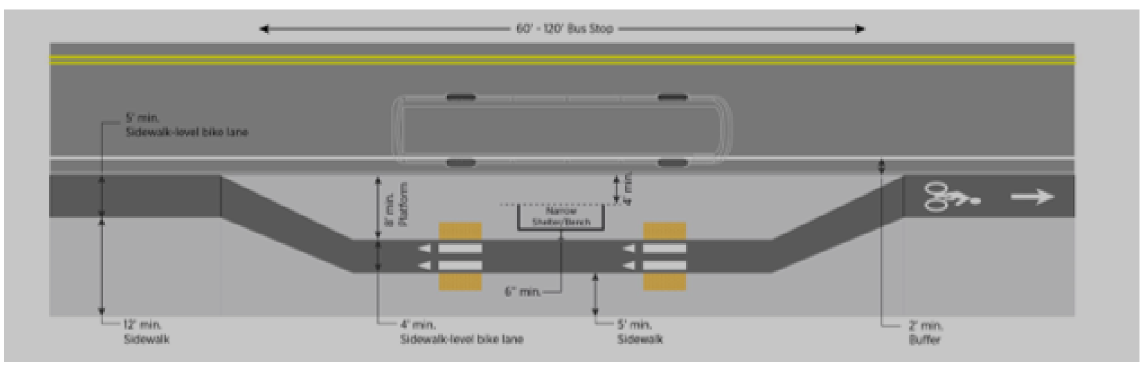


a) No Platform Floating Bus Stop



b)

Partial-width Floating Bus Stop



c) Full-width Floating Bus Stop

Figure 2.2: Floating Bus Stop Types

There are two bus stops with full-width platforms, two bus stops with partial-width platforms, and one bus stop with no platform, which are located in the cities of Boston, Somerville, Everett, and the town of Brookline; see Figure 2.3 (below) for a map showing the locations of the five study sites in Massachusetts. Complete descriptions of each of these intersections, including a map layout of their proximity, are included in the next sections.

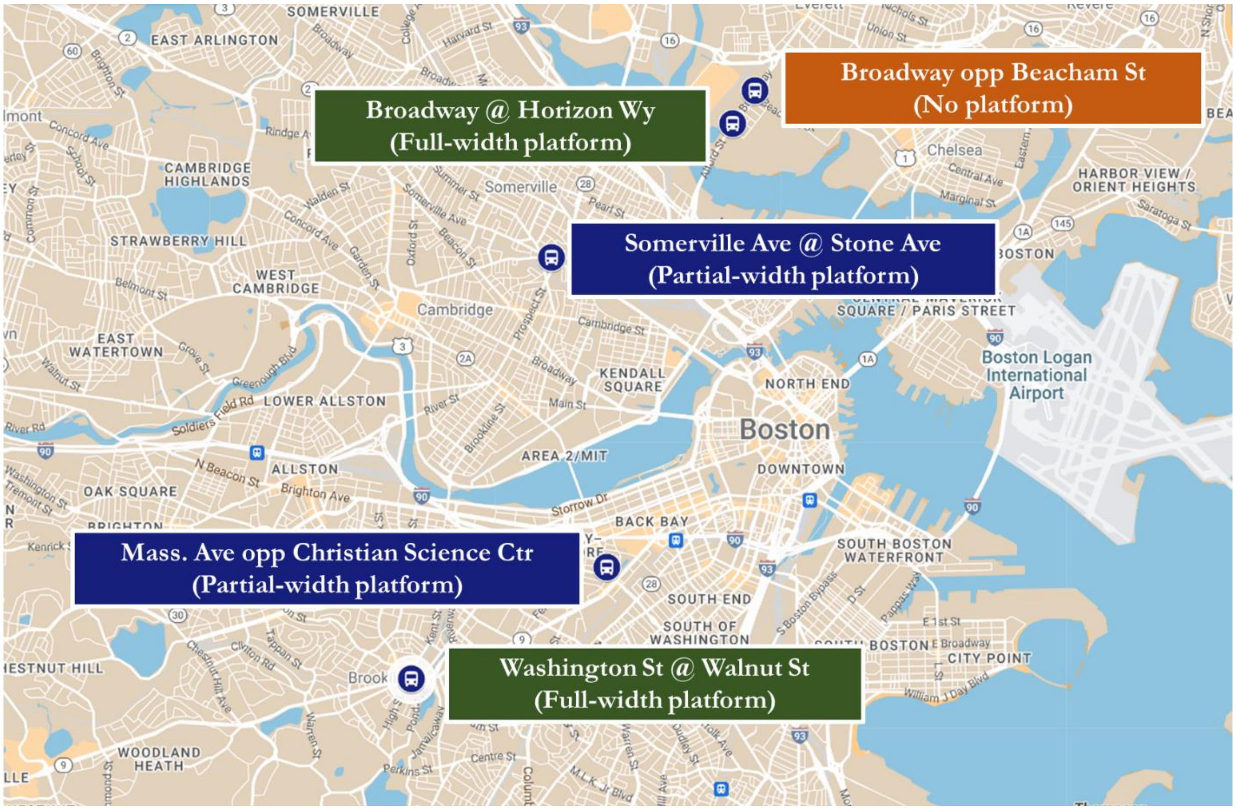


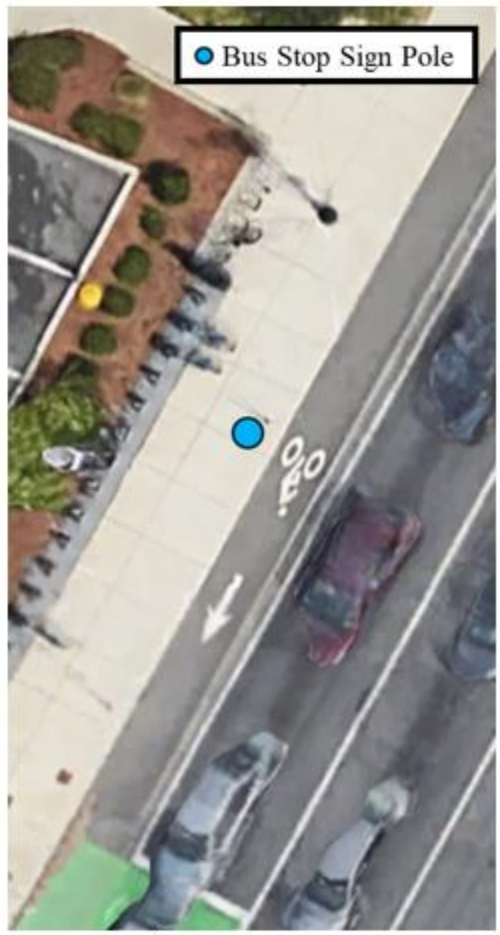
Figure 2.3: Map of study sites

Broadway opp. Beacham Street, Everett, MA (October 16, 2023: 4 hours)

This is a no platform floating bus stop located on the southbound side of Broadway in Everett, MA serving bus routes 104, 105, and 109. This bus stop is characterized by an average of 110 boardings and alightings per day. An average daily count of 440 bike trips per day is also observed. There are no shelters at the bus stop, and the bus stop sign is located on the sidewalk. Adjacent to the bus stop is a one-way bike lane with a width of 4.5 feet, and there are no crosswalks provided for bus riders to use when crossing the bike lane to board or exit the bus. Figure2.4 displays images from this study site, with the blue dot on the satellite map indicating the location of the bus stop sign.

(a) Street view

(b) Upstream end view



(c) Aerial image

Figure 2.4 : Broadway opp. Beacham Street bus stop

Massachusetts Avenue opp. Christian Science Center, Boston, MA (November 3, 2023: 12 hours)

This is a *partial-width* floating bus stop located on the southbound side of Massachusetts Avenue in Boston, MA, with a platform width of 5 feet. This bus stops serves bus route 1 with an average of 200 bus passengers per day using this bus stop and an average of 1,140 bikes per day passing by that location. There is one shelter located on the sidewalk, and the bus stop sign is on the platform. Adjacent to the bus stop is a one-way bike lane with a width of 4.3 feet, and one crosswalk without tactile pavement at the ramp is provided for bus riders to use when crossing the bike lane to board or exit the bus. Figure 2.5 presents images from this study site, with the blue dot indicating the location of the bus stop sign, the red box indicating the shelter, and two green boxes indicating the crosswalks on the satellite map.

(a) Street view

(b) Downstream end view

(c) Aerial image

Figure 2.5: Massachusetts Ave opp. Christian Science Center bus stop

Somerville Avenue at Stone Avenue, Somerville, MA (November 1, 2023: 12 hours)

This is a *partial-width* floating bus stop located on the westbound side of Somerville Avenue in Somerville, MA, with a platform width of 7.1 feet. This bus stop serves bus routes 86, 87, 91, and 747 with an average daily ridership of 390 bus passengers and 870 bike trips per day going through this location. There is one shelter located on the sidewalk, and the bus stop sign is on the platform. Adjacent to the bus stop is a one-way bike lane with a width of 4.5 feet, and two crosswalks with tactile pavements at the ramps are provided for bus riders to use when crossing the bike lane to board or exit the bus. Additionally, there are two yielding markings near both crosswalks and a pedestrian warning sign near one of the crosswalks. Figure 2.6 displays images from this study site, with the blue dot indicating the location of the bus stop sign, the red box indicating the shelter, and two green boxes indicating the crosswalks on the satellite map

(a) Street view

(b) Downstream end view

(c) Aerial image

Figure 2.6: Somerville Avenue at Stone Avenue bus stop

Broadway at Horizon Way, Everett, MA (October 16, 2023: 4 hours)

This is a *full-width* floating bus stop with a width of eight feet, located on the southbound side of Broadway in Everett, MA. This bus stop serves bus routes 104, 105, and 109, has an average daily ridership of 150 bus passengers and 450 daily bike trips traveling through this location. There is one shelter located on the platform, and the bus stop sign is also on the platform. Adjacent to the bus stop is a one-way bike lane with a width of four feet, and four crosswalks featuring tactile pavement at the entrance and exit of the crosswalk are provided for bus riders to use when crossing the bike lane to board or exit the bus. Figure 2.7 displays images from this study site, with the blue dot indicating the location of the bus stop sign, the red box indicating the shelter, and four green boxes indicating the crosswalks on the satellite map.

(a) Upstream end view

(b) Downstream end view

(c) Aerial image

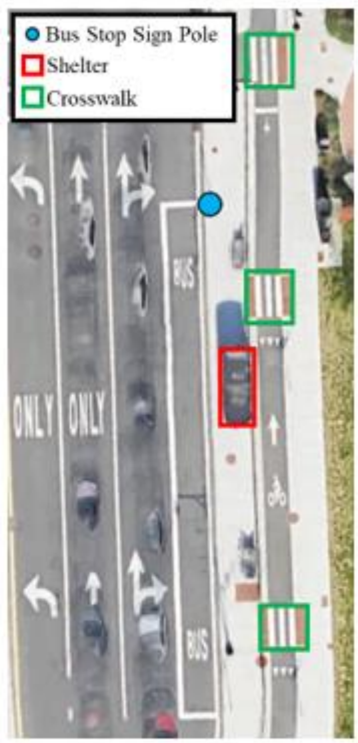
Figure 2.7: Broadway at Horizon Way bus stop

Washington Street at Walnut Street, Brookline, MA (October 2, 2023: 4 hours)

This is a *full-width* floating bus stop located on the eastbound side of Washington Street in Brookline, MA, with a platform width of 8 feet. This bus stop serves bus routes 60, 65, and 66 and has an average daily ridership of 410 passengers. Bike counts through that location indicate an average of 820 bike trips per day. There is one shelter located on the platform, and the bus stop sign is also on the platform. Adjacent to the bus stop is a one-way bike lane with a width of four feet, and two crosswalks with tactile pavement at their entrances and exits are provided for bus riders to use when crossing the bike lane to board or exit the bus. Additionally, there are two yielding markings and two yielding signs near the crosswalks. Figure 2.8 displays images from this study site, with the blue dot indicating the location of the bus stop sign, the red box indicating the shelter, and two green boxes indicating the crosswalks on the satellite map.

(a) Upstream end view

(b) Downstream end view



(c) Aerial image

Figure 2.8: Washington Street at Walnut Street bus stop

2.5.2 Data Collection Equipment

In this study, the Ouster OS1-128 LiDAR sensor was used to collect the point cloud data at each selected bus stop and subsequently used for vehicle/pedestrian/bicyclist extraction and trajectory analysis. The LiDAR sensor was operated at 20 Hz, which means that every 0.05

seconds, the motor within the sensor will complete a full revolution and create a point cloud that contains 1024 by 128 points. The number 1024 corresponds to the sample points for each revolution, meaning the sensor creates a line scan at approximately 50ms, and each line contains 128 points covering a 45-degree field of view. The LiDAR scanner was accompanied by an Insta360 X3 panoramic video camera that had full coverage of the scanning area at 30 fps. The video footage was used to complement the LiDAR point cloud data when the identification of the road users failed due to limited point density or occlusion. The video camera was temporarily mounted behind the signpost near the bus stop (see Figure 2.9), whereas the LiDAR sensor was mounted on top of a pan-tilt-controlled tripod behind some fixtures on site (see Figure 2.10). Both the LiDAR sensor and the camera at each of the selected bus stops were installed in such a way that the distraction from the passengers, bicyclists, and drivers was minimized. Figure 2.11 shows the sample data for the point cloud and the video footage. In total, approximately 45 hours of point cloud data and corresponding video footage was collected across the five bus stops described earlier. However, only 35 hours of point cloud data and video footage were used for behavioral analysis, as there were duplicated 4-hour sessions at two locations, and 2-hour mis-synchronized LiDAR and video datasets were deleted.

Figure 2.9: Configuration of the 360º video camera (with battery and the camera magnetically mounted on the sign post as shown in the yellow and red boxes)

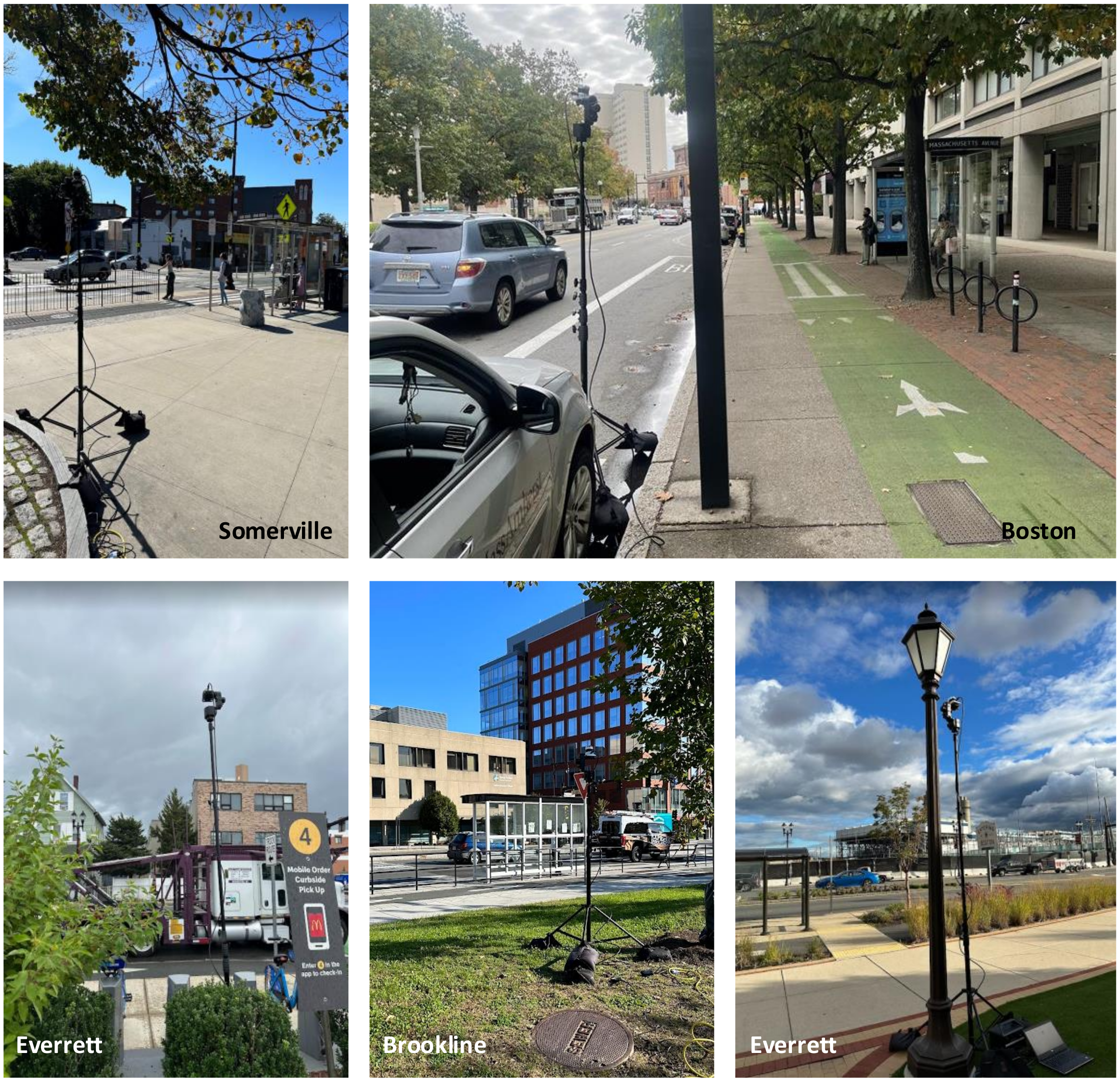


Figure 2.10: LiDAR scanning scene for infrastructure and trajectories (Somerville Avenue and Stone Avenue, Somerville, MA)

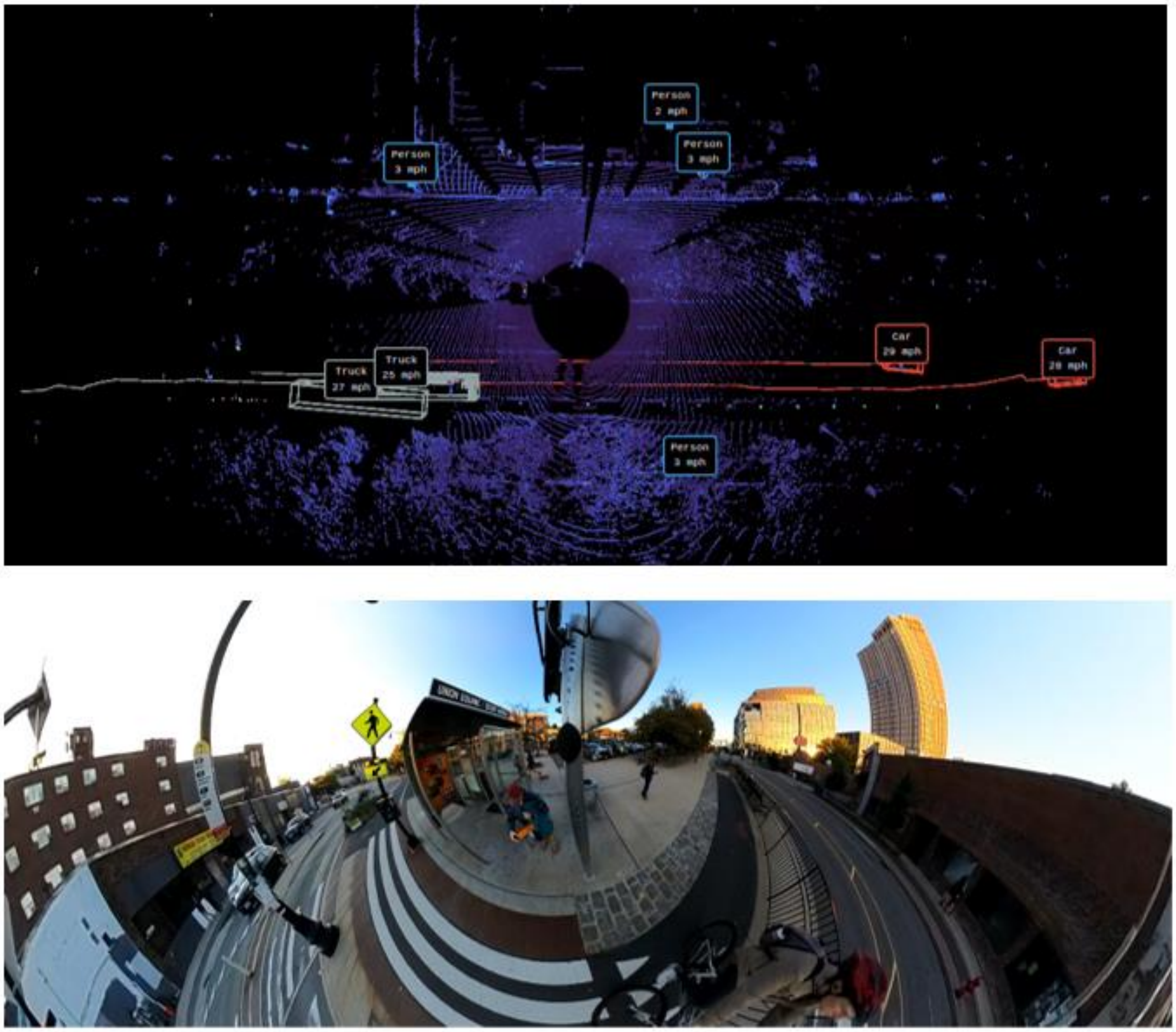


Figure 2.11: Satellite image and 360° video image (Somerville Avenue and Stone Avenue, Somerville, MA)

2.5.3 Trajectory Analysis

Data obtained from LiDAR were stored in the form of point cloud data. All stationary and moving objects within the LiDAR scanning range were detected and recorded in the point cloud data, as shown in Figure 2.12.

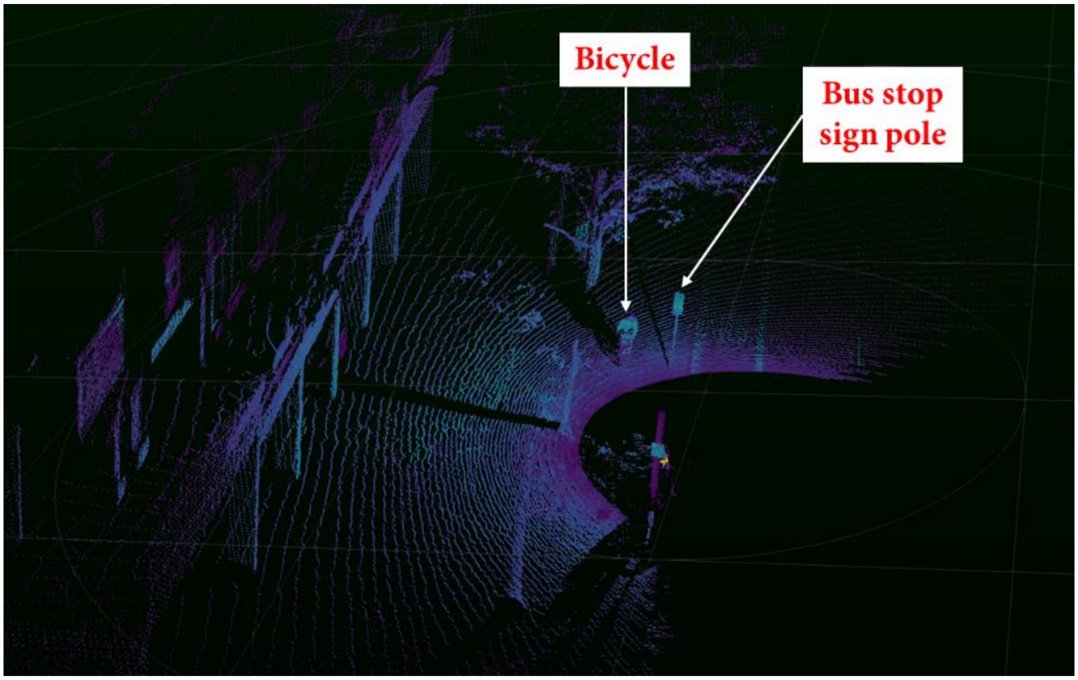


Figure 2.12 LiDAR point cloud data (Massachusetts Avenue opp. Christian Science Center, Boston, MA)

Next, all moving objects were categorized by their size into five different types of road users: person, two-wheeler, car, truck/bus, and unknown, examples of which are shown in Figure 2.13, followed by a trajectory extraction process that associated the detected objects into continuous trajectories (formulated as data records of timestamp, speed, and coordinates). The dimensions for the size of the road user categories may be defined flexibly in the algorithm. In this study, the thresholds are defined by the volumetric values of the bounding boxes for a person, two-wheeler, car, and truck/bus; they are 16 ft^3, 50 ft, 400 ft^{3,} and 2000 ft^3. These volumetric thresholds were empirically determined based on the sensor configurations and fields of view at different bus stops, where these values rendered the best performance. The classifications were further confirmed if the volumetrics values were consistent across the consecutive two frames. Because the frequency of data collected by the LiDAR is 20 Hz (i.e., 20 records per second), the trajectory data were also extracted at the same frequency. Each moving object was assigned a specific ID to allow for differentiation from other objects.

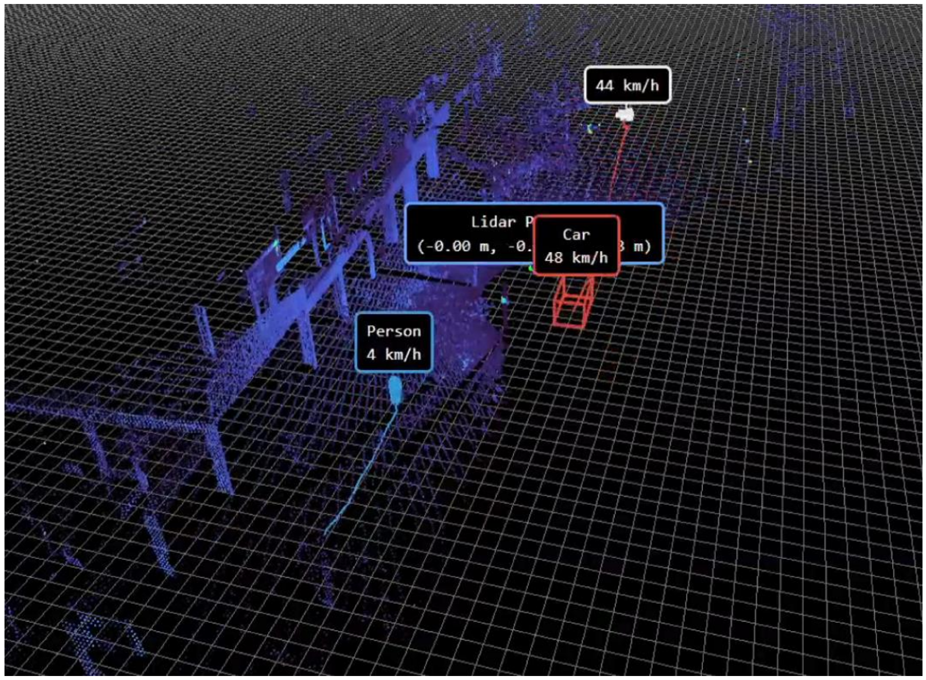


Figure 2.13 Example trajectories and real-time speeds for moving objects (Massachusetts Avenue opp. Christian Science Center, Boston, MA)

Obstacles blocking the scanning area, the scanning angle, or other interference factors could cause misclassification of objects and, therefore, trajectory adjustments to the initial classification are necessary. First, trajectories detected for less than one second were excluded, as they are difficult to classify. Next, because moving objects may not be well detected when entering the scanning area, the classification of the entire trajectory was replaced with that of the largest size detected within that trajectory; see Figure 2.14 for an illustration of this. As the bus enters the scanning area, the proportion of the bus detected increases until the entire bus is within the area. The classification of the bus changes from unknown to car and eventually to truck/bus. Therefore, the largest size classification identified in each trajectory was selected and applied to the entire trajectory to prevent misidentifications.

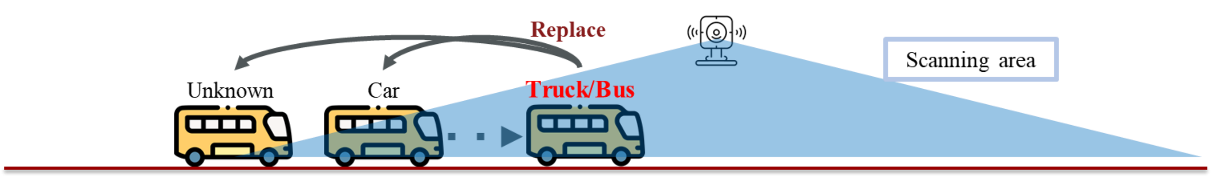


Figure 2.14: Adjustment method for user type classification

In addition to the classification issue, the speed value can also be affected by interference factors, leading to unreasonable outliers at certain timeframes within a trajectory. To address this problem, the median filtering method with a time interval of 0.5 seconds was used to smooth the speed value.

Table 2.1 provides an example of the speed smoothing used in this study. For each specific object and time interval, there is an original speed value. The adjusted speed is calculated by taking the median of the five previous speed values from the five previous timestamps. For example, the adjusted speed for timeframe five is the median of the speed values for timeframes one through five, which is the median of (25, 24, 22, 21, 50) = 24. The adjusted speed value for timestamps one through four in each trajectory is not applicable since there are not enough speed values to calculate the median value based on the requirement used in this smoothing of five-speed values. Following the speed smoothing, the average speed distributions by type of road user were plotted for each of the five bus stops. Figure 2.14 and Figure 2.15 show examples of speed distributions of two-wheelers before and after the speed adjustment at the Massachusetts Avenue opposite Christian Science Center bus stop.

Table 2.1: Example of median filtering method for speed smoothing

ID	Timestamp	Original speed	Adjusted speed
1	1	25	N/A
1	2	24	N/A
1	3	22	N/A
1	4	21	N/A
1	5	50	24*
1	6	22	22
1	7	23	22
1	8	24	23
1	9	23	23
1	10	22	23
1	11	20	23

* 24 is the median number of (25, 24, 22, 21, 50)

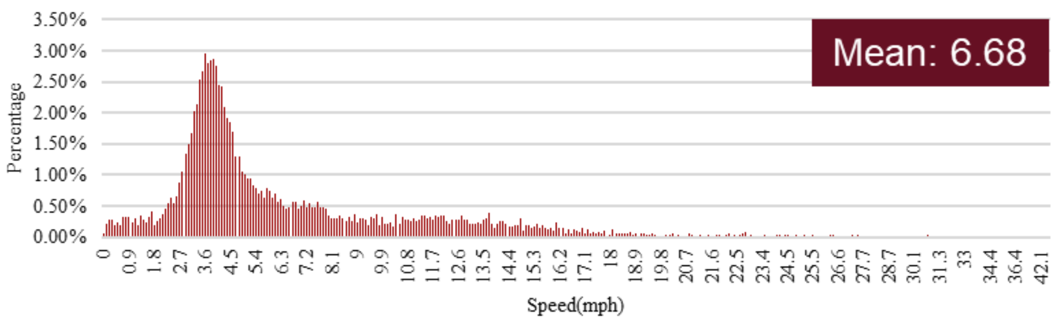


Figure 2.15: Average speed distribution of two-wheelers at Massachusetts Avenue opp. Christian Science Center bus stop

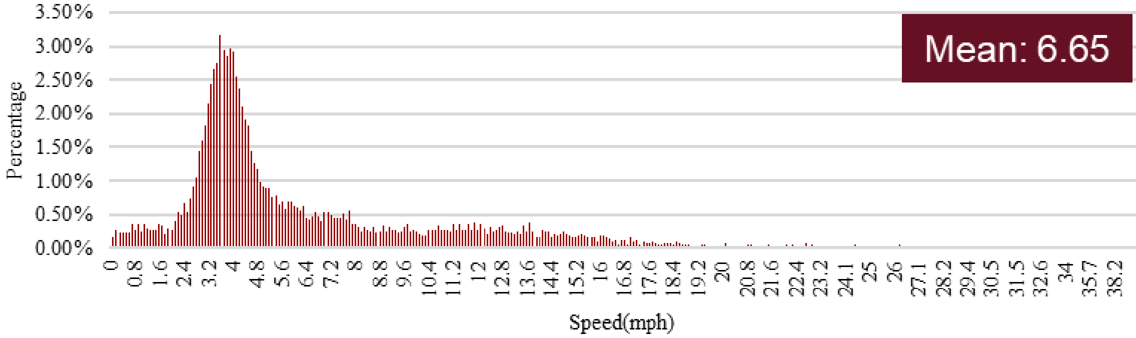


Figure 2.16: Adjusted average speed distribution of two-wheelers at Massachusetts Avenue opp. Christian Science Center bus stop

The collected trajectory data were then used to answer the following questions.

Question 1: ***Do horizontal curves in the separated bike lane affect bicyclist speed?***

This question can help inform the geometric design and, in particular, the horizontal alignment of separated bike lanes that are adjacent to bus stops. Horizontal alignment (or horizontal curve) in this study is referred to the deflection of the bike lane geometry, which is introduced for bike lanes to smoothly circumvent different roadway alignment changes (e.g., orientations of sidewalks and curbs). Figure 2.17 shows an example of S-shape horizontal curves near the bus stop at Washington Street at Walnut Street where the driveway is widened for bus stop.

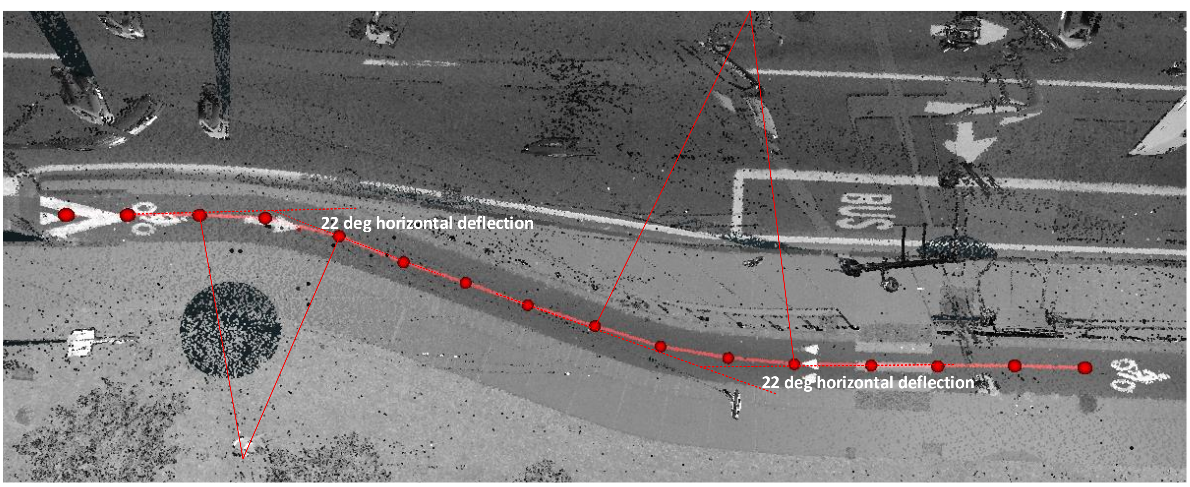
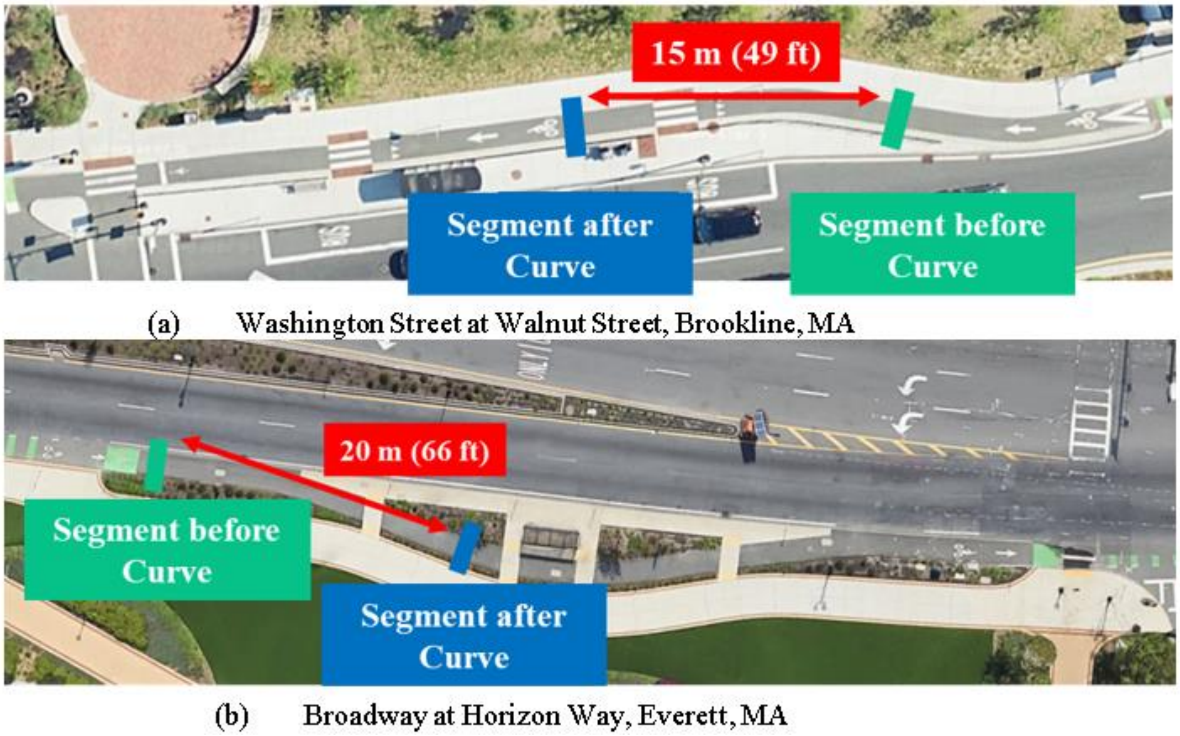


Figure 2.17: Illustration of the horizontal curve introduced the bike lane entering the bus stop at Washington Street at Walnut Street

The floating bus stops that present a horizontal curve in the adjacent separated bike lane are the Washington Street at Walnut Street in Brookline, MA, and the Broadway at Horizon Way bus stop in Everett, MA, both of which are full-width floating bus stops. To answer this question two detection zones were defined for which speeds were recorded, as shown in Figure 2.18. Detection zones of approximately 30 square feet were set to capture relevant speed data from the LiDAR dataset. The average speed of each bicycle was calculated using all its trajectory points detected within these zones. One of the detection zones was placed on the bike lane segment before the curved part, and another one on the segment after the curve. The trajectories of bicyclists who passed these two detection zones were extracted to analyze any average speed differences between these two locations. In the case of Washington Street at Walnut Street, both detection zones were placed on the fenced sections of the horizontal curve to control for the presence of the fence.



Source: [17]

Figure 2.18: Speed detection zones for assessing whether horizontal curves in the separated bike lane affect bicyclist speed (Question 1)

Question 2: ***Does fencing along the separated bike lane affect bicyclist speed?***

This question can help inform fencing placement decisions for bicyclist speed management. The only floating bus stop that feature fencing or a shelter wall along the separated bike lane is Somerville Avenue and Stone Avenue in Somerville, MA (partial-width). The bus stop on Washington Street at Walnut Street, Brookline, MA, also features fencing; however, at this bus stop, there is also a horizontal curve along the separated bike lane. As a result, data from this bus stop were not used as it would be hard to differentiate the impact of the fencing versus the horizontal curve on bicyclist speeds. To answer this question, two detection zones were defined for which speeds were recorded, as shown in Figure 2.19. One of the detection zones was placed along the fencing segment, and the other along the segment leading to the fencing part that was free of fencing. Each detection zone was approximately 30 square feet, the same as configured in Question 1. The trajectories of bicyclists who passed these two zones were extracted to analyze any average speed differences between these two locations.

Source: [17]

Figure 2.19: Speed detection zones for assessing whether fencing along the separated bike lane affect bicyclist speed (Question 2) (Somerville Avenue and Stone Avenue)

Question 3: ***How do waiting transit riders interact with the separated bike lane?***

a. ***How many and how long do waiting transit riders stand in the separated bike lane?***

b. ***How many pedestrians go back and forth across the separated bike lane more than two times?***

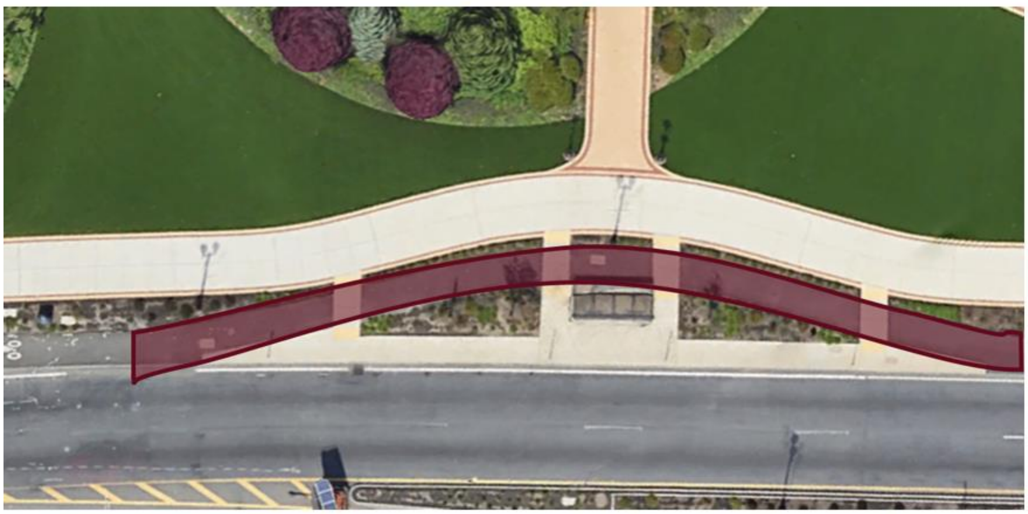
This question was introduced to improve our understanding of the frequency of interactions between transit users and bicyclists on the separated bike lane and inform floating bus stop design, shelter placement, and educational campaigns. All five floating bus stops were used to answer this question. A detection zone was defined as part of the separated bike lane within the range of the LiDAR device to collect relevant data; see Figure 2.20. Any pedestrian trajectories that passed through this detection zone at any point were extracted so that the standing pedestrians could be identified. A standing pedestrian was defined as having a speed lower than 2 mph for three consecutive seconds, and a crossing behavior was defined as having a perpendicular to a bike lane speed higher than 1.5 mph. It should be noted that the trajectory data do not allow for differentiation between a passing pedestrian and a transit user passenger. To address this, pedestrians walking along the sidewalk behind the shelter and never interacting with the separated bike lane were excluded from the analysis.

(a) Broadway opp. Beacham St

(b) Massachusetts Ave opp. Christian Science Center

Figure 2.20: Detection zone for assessing how waiting transit riders interact with the separated bike lane (Question 3) (continued next page)

(c) Somerville Ave @ Stone Ave



(d) Broadway @ Horizon Way

(e) Washington St @ Walnut St

Source: [17]

Figure 2.20 cont.: Detection zone for assessing how waiting transit riders interact with the separated bike lane (Question 3)

Question 4: ***What percentage of transit riders use crosswalks versus crossing elsewhere?***

Answering this question is important to inform crosswalk and fencing placement at floating bus stops. Four of the five bus stops were used to answer this question: Washington Street at Walnut Street, Brookline, MA (full-width); Somerville Avenue at Stone Avenue, Somerville, MA (partial-width); Massachusetts Avenue opposite Christian Science Center, Boston, MA (partial-width); and Broadway at Horizon Way, Everett, MA (full-width) since all feature crosswalks traversing the adjacent bike lane (see Figure 2.21). As before, the bike lane and crosswalk areas were defined as the detection zones used to extract the trajectories of pedestrians crossing the bike lane. These trajectories were then analyzed to determine whether pedestrians crossed the bike lane inside or outside the crosswalk areas. The definition of crossing is consistent with that of Question 3b. It should be noted that the crosswalk on the right side of Washington Street at Walnut Street bus stop exceeded LiDAR’s scanning area, and therefore, pedestrians crossing the bike lane at that crosswalk could not be captured by LiDAR.

(a) Massachusetts Ave opp Christian Science Center

(b) Somerville Avenue at Stone Avenue

Figure 2.21: Detection zone for assessing the percentage of transit riders that use crosswalks versus crossing elsewhere (Question 4) (continued on next page)

(c) Broadway at Horizon Way

(d) Washington St at Walnut Street

Source: [17]

Figure 2.21 cont.: Detection zone for assessing the percentage of transit riders that use crosswalks versus crossing elsewhere (Question 4)

Question 5: ***How many and how long do passengers walk along the separated bike lane?***

This question focuses on pedestrians walking along the separated bike lane in contrast to Question 3 that focuses on walking on the bike lane in a perpendicular way (i.e., crossing). Data from all five floating bus stops were used to answer this question. Information obtained from analyzing data to answer this question can assist with bike lane design that discourages pedestrians from walking in the bike lane. As with Question 3, trajectories of pedestrians who walked in the bike lane after defining the bike lane within the LiDAR range as the detection zone were extracted. However, considering that pedestrians do not always walk in one straight direction, walking along the bike lane was defined as the passenger having a dwelling time of three seconds within the bike lane and a speed greater than 2 mph.

Question 6: ***When a pedestrian is standing in the separated bike lane, how much do approaching bicyclists slow down, and with how much clearance do they pass the pedestrian?***

This question aims to understand the frequency of near misses between bicyclists and pedestrians. The definition of standing is consistent with that of Question 3a. To answer this question, the time when there was a pedestrian standing in the separated bike lane was marked and the trajectories of bicyclists who interacted with the standing pedestrian were extracted. An interaction was recorded if the minimum distance between the two trajectories was less than 10 meters (~33 ft); otherwise, no interaction was assumed. The bicyclist and pedestrian trajectories were then analyzed to describe their speed before, during, and after the interaction. Data from the Massachusetts Avenue opposite Christian Science Center, Boston, MA (partial-width) bus stop were used to answer this question as it had the highest bicyclist and pedestrian volumes among the five studied floating bus stops.

Question 7: ***In the absence of platforms (i.e., no platform bus stops), do bicyclists approaching the stop while a bus is there adjust their speeds?***

This question sheds light on bicyclist behavior, in particular, their speed, while a bus is stopped when more pedestrian crossings of the bike lane are expected to inform speed management features and yielding/warning signage and/or pavement marking placement. As with Question 4, the time window when a bus was stopped at the bus stop was marked and the trajectories of bicyclists within that time interval were extracted so that the speeds of those bicyclists can be analyzed. Data from the one no platform bus stop, i.e., the Broadway opposite Beacon Street bus stop in Everett, MA, for which data were available, were used to answer this question.

2.5.4 Manual Video Review

Video recordings were manually reviewed to obtain information on transit rider behavior. Manual video observations were used to analyze aspects that the LiDAR cannot capture, primarily the glancing behavior of transit riders as the cross the bike lane before boarding on or alighting from the bus since this is not possible to extract from the LiDAR data.

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3.0 Results

3.1 Inventory Analysis

The floating bus stop inventory for MBTA's service area was completed with information from the MBTA in addition to visual review of aerial images that are available on the Internet and field visit observations. Additional detailed dimensions were collected but only for the five selected floating bus stops.

A total of 56 floating bus stops were identified within MBTA's service area. The municipality, location, and the feasibility of studying each stop are shown in Figure 3.1 and Table 3.1.

Table 3.1: Number of floating bus stops by municipality

Municipality	Number of Floating Bus Stops
Boston	22
Cambridge	17
Somerville	10
Everett	3
Watertown	2
Brookline	2
Total	56

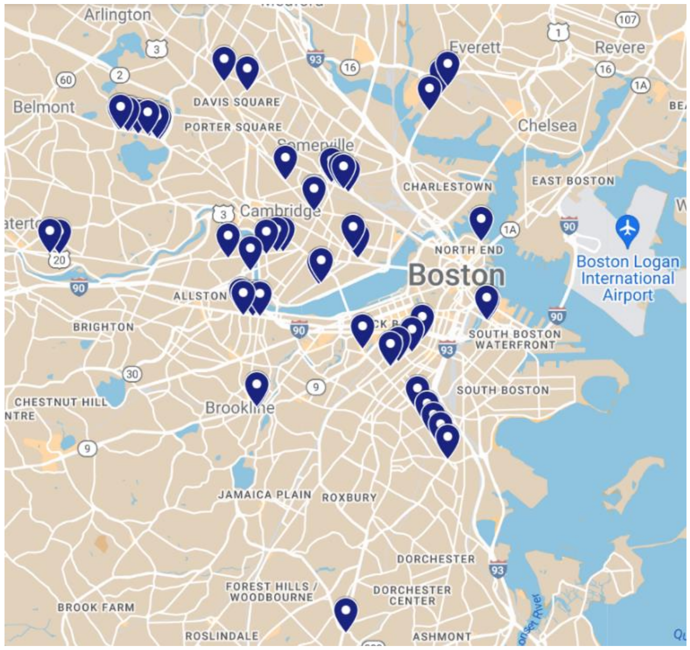


Figure 3.1: Location of Floating Bus Stops

3.1.1 Floating Bus Stop Type

In terms of floating bus stop type, 45% of them (25 bus stops) are full-width platform bus stops, 32% of them (18 bus stops) are partial-width platform bus stops, and the remaining 23% (13 bus stops) are no platform bus stops. The percentages for each bus stop design and their respective locations are shown in Figure 3.2 and Figure 3.3. Examples of the full-width platform bus stops, partial-width platform bus stops, and the no platform bus stops are presented in Figure 3.4, Figure 3.5, and Figure 3.6.

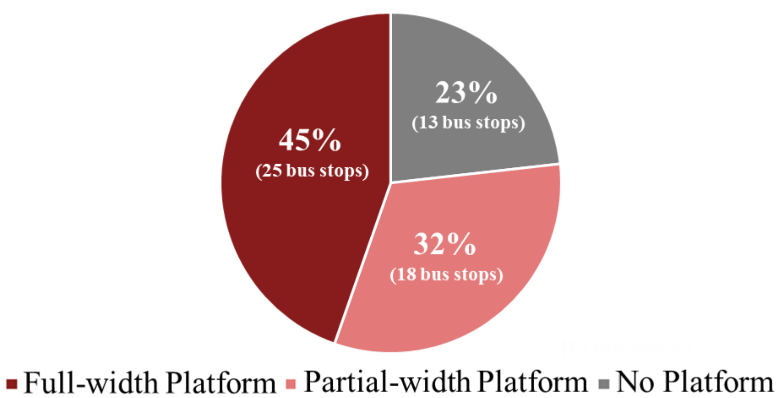


Figure 3.2: Floating bus stop type distribution in MBTA's service area

Source: [16]

Figure 3.3: Floating bus stop types in MBTA's service area

Source: [17]

Figure 3.4: Full-width platform bus stop (Commonwealth Ave at Babcock St, Boston, MA)

Source: [17]

Figure 3.5: Partial-width platform bus stop (Vassar St opp. Pacific St Extension, Cambridge, MA)

Source: [17]

Figure 3.6: No platform bus stop (Broadway at Bowdoin St, Everrett, MA) Bike Lane Width

In terms of bike lane width at floating bus stops, only 9 are two-way bike lanes. The remaining 46 bike lanes have a width ranging from 3.2 ft to 8 ft for a single direction, with an average width of 5.13 ft and a standard deviation of 1.17.

3.1.2 Bike Lane Width

In terms of bike lane width at floating bus stops, only 9 are two-way bike lanes. The remaining 46 bike lanes have a width ranging from 3.2 ft to 8 ft for a single direction, with an average width of 5.13 ft and a standard deviation of 1.17

3.1.3 Vertical/Horizontal Curves Along Bike Lanes

Having a vertical or horizontal curve for bike lanes is an effective way to manage bicyclists' speeds by essentially encouraging them to slow down when they are biking through the floating bus stop area. The percentage of bike lanes featuring vertical curves or horizontal curves by floating bus stop type is shown in Figure 3.7. As the figures illustrate, vertical curves are more common at full-width platform bus stops (48%), while horizontal curves are only found at full-width platform bus stops; 32% of full-width platform bus stops are adjacent to bike lanes that feature a horizontal curve. This might be correlated to the fact that full-width platforms are typically implemented at locations with more space availability. Examples of the vertical/horizontal curves along the bike lanes are presented in Figure 3.8, Figure 3.9, and Figure 3.10.

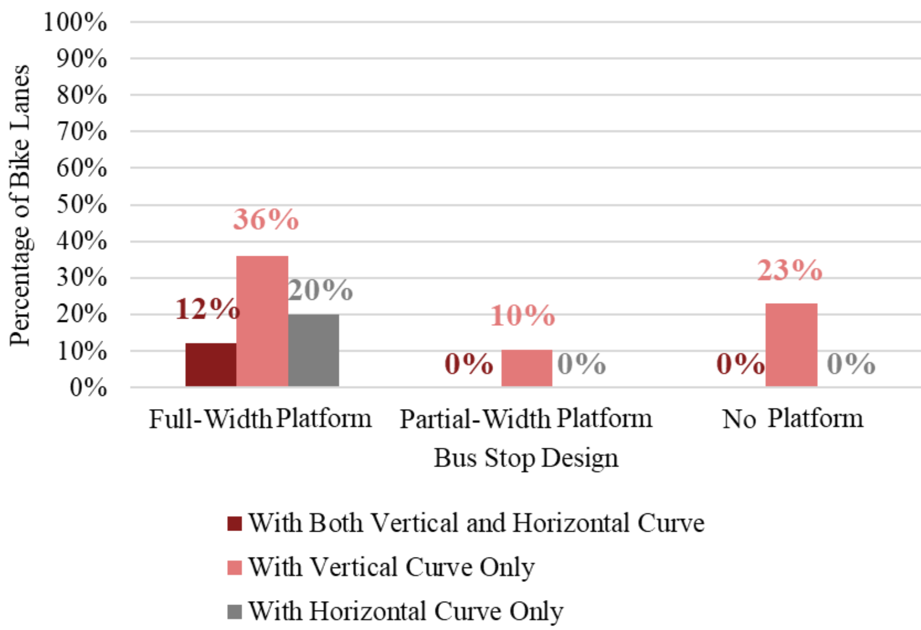
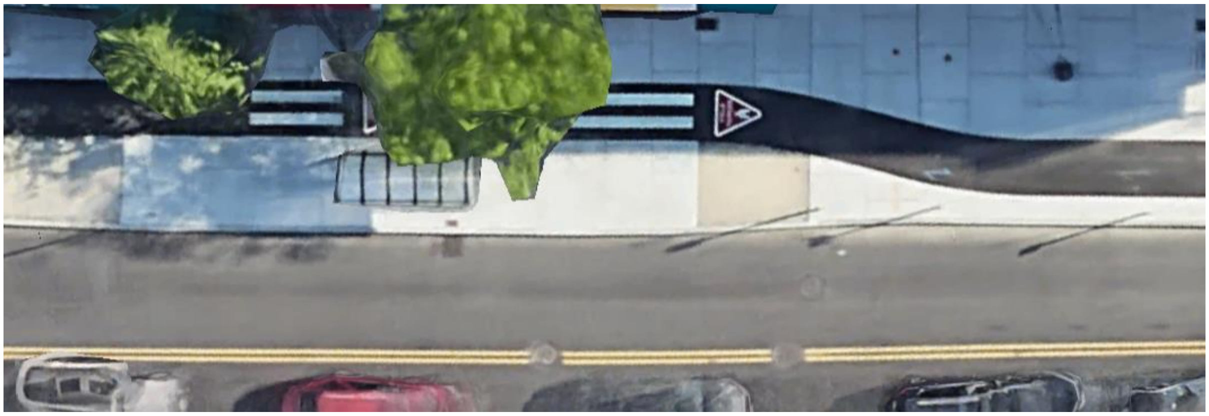


Figure 3.7: Distribution of bike lanes at floating bus stops with vertical or horizontal curves by floating bus stop type



Source [17]

Figure 3.8 Horizontal curve along the adjacent bike lane (Cambridge St at Springfield St, Cambridge, MA)

Figure 3.9 Vertical curve along the adjacent bike lane (Massachusetts Ave at Island St, Boston, MA)

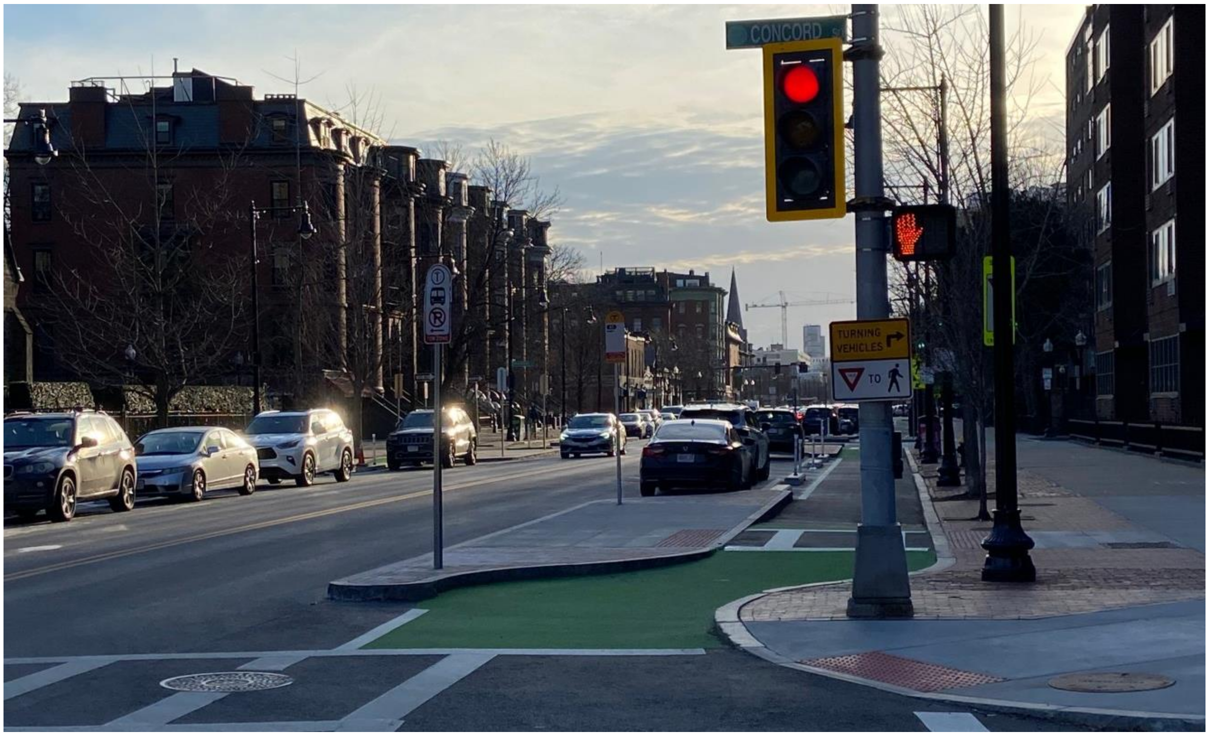


Figure 3.10 Horizontal and vertical curve along the adjacent bike lane (Tremont St at Concord Sq, Boston, MA)

3.1.4 Bus Shelter Location

The bus shelter provides bus passengers with a sheltered space to wait for the bus, offering protection from wind and rain, a place to rest briefly, and an opportunity to observe whether the bus has arrived. 19 of the 56 floating bus stops are equipped with bus shelters, with 12 located on the platform and the others on the sidewalk. The distribution of bus stop shelter location by floating bus stop type is shown in Figure 3.11. Full-width platforms are the most likely to feature a shelter, even though at least half of them still do not have one. All full-width platform bus stops with shelters have them located on the platform, in contrast with partial-width and no platform bus stops that have their shelters on the sidewalk. Interestingly, partial-width platforms are the least likely to feature a bus stop shelter. Examples of the bus shelter locations are presented in Figure 3.12 and Figure 3.13.

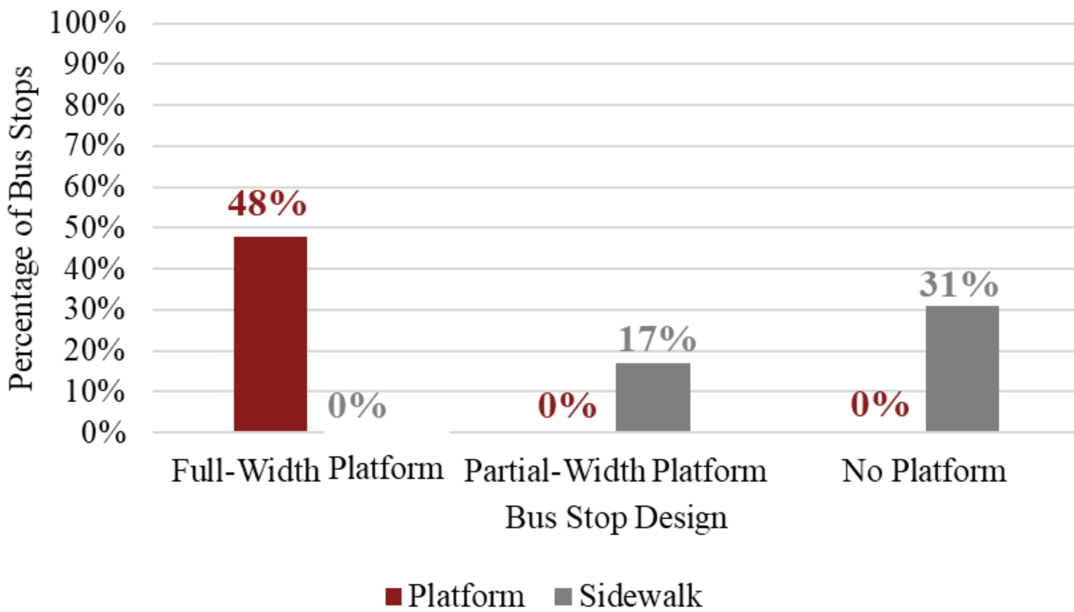
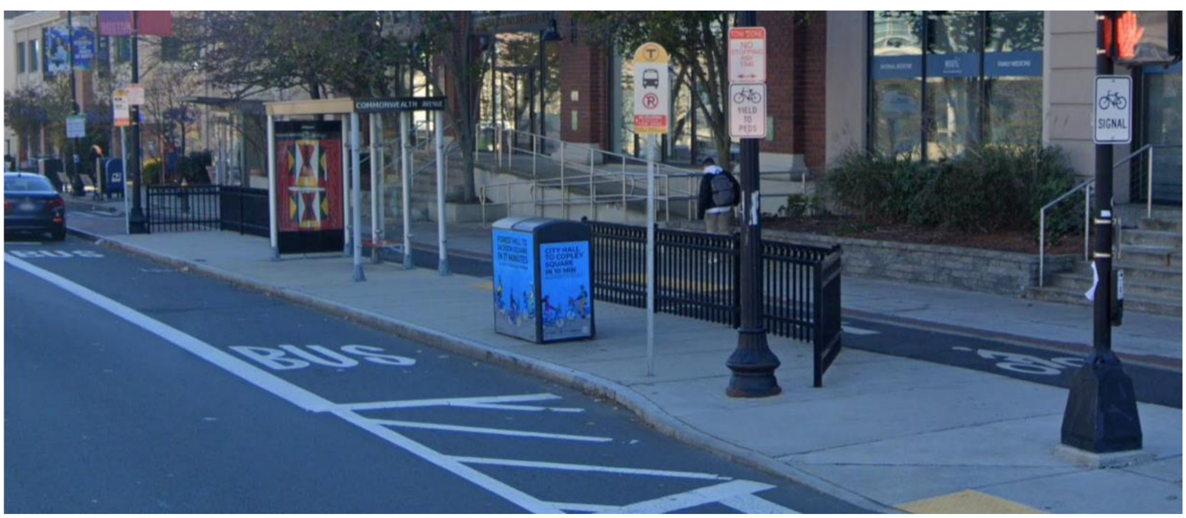
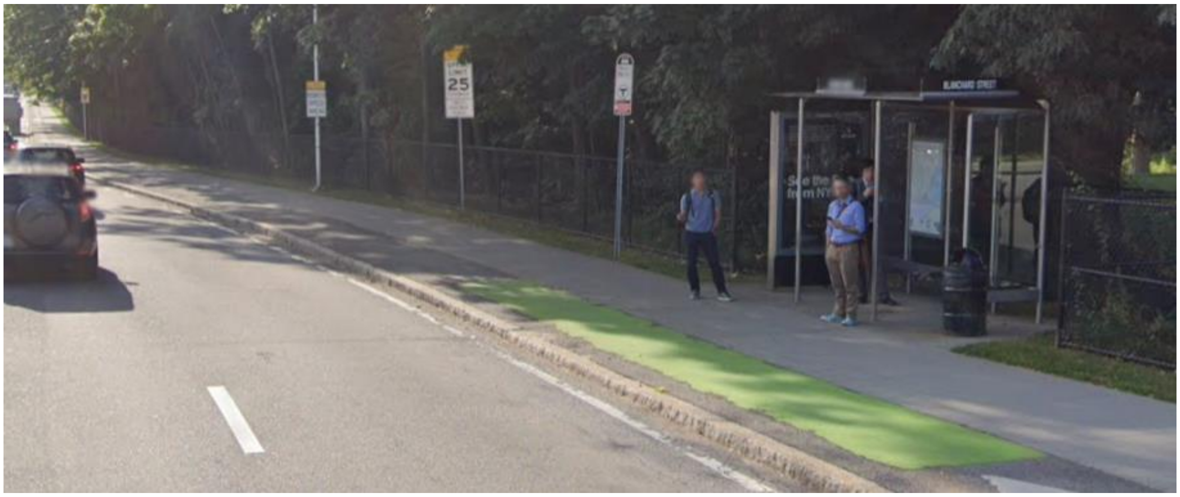


Figure 3.11: Distribution of bus stop shelter location by floating bus stop type



Source: [17]

Figure 3.12: Bus stop shelter located on the platform (Commonwealth Ave at Pleasant St, Brookline, MA)



Source:[17]

Figure 3.13: Bus stop shelter located on the sidewalk (Concord Ave at Blanchard Rd, Cambridge, MA)

3.1.5 Bus Stop Sign Location

Bus stop sign location is important, especially for visually impaired transit riders, as they use them to confirm the bus stop location where they typically wait to board the bus. The distribution of bus stop sign locations by floating bus stop type is shown in Figure 3.14. Most of the full-width and partial-width bus stops are located on the platform, in contrast with the no platform ones that lack platforms and, therefore, feature bus stop signs on the sidewalk. However, even for the full-width bus stops, only one of them (4%) has the bus stop sign pole adjacent to the bus shelter and located on the platform. Examples of the bus stop sign locations are presented in Figure 3.15 and Figure 3.16.

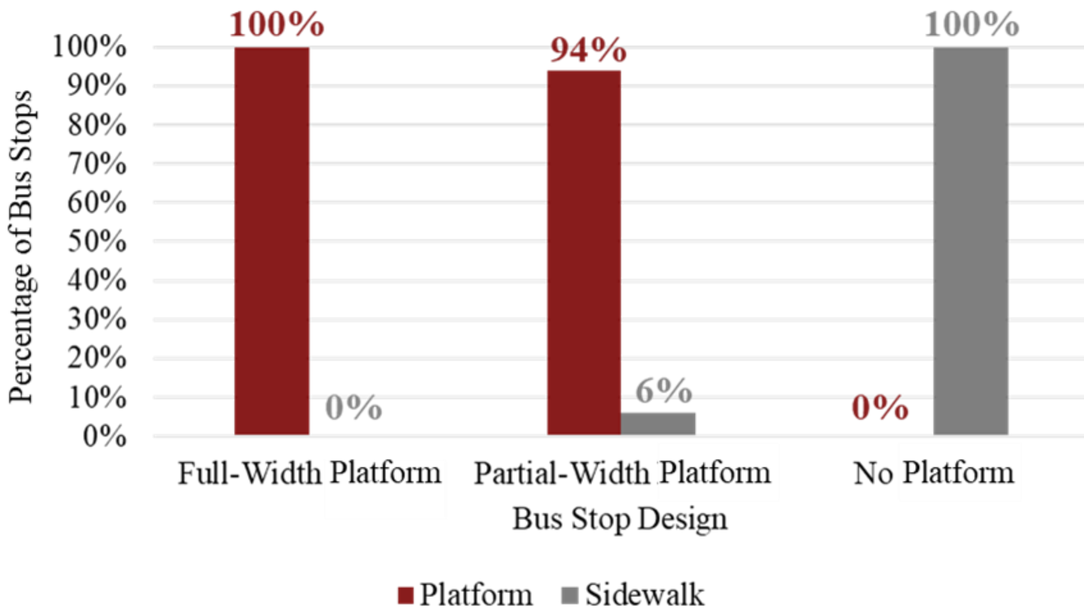


Figure 3.14: Distribution of bus stop sign location by floating bus stop type

Source: [17]

Figure 3.15: Bus stop sign located on the platform (130 Western Avenue, Boston, MA)

Source: [17]

Figure 3.16: Bus stop sign located on the sidewalk (Concord Avenue at Spinelli Place, Cambridge, MA)

3.1.6 Bus Stop Benches

Benches provide bus riders with the opportunity to sit and rest while waiting for the bus to arrive. They are crucial for passengers who have difficulty standing, such as the elderly and disabled individuals. The percentage of bus stops with benches on the platform or in the shelter is shown in Figure 3.17. Over half of the full-width platform bus stops have benches either on the platform or in the shelter, unlike the partial-width bus stops and the no platform bus stops with much smaller percentages of those bus stops featuring benches. Example of bus stop benches on the platform or shelter is presented in Figure 3.18.

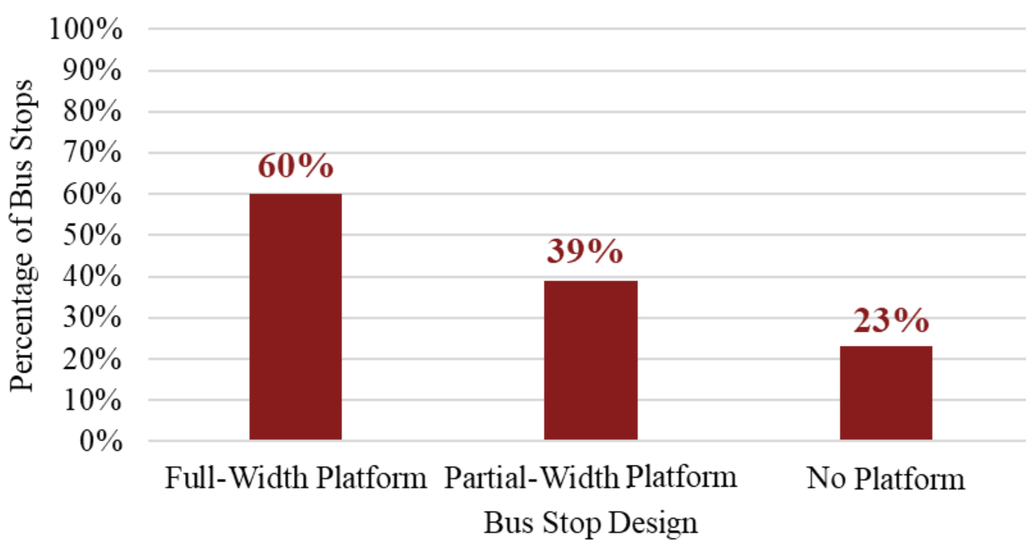


Figure 3.17: Percentage of floating bus stops with benches on the platform or shelter by floating bus stop type

Source: [17]

Figure 3.18: Bus stop benches on the platform (Western Ave at Putnam Ave, Cambridge, MA)

3.1.7 Fencing

Fencing defines and restricts the platform area, separating bicyclists and pedestrians. Fences also create a channelized scene for bicyclists to capture their attention and slow them down. The percentage of bus stops with fences is shown in Figure 3.19. These results indicate that fencing is not common, yet it is more likely to be integrated with full-width floating bus stops compared to partial-width ones. Example of floating bus stop with fencing is presented in Figure 3.20.

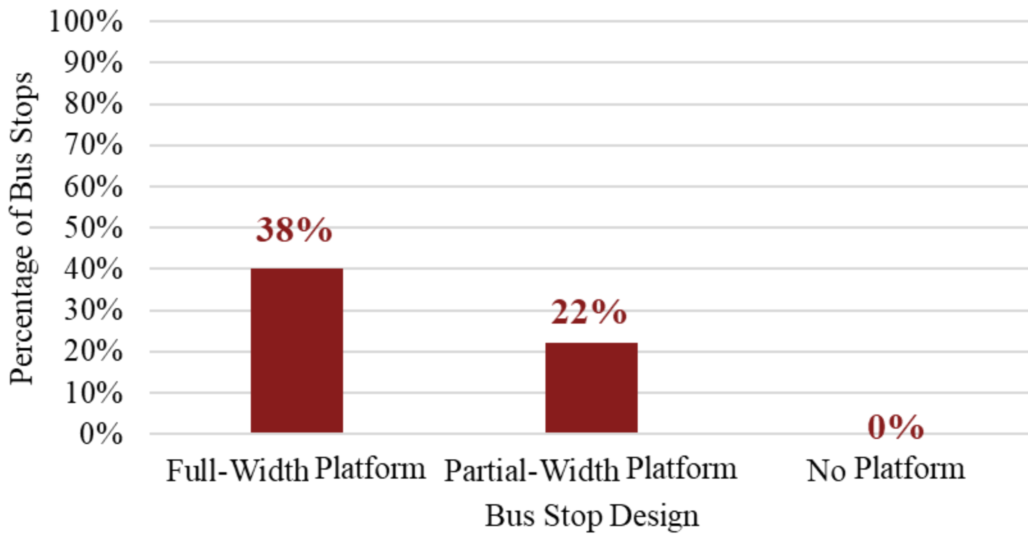


Figure 3.19: Percentage of floating bus stops with fencing

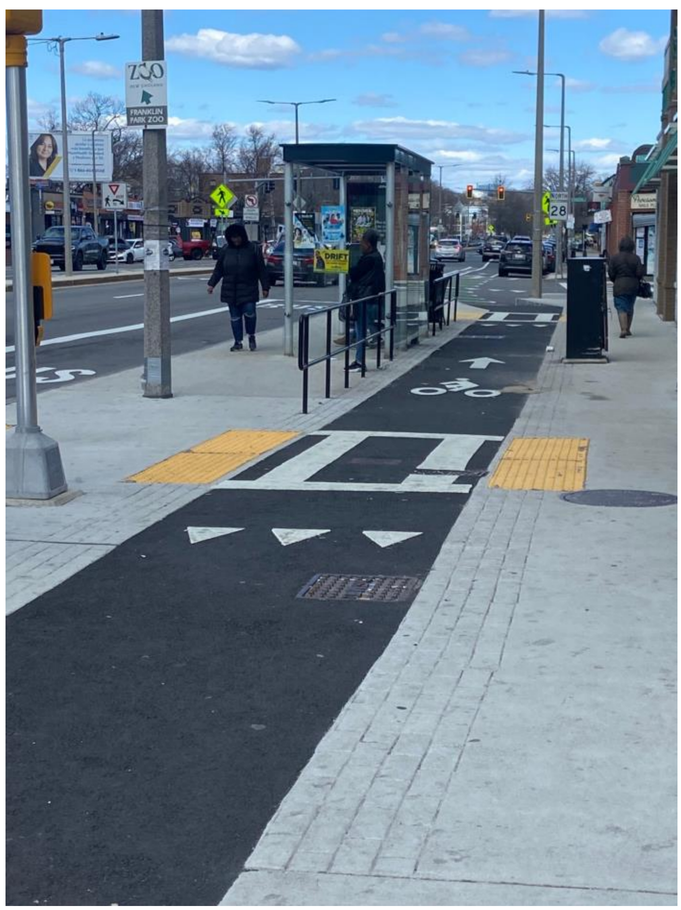


Figure 3.20: Floating bus stop with fencing (Morton St at Blue Hill Ave, Boston, MA)

3.1.8 Tactile Pavement

Tactile pavement helps visually impaired pedestrians navigate infrastructure and is typically located along sidewalks or to indicate the stops. Example of floating bus stops with tactile pavement is presented in Figure 3.22.

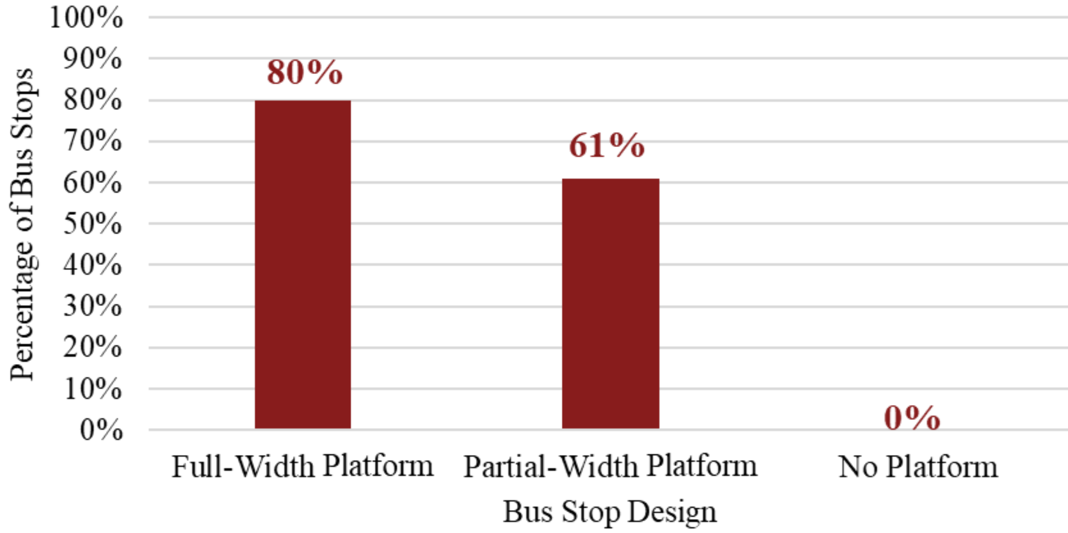


Figure 3.21: Percentage of floating bus stops with tactile pavement at crosswalks by floating bus stop type

Figure 3.22: Floating bus stop with tactile pavement (Hampshire St. at Cambridge St., Cambridge, MA)

3.1.9 Signage & Pavement Markings

When bicyclists pass through crosswalks, they should yield to pedestrians and transit riders when those are crossing the bike lane to either board or alight the bus or enter the platform when there is one. Having signs or pavement markings is a way to remind and warn bicyclists that there might be pedestrian crossings and that they might need to adjust their speeds and yield to crossing pedestrians. The related signs include yield signs (Figure 3.23), pedestrian warning signs (Figure 3.24), and bicycle yield to pedestrian signs (Figure 3.25). The related pavement markings include yield line (Figure 3.26) and yield to pedestrian pavement markings (Figure 3.27). Figure 3.28 shows the percentage of floating bus stops with signage and/or pavement markings. The results show that the partial-width bus stops have the highest percentage of both signs and markings near crosswalks, and the no platform bus stops have the highest percentage of having signs only.

Source: [19]

Figure 3.23: Yield sign

Source: [19]

Figure 3.24: Pedestrian warning sign

Source: [19]

Figure 3.25: Bicycle yield to pedestrian sign

Source: [19]

Figure 3.26: Yield line

Figure 3.27: Yield to pedestrian marking

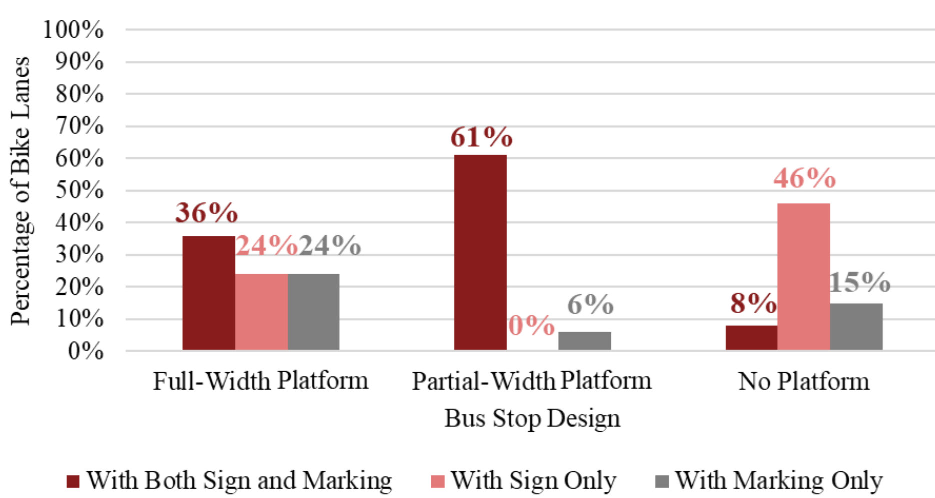


Figure 3.28: Percentage of floating bus stops with signage and/or pavement markings

Although the inventory data obtained from publicly available data (e.g., Google Maps and Streetview) provides a sufficient amount of information for the research team to distinguish the bus stop designs and support the subsequent behavioral analysis at the selected bus stops, additional geometry information (e.g., crosswalk width, fence height, etc.) is helpful for understanding bus stop design and its implications on transit rider safety. Table 3.2 lists the dimensions of the selected bus stops as calculated by LiDAR point cloud data. Figure 3.29 illustrates how the geometries were measured from the collected point cloud data.

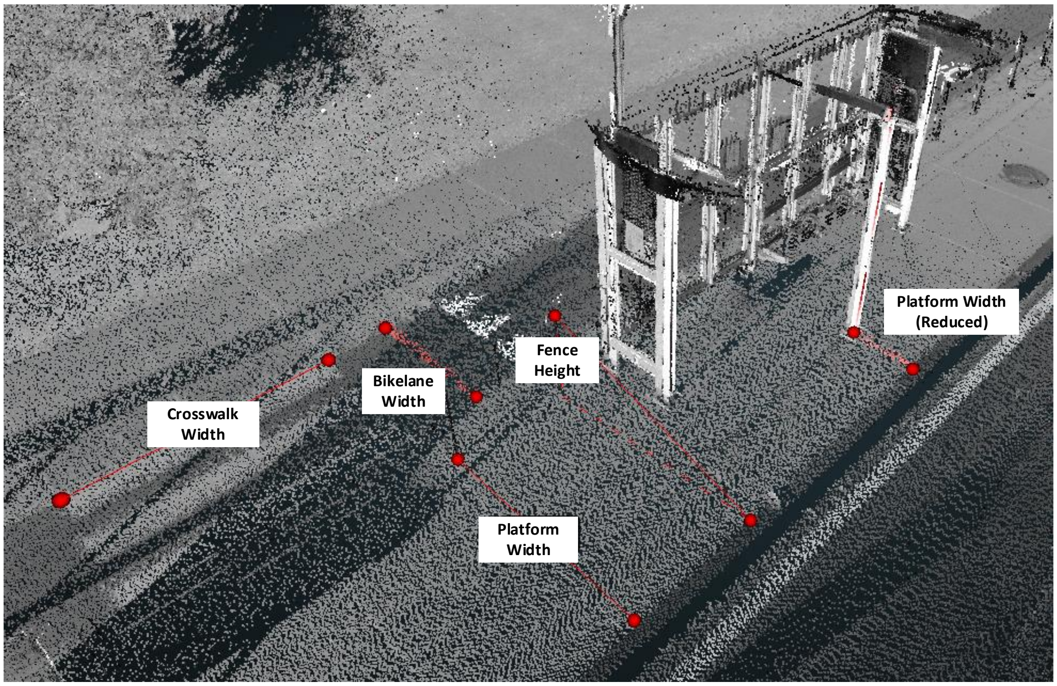


Figure 3.29: Illustration of the measurement for the detailed dimensions (Bus Stop at Washington St. at Walnut St.)

Table 3.2: Detailed dimensions for selected floating bus stops

Bus Stop Google Maps	Google Maps Width (ft.) Platform	Google Maps Width (ft.) Bike Lane	LiDAR Scan Width (ft.) Platform	LiDAR Scan Width (ft.) Bike Lane	LiDAR Scan Width (ft.) Crosswalk	LiDAR Scan Height (ft.) Fence
Massachusetts Ave. opp. Science Ctr	5.0	4.3	4.5	4.7	4.8	-
Washington St. at Walnut St.	8.0	4.0	7.8 (4.5)	4.8	6.4	2.8
Broadway opp. Beacham St.	0.0	4.5	0.0	4.6	5.9	-
Broadway at Horizon Way	8.0	4.0	7.5	5.8	10.5	-
Somerville Ave. at Stone Ave.	7.1	4.5	6.7 (5.1)	4.9	9.4	3.5

LiDAR can not only provide more accurate geometry measurements but can also more critical information that is not feasible from aerial images and data sources like Google Maps. For example, for the bus stops at Washington Street at Walnut Street and Somerville Avenue at Stone Avenue, the platform width is straightforward to measure (i.e., the width of the "island platform"). The same holds for other horizontal measurements, i.e., Google Maps and LiDAR scans provide similar measurements. However, from Google Maps, many vertical fixtures that may reduce the effective clearance of the platform (i.e., width), such as shelter supports and fences, are hard to capture. In contrast, a LiDAR scan can provide detailed in-situ contexts for identifying these vertical fixtures. Therefore, Table 3.2 shows two different platform widths under the LiDAR scan column Figure 3.30 illustrates such a scenario at the bus stop at Washington Street at Walnut Street.

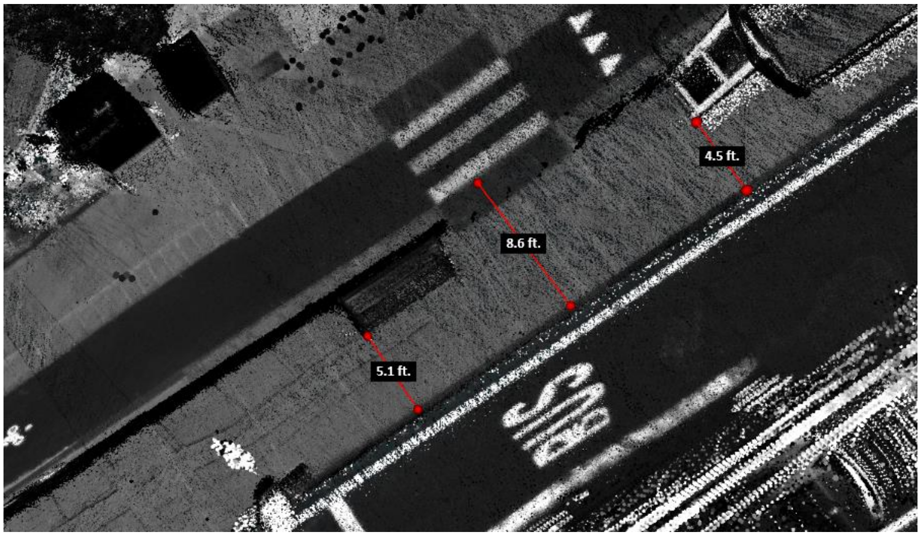


Figure 3.30: Illustration of the impact of vertical fixtures on platform width measurements at Washington Street at Walnut Street

The impact of the geometry shift along the bike lane, e.g., horizontal deflection and vertical slope were also considered. While these parameters may be observable from Google Streetview, they are hard to quantify. In contrast, the inventory data from the LiDAR scan can conveniently provide detailed measurements for the geometry shift. Figure 3.31 shows an example of the longitudinal profile along the redline of the bike lane at Washington Street at Walnut Street.

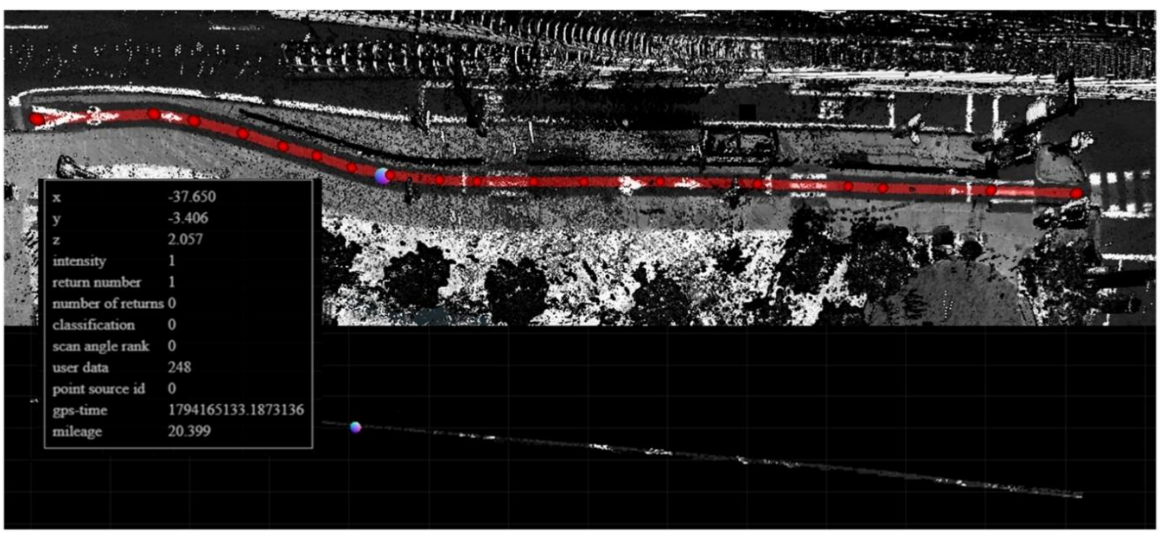


Figure 3.31: Longitudinal profile (with vertical grade) of the bike lane near the bus stop at Washington Street and Walnut Street

Summary of Inventory Findings

A thorough review of the elements associated with the 56 floating bus stops within MBTA's service. Approximately half of the floating bus stops are full-width platforms, about one third of them partial-width platforms, and the rest are no platform floating bus stops and primarily concentrated in Somerville. Most floating bus stops feature one-way bike lanes. Horizontal and vertical curvature is common at full-width platform bus stops and less so at partial-width or no platform bus stops. In fact, no horizontal curves were identified at partial-width and no platform bus stops possibly due to space limitations.

Bus shelters are only present in fewer than half of all floating bus stops and exclusively located on the platform for the full-width platform bus stops and on the sidewalk for the rest of the floating bus stop types, when present. Bus stop signs while present in the vast majority of floating bus stops are located on the platform for full- and partial-width platform bus stops and the sidewalk for no platform bus stops. This indicates that in most cases partial-width platform bus stops do not feature their bus stop signs next to the bus stop shelters. In addition, bus stop benches are only present to a subset of bus stops that is diminishing as we go from full-width to partial-width, to no platform bus stops.

Fencing is not commonly found at these floating bus stops and restricted to full-width and partial-width platform bus stops. In addition, tactile pavement at the two ends of crosswalks was not present at all bus stops with full-width platform bus stops featuring a higher percentage compared to partial-width platform bus stops. The presence of yield and warning signage varied drastically from one floating bus stop type to another with the combination of signage and pavement markings being more common at partial width bus stops. Lastly, LiDAR scans provided point cloud data that were useful for determining dimensions otherwise hard to obtain through aerial images, such as fencing height. Measurements at the five selected bus stops show a variety of crosswalk widths and fencing heights. In addition, these measurements when compared with those obtained from Google Maps, showcase the accuracy obtained when measuring other widths such as platform widths as it can account for vertical features, such as poles and fencing that can be reducing the effective width of the platform. Overall, this inventory effort provides evidence of the variability existing in the design of floating bus stops even within the same floating bus stop type. As a result, it is critical to understand the impact of design elements on bicyclist and transit rider behavior and interactions and develop design guidelines to improve accessibility and safety critical. To achieve this, it is crucial to first understand existing guidance and the state-of-practice related to the design of floating bus stops.

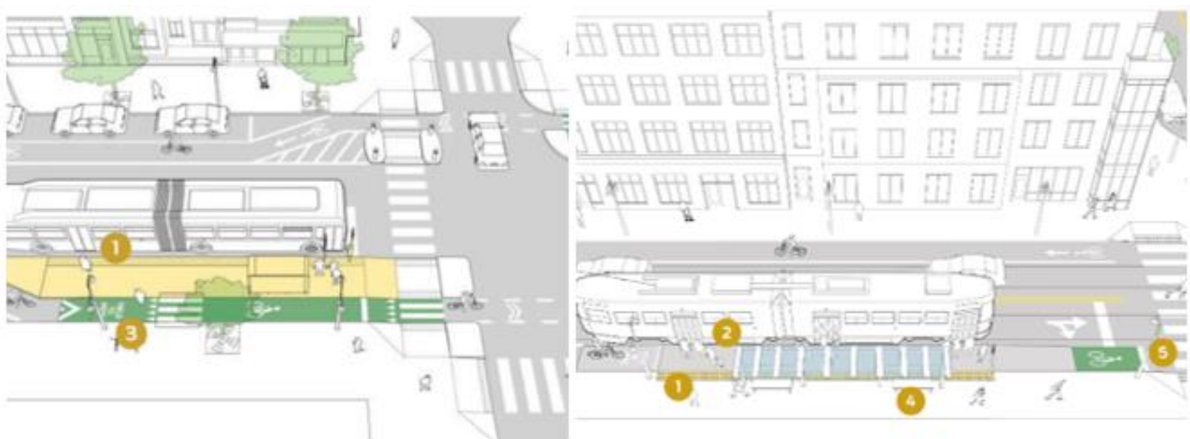
3.2 Literature Review

The review of the literature consisted primarily of guidebooks that include guidance related to the design and implementation of floating bus stops, both in the United States and abroad. An attempt to identify research publications related to the design of floating bus stops and the impact of such design on bicyclist and transit rider behavior and interactions was not fruitful as no study prior to this one has studied these interactions in a comprehensive manner. The following sections present design guidelines related to floating bus stops, by guidebook.

3.2.1 Accessible Bus Stop Design Guidelines in the United States

NACTO Transit Street Design Guide [1]

The National Association of City Transportation Officials Transit Street Design Guide uses the term “Side Boarding Island Stop” to refer to both the full-width platform and the partial-width platform floating bus stops and “Shared Cycle Track Stop” for the no platform bus stop; see Figure 3.32.



(a) Side boarding island stop **(b) shared cycle track stop**

Source: [1]

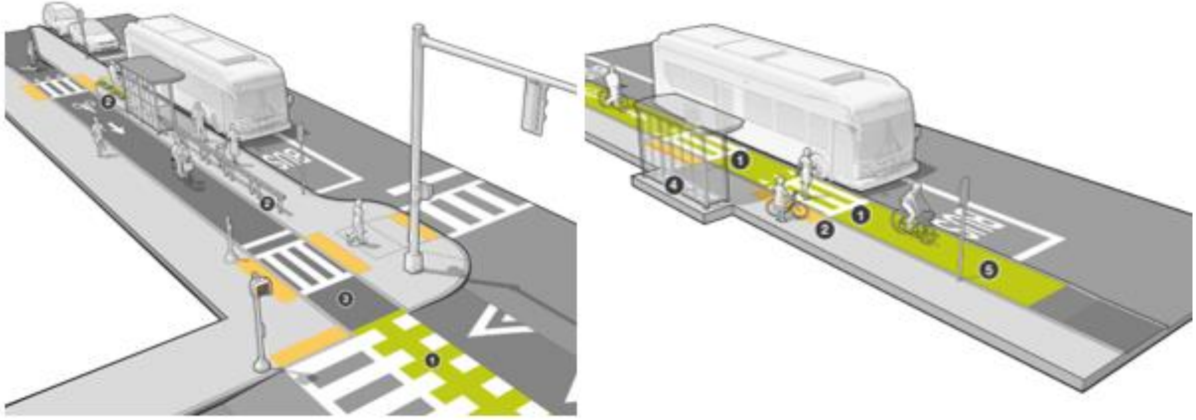
Figure 3.32: Floating bus stop types based on the NACTO Transit Street Design Guide

Guidelines related to the side boarding island stops suggest a minimum bike lane width of 5 feet. Bicyclists are expected to yield to transit riders crossing the bike lane, and this yielding behavior can be motivated with the use of markings, colored pavement, and signs. These guidelines suggest that the boarding area has dimensions of 8 x 5 feet to ensure that wheelchair users can be accommodated. In addition, platform access ramps must have a maximum slope of 1:12 at crosswalks, other crossing places, walkways, and while transferring onto the platform to ensure compliance with accessibility regulations. It is recommended that shelters be placed at least 10 feet away from crosswalks to allow for adequate sight and safety between bicyclists and those exiting the platform. Furthermore, the insertion of leaning rails along this gap might provide additional support and convenience to pedestrians. When a bike lane or cycle track requires bicyclists to yield to pedestrians at a crosswalk from the sidewalk into the platform, the placement of the "BIKES YIELD TO PEDESTRIANS" sign (MUTCD R9-6) and yield triangle markings is required. A YIELD stencil marking in the bike channel before the crosswalk is an optional feature that can be implemented to reinforce the yielding requirement. Reflective signage or elevated components on the platform’s leading corner are critical for visibility, with "KEEP LEFT" or "KEEP RIGHT" signage (MUTCD R4-8) or object markers (OM-3) being the two options that can be used.

Shared cycle track stops are a retrofit solution for transit corridors with limited space when traditional boarding islands are not possible. In this case, the bike lane or protected bike lane is raised and aligned with it along the expanded curb. In the absence of transit vehicles, bicyclists can freely travel on the boarding area, but they must yield to passengers boarding and alighting from buses or streetcars at stops. To improve safety and accessibility, it is critical to install detectable warning strips along the sidewalk edge where passengers enter the shared raised boarding area, as well as along the boarding area curb where passengers board the transit vehicle. In addition, the inclusion of shark teeth yield markings near the top of the bicycle ramp leading to the platform can improve awareness and encourage yielding behavior. Another critical design element for the shared cycle track stops is the designation of a waiting area that is accessible to wheelchair users. This waiting area should be deliberately positioned away from potential conflict areas, providing wheelchair users with a safe and unrestricted path. The whole width of the shared cycle track can be used as an accessible boarding area for wheelchair lifts, providing seamless access. Furthermore, it is recommended that the boarding platform ends at least 10 feet away from the crosswalk to encourage efficient traffic flow and reduce conflicts. This separation allows bicyclists to wait ahead of transit vehicles while pedestrians are crossing at the crosswalk upstream.

Massachusetts Department of Transportation (MassDOT) Separated Bike Lane Planning & Design Guide [2]

MassDOT Separated Bike Lane Planning & Design Guide lists two types of bus stops, namely the floating and constrained bus stops, with floating referring to those presenting a platform and constrained being equivalent to the no platform bus stop design; see Figure3.33.



Source: [2]

Figure 3.33: Platform and no platform floating bus stops based on the Massachusetts Department of Transportation Separated Bike Lane Planning & Design Guide

Based on this guide, the recommended platform width for floating bus stops is 8 feet. A pedestrian access route connecting the sidewalk, the boarding and alighting areas, and any shelters or benches must be present. Although it is recommended to have two pedestrian crossings, guidelines do not require them. Additionally, it is recommended that the bike lane be raised to the sidewalk level, or pedestrian crossings should be offered at level in cases where there is insufficient space. The location of bicycle transition ramps should be away from any lateral movement in the bike lane and close to crosswalks. Shelters and other vertical objects that are 36 in or higher should be located at least 6–12 in. from the edge of the bike lane. At the back of high ridership stops or along two-way separated bike lanes, railings or planters (with a maximum height of 3 ft.) can be installed to direct pedestrians toward marked crossings and to safeguard bicyclist safety. To make the area safer for bicyclists, the railings' ends ought to be flared inward toward the bus stop and away from the bike lane.

In constrained areas where space is limited, it is recommended to narrow the bike lane along the bus stop. To minimize the risk of pedal strikes on curbs, it is advised to raise the bike lane to sidewalk level if the width is reduced to 4 feet (any width less than 5 feet requires a design exemption). Two-way bicycle facilities should have a minimum width of 8 feet available. To provide accessible and safe movement for passengers when dealing with an intersection floating bus stop, it is crucial to ensure a level landing area at curb ramps, with a minimum size of 4 ft. by 4 ft.

When narrowing the bike lane is not possible, constrained bus stops are implemented; see Figure 3.20. At this type of bus stop, the bike lane is elevated to the sidewalk level and serves as a platform for the bus stop. Bicyclists should use caution to avoid conflicts with waiting passengers at all other times, and they must yield to anyone getting on or off the bus. Although a design exemption is necessary for bike lane widths less than 5 feet, it is crucial to keep the bike lane short to a width below 4 feet. Additionally, the combined width of the bike lane and the sidewalk must be at least 8 feet for it to be considered an accessible boarding and alighting space. To improve safety, a "DO NOT PASS WHEN BUS IS STOPPED" sign is recommended for placement ahead of the first pedestrian crossing seen by bicyclists, which corresponds to the rear door clear zone. Additionally, inside the confined bike lane, the use of optional colored pavement can be considered.

Massachusetts Bay Transportation Authority Bus Priority Toolkit [3]

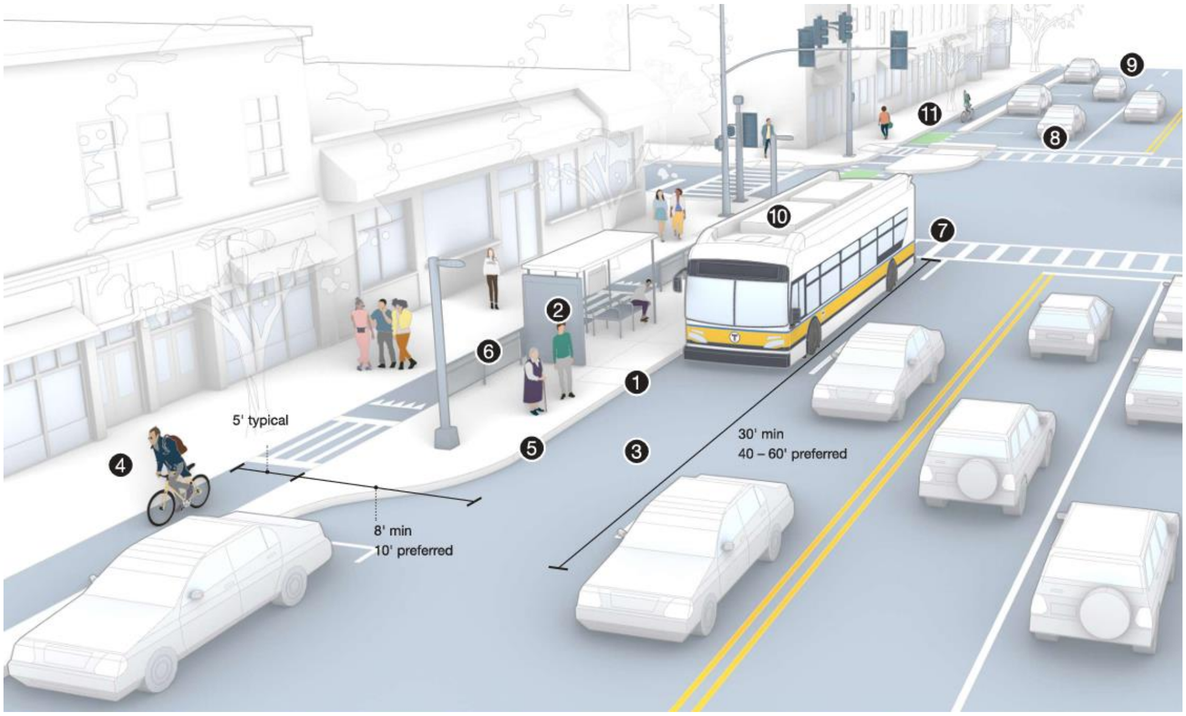
MBTA's bus priority toolkit introduces the benefits and challenges of implementing floating bus stops, which include reduction of conflicts between bicycles and buses and reduced dwell times and the introduction of conflicts between bicyclists and passengers crossing the bike lane.

Figure 3.34 presents the design dimensions of floating bus stops. The minimum width requirement for the platform is 8 feet, with a recommended width of 10 feet. The minimum length requirement for the bus stop area is 30 feet, with a recommended length of 40 feet. The typical adjacent bike lane width is 5 feet.

In order to slow bicyclists down and indicate crossings over the bike lane, effective signage and stripping are required for the bike lane – at minimum, a bike symbol and yield marking for crossing pedestrians. The bike lane can be at the sidewalk or street level. When the bike lane is at the sidewalk level, it should be painted to be easily distinguishable from the sidewalk and supplemented with yield pavement markings placed on the bike lane approach to the crosswalk.

Crosswalks should preferably be implemented at each end of the floating bus stops. Fencing and seating should serve as a barrier between the platform and the bike lane at bus stops with high volumes of pedestrians and bicyclists.

MBTA has also published the MBTA Bus Stop Planning Guide [4], which however, does not mention floating bus stops or provide any design guidelines for such bus stops.



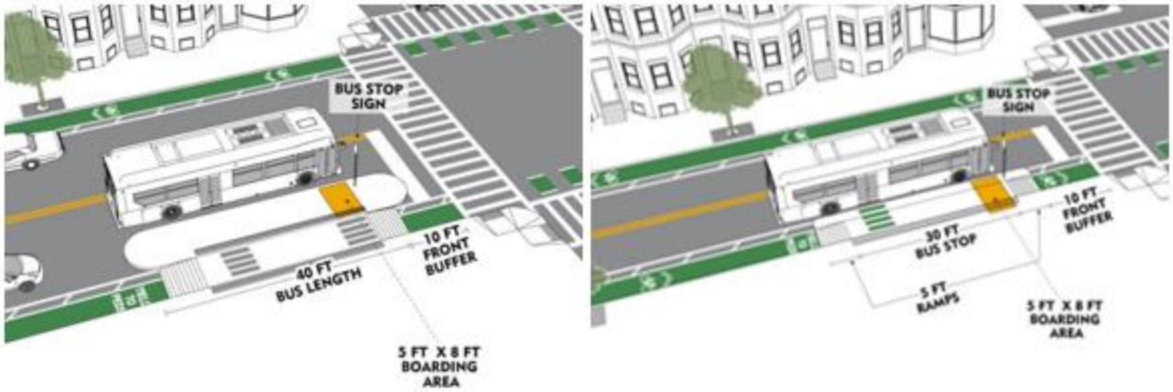
Source: [3]

Figure 3.34: Design dimensions of floating bus stops based on MBTA's Bus Priority Toolkit

Maryland Department of Transportation (MDOT) Bus Stop Design Guide [5]

The MDOT bus stop design guidelines use the same terminology of "boarding island stops" and "shared cycle track bus stops" to refer to floating bus stops with platforms versus the no platform ones; see Figure3.35.

MDOT's guidelines for the boarding island stops (Figure 3.22a) state that the boarding area should be at least 5 feet by 8 feet wide; however, there is no width restriction for the platform itself. To ensure accessibility, a walkway from the boarding island to the sidewalk must be established, with curb ramps planned with slopes not exceeding 1:12. The boarding island should be built to allow for level or near-level boarding aboard buses. The presence of an elevated crosswalk between the boarding island and the sidewalk can help with access to the boarding island stop. In the case of concrete boarding island stops, bus stop signage should be installed on the boarding island and for boarding island stops utilizing temporary boarding platforms, it should be positioned on the existing sidewalk and aligned with the boarding area. It is recommended that the bicycle channel be distinguished from the sidewalk and bus stop in the context of boarding island stops with a bicycle channel at sidewalk level by using contrasting materials or implementing green color treatments widely utilized for bicycle facilities.



a) Boarding Island Stop b) Shared Cycle Track Bus Stop

Source: [5]

Figure 3.35: MDOT's Floating Bus Stop Types

The "Shared Cycle Track Stop" is another kind of bus stop design that is used when there is insufficient street width to construct a separate bicycle channel behind a boarding island stop; see Figure3.22b. In this configuration, a bicycle lane or cycle track rises to curb height, extends through the boarding area, and then returns to street height. The elevated portion of the bicycle facility also serves as the boarding and alighting area. The use of pavers or contrasting materials to differentiate the area adjacent to the curb and alert bicyclists to the presence of the bus stop is recommended for shared cycle track stops. The slopes of the bicycle ramps (i.e., vertical curve) on either side of the bus stop must not exceed a 1:8 ratio. It is critical to provide a waiting area free of conflicts with bicycles for wheelchair users while simultaneously ensuring that passengers with visual impairments receive multi-sense information to avoid conflicts with bicycles. Furthermore, the width of the bicycle lane or cycle track should be designed to allow for the cleaning of snow and debris by available sweeping and plowing equipment.

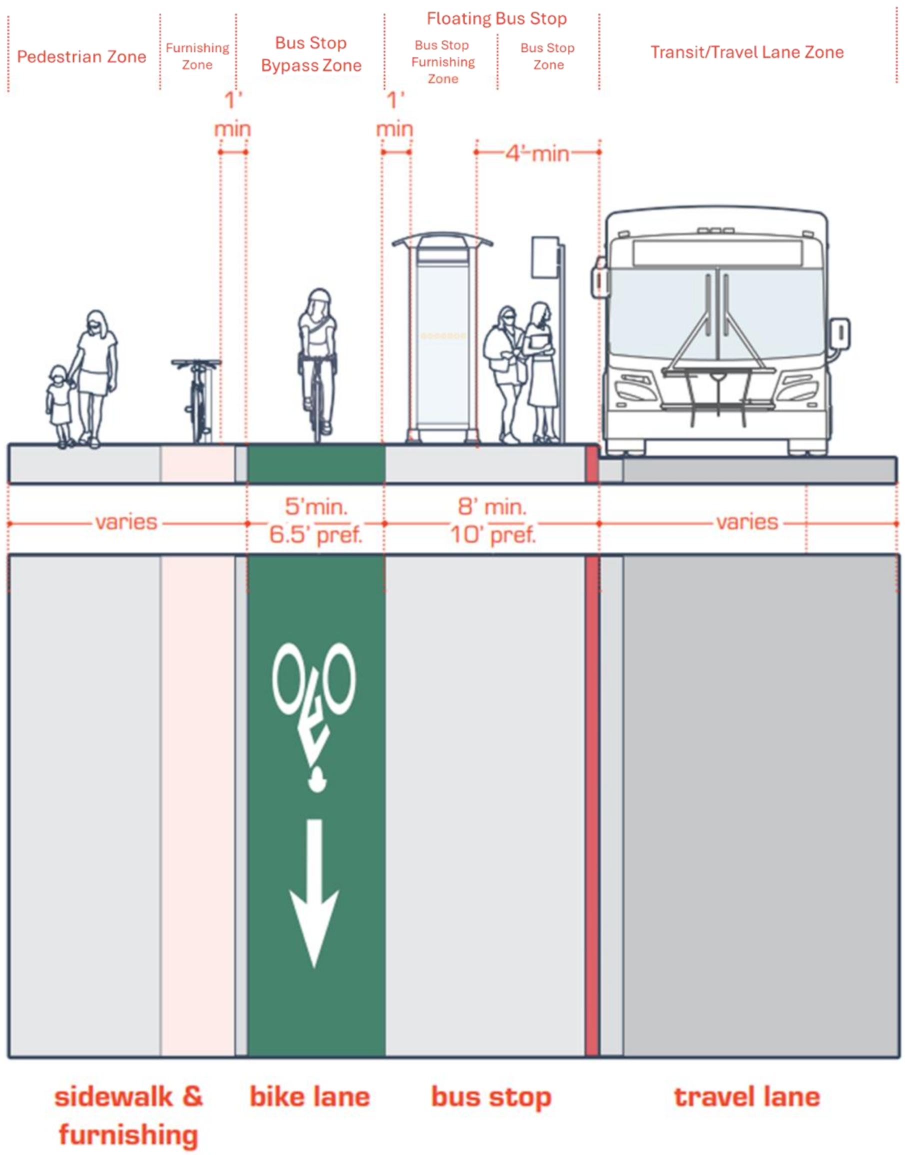
Rhode Island Bus Stop Design Guide [6]

The Rhode Island Bus Stop Design Guide describes design guidelines for "floating bus stops" or "bus islands," but it does not get into the specific dimensions of their design. Bike lanes can be flush with the sidewalk grade, at roadway grade, or even lower than the sidewalk and curb extension grades, with connections formed via crosswalks and curb ramps. While conflicts between bicyclists and crossing bus riders may develop, bicyclists must always yield to pedestrians. To highlight this priority, signs and striping are used within the bike lane. The bike lane should have at least minimal striping, such as a bike symbol and yield signs for crossing pedestrians. Depending on the design, the bike lane can be situated at street level, sidewalk level, or an intermediate position, and it may or may not be painted. The green paint of the bike lane adds emphasis to the conflict zone.

Alameda Contra-Costa County Transit (AC Transit) Multimodal Corridor Guidelines [7]

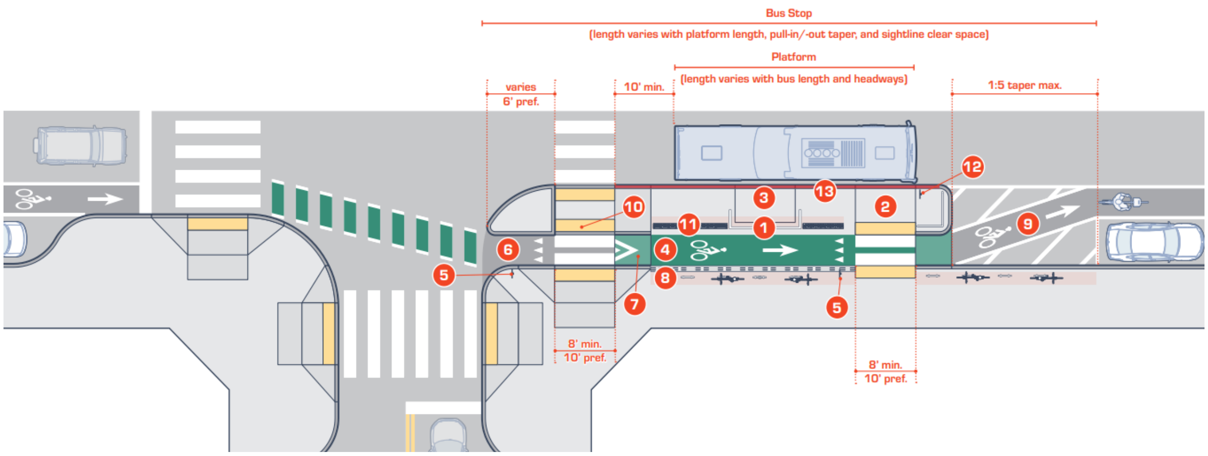
The AC Transit guidelines categorize floating bus stops into different typologies based on the location of the bicycle facility relative to other elements, such as the curbside parking lane, general traffic lane, or parking lane. To improve safety, design features at the floating bus stop and furnishing zone should be at least 1 ft away from the bike facility. Figure3.36 presents a section view of a floating bus stop, showing contest zones and the minimum and preferred dimensions for the different elements that can be present at those bus stops. A bus stop area is divided into a pedestrian zone, furnishing zone, bus stop bypass zone, floating bus stop, and travel lane zone. Among them, the furnishing zone is typically reserved for seating, lights, parking stations, and other utilities supporting a multimodal environment, which is essential for accessibility. It can also vary between blocks and along the corridor. Bicyclists are required to yield to pedestrians at designated crossings, which are marked with yield markings and optional signs. Detectable panels can guide visually impaired pedestrians.

The guidelines for the floating bus stop specify a maximum bicycle ramp slope of 1:12 from street to sidewalk level to ensure ADA compliance. The optimum bike lane transition taper is 1:10, with a maximum of 1:5; see Figure3.37. Bus shelter placement is optional for all typologies. The accessible landing zone should be a minimum of 5 feet by 8 feet. The use of green pavement to mark the bicycle lane is also optional, and so is the inclusion of a "Bikes Yield to Pedestrians" sign. The adoption of a red curb zone, marking the bus stop platform length, is also optional.



Source: [7]

Figure 3.36: AC Transit Section View of Floating Bus Stop

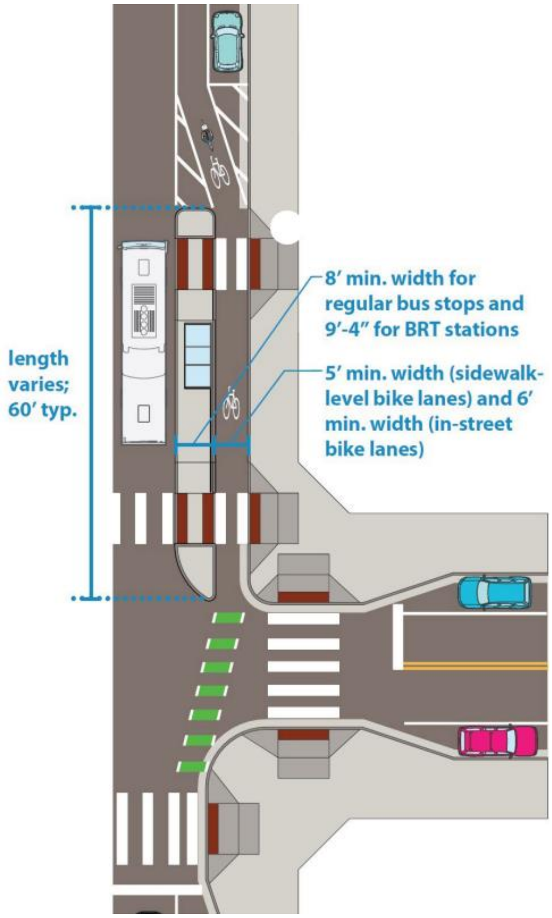


Source: [7]

Figure 3.37: AC Transit Plan View of Floating Bus Stop

Street Design Guidance-City of Minneapolis [8]

The City of Minneapolis Street Design Guidance states that, at floating bus stops, bicyclists are expected to yield to pedestrians. The bus stop platform dimensions ought to align with specifications for regular-route bus stops and Bus Rapid Transit (BRT) stations, with minimum widths of 8' and 9'4", respectively. A preferable 2' clear zone is recommended between the bikeway and the floating bus stop, while a 0' clear zone might be considered in constrained corridors. The curb height for regular service bus stops is typically sidewalk-level (6"), while BRT stations have a 9" elevation. A minimum bike lane operating width of 6' must be maintained for maintenance operations. Raised pedestrian crossings and crosswalk pavement markings should be considered to promote yielding to pedestrians, and colored concrete can be utilized to visibly identify the bike lane operating zone. Figure 3.38 shows the configuration of the floating bus stop and relevant dimension requirements per the City of Minneapolis Street Design Guidance.



Source: [8]

Figure 3.38: Floating Bus Stop Design Requirements based on the City of Minneapolis Street Design Guidance

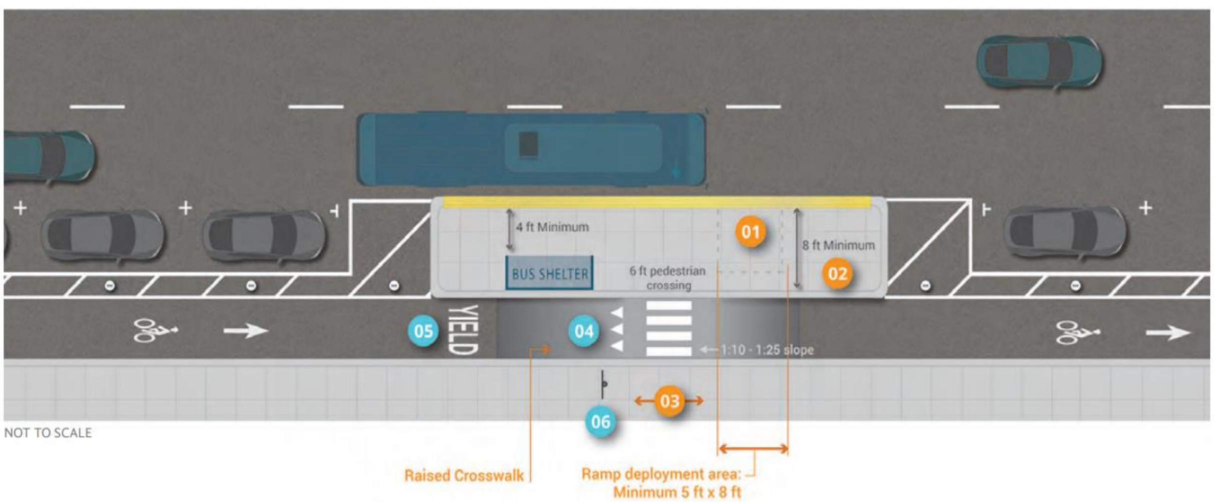
Arlington Transit Bus Stop Guidelines [9]

The Arlington Transit Bus Stop guidelines were updated in 2022 to include design specifications for floating bus stops. The guidelines state that the concrete island at floating bus stops should have a preferred width of 10 feet, with a minimum of 9 feet perpendicular to the travel lane. The height should be at least 6 inches, and it should be installed at a 1-foot distance from the travel lane. The island's length should accommodate a 45-foot stopping area for a single bus, with the possibility of reducing it for shorter buses. For single-direction bike facilities, the bike lane should be a minimum of 5 feet wide, while for two-way bike facilities, a minimum of 10 feet of width is required, and a 12-foot width is considered ideal. The bike lane width may be reduced at pedestrian crossing locations with collaboration from Transit Bureau officials. The bike lane should have a distinct variation in color from the pedestrian area and bus island, achieved by material variances or lane painting.

Reflective bicycle traffic control signs should be placed before the bus stop zone, including signs for pedestrian crossings, speed reduction, and yielding to pedestrians. High-visibility pavement markings for the bike lane include marked crosswalks, yield markings, bicycle stop bars, and raised crosswalk markings should also be installed. A detectable warning surface should be present at the loading area, and the island should include at least one pedestrian access point. A longitudinal directional indicator should be installed on the sidewalk to guide visually impaired individuals to the bus stop and crosswalk. Detectable warning surfaces should be provided at ADA-compliant ramps and pedestrian access pathways, including a 5'x8' loading area and a second area extending from the bus stop flag installation.

Federal Highway Administration (FHWA) Separated Bike Lane Planning and Design Guide [10]

This guidebook presents two types of island platform stops and one type of transit stop without a platform. The island platform with no separated bike lane bend (see Figure 3.39) is suitable for locations where the transit vehicle can stop in a travel lane. This design maintains the separated bike lane alignment, preserves sidewalk space, and allows for more on-street parking. Recommendations include providing a minimum clear space of 5 ft by 8 ft at the front end of the platform for accessible ramp deployment and ensuring a minimum crosswalk width of 6 ft, with the possibility of a wider crosswalk depending on transit boardings. Curb ramps with clearly marked crosswalks and detectable warning surfaces are recommended. Optionally, a raised crosswalk can be utilized to increase awareness and indicate a preferred crossing location, with a ramp slope of 1:10–1:25. As for requirements, yield line pavement markings can be placed before the crosswalk as per the MUTCD (2009), and a "YIELD HERE TO PEDESTRIANS" (MUTCD R1–5) sign should be installed prior the crosswalk.

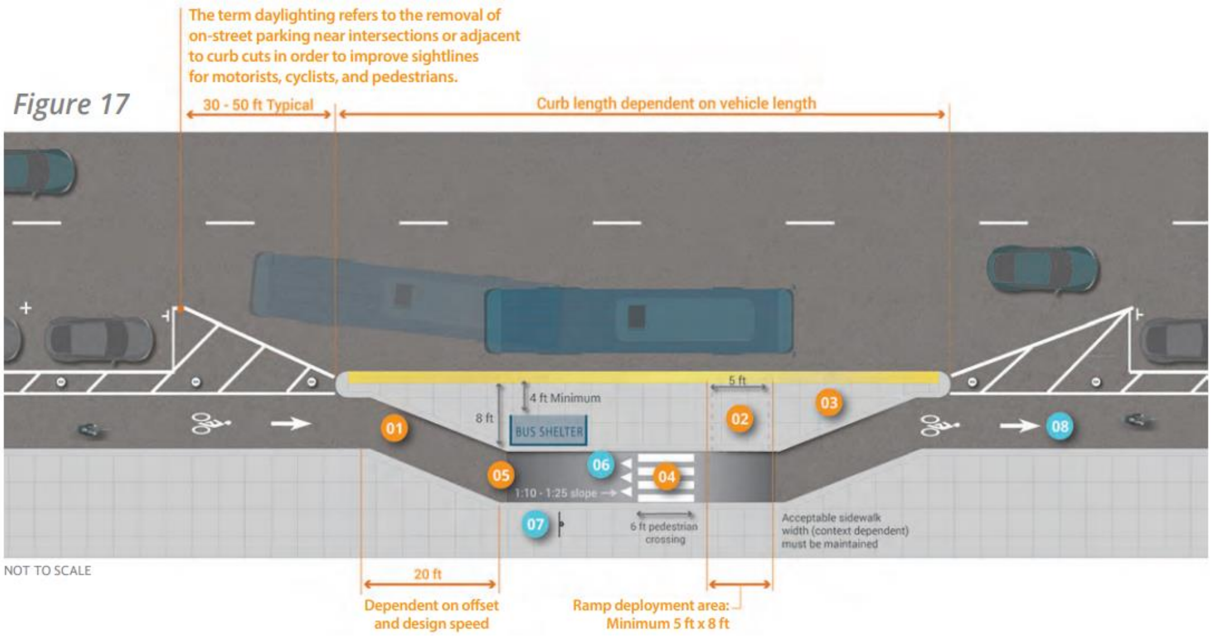


Source: [10]

Figure 3.39: Island Platform with No Separated Bike Lane Bend per FHWA's Separated Bike Lane Planning and Design Guide

In circumstances where the transit vehicle must move out of the travel lane, the guideline recommends using an island platform with a separated bike lane bend; see Source: [10]

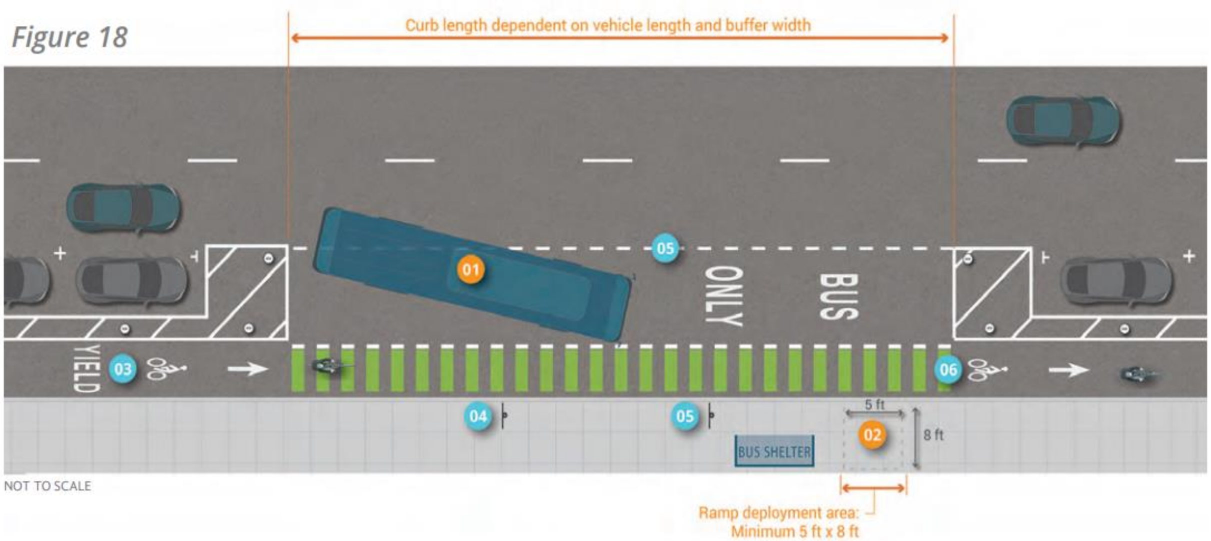
Figure 3.40. It is recommended that a minimum clear space of 5 ft by 8 ft be provided at the platform's front end to accommodate the deployment of an accessible ramp. If on-street parking is limited or absent, a narrower transit platform may be used, as long as the 5 ft by 8 ft level space is preserved. The island platform design with and without a separate bike lane bend is similar to the full-width floating bus stop mentioned earlier in other guidebooks.



Source: [10]

Figure 3.40: Island Platform with Separated Bike Lane Bend per FHWA's Separated Bike Lane Planning and Design Guide

In cases where bus service is infrequent (approximately four buses per hour or fewer), transit stops can be integrated into the separated bike lane; see Figure3.41. The front end of the platform should have a minimum clear space of 5 ft by 8 ft to allow for the deployment of an accessible ramp. It is recommended that optional "YIELD" markings be considered in the bike lane. Additionally, the installation of a "NO PARKING BUS STOP" sign (MUTCD R7-7) and optional BUS ONLY pavement markings (MUTCD Figure 3B-23) is required. This is a similar design to the no platform floating bus stop mentioned earlier.



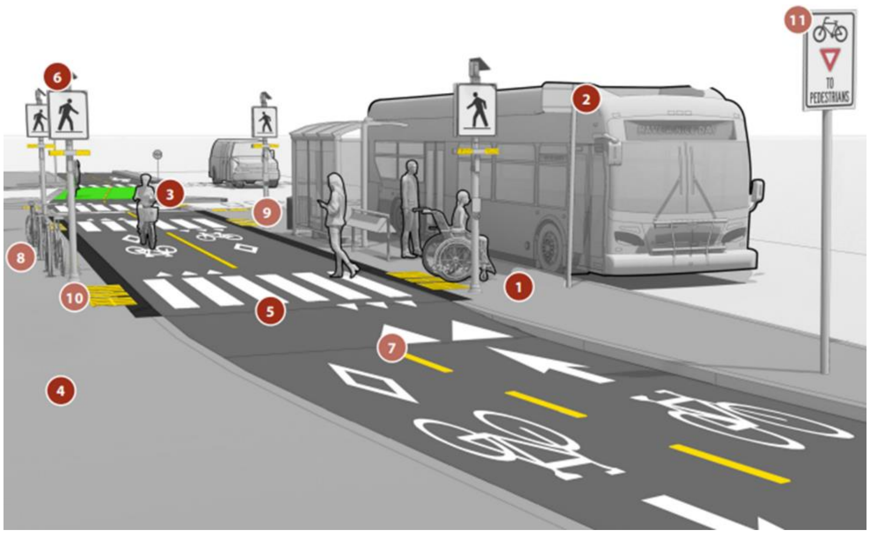
Source: [10]

Figure 3.41: Transit Stop Mixing with Separated Bike Lane per FHWA's Separated Bike Lane Planning and Design Guide

3.2.2 Accessible Bus Stop Design Guidelines in Other Countries

British Columbia [11]

Based on a British Columbia Human Rights Tribunal ruling (BCHRT 197) in November 2020, the Ministry of Transportation and Infrastructure updated its guidelines for floating bus stops to ensure that they are accessible to all users. The interim guidance, which is consistent with the ruling, calls for the installation of rapid rectangular flashing beacons (RRFBs) with a push button and an audible message at the crosswalk between the sidewalk and the floating bus stop. The minimum design elements, shown in Figure 3.42, according to this guideline include ① accessible landing pads, ② transit route identification pole, ③ rear clear zone, ④ pedestrian connection, ⑤ crosswalk, and ⑥ RRFBs with pedestrian push buttons and acoustic messages. Desired design elements consist of ⑦ ramp grade, ⑧ bicycle parking, ⑨ shelters and benches, garbage receptacles, ⑩ tactile walking surface indicator (with optional wheel gaps for mobility aids), and ⑪ a 'Cyclists Yield to Pedestrians' sign.



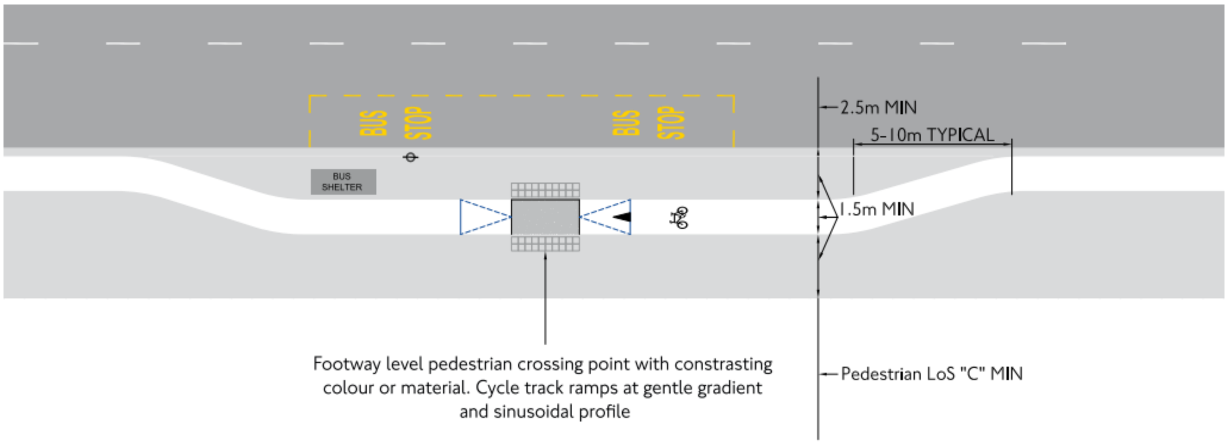
Source: [11]

Figure 3.42: Floating Bus Stop Elements

London, UK [12]

London’s Accessible Bus Stop Design Guidance uses the term "bus stop bypass" instead of floating bus stops. The bus stop bypass is an alternative to the shared bike-pedestrian zone, which typically involves building a shared footway for pedestrians around the bus stop and routing bicyclists around the rear of the bus stop. However, unless bicyclist volumes are low, this approach may present difficulties, particularly for pedestrians.

Figure 3.43 presents a layout for the bus stop bypass, showing some of the required dimensions. The recommended design for a bus stop bypass includes an island with a minimum width of 2.5 meters (8.2 ft) to accommodate wheelchair ramps and allow for comfortable maneuvering for wheelchair users. Wider islands are necessary for bus stops with significant passenger activity. The length of the bus stop should be considered based on bus flows. It is recommended to retain a minimum of 2 meters (6.6 ft) of clear width for the footway, with wider widths for potential obstructions. A clearly marked bus passenger crossing point with truncated domes, tactile pavement, and flush curbs along the cycle track must be provided. Narrowing the cycle track behind bus stops to slow down cyclists and allow safe crossings for bus passengers should also be considered. The cycle track crossing should be on a raised table, providing level access for pedestrians, bus passengers, and wheelchair users while promoting reduced speed and cyclist courtesy. Multiple crossing points should be considered for stops with multiple bus stop flags or high passenger numbers when pedestrian desire lines do not align with a single crossing location.



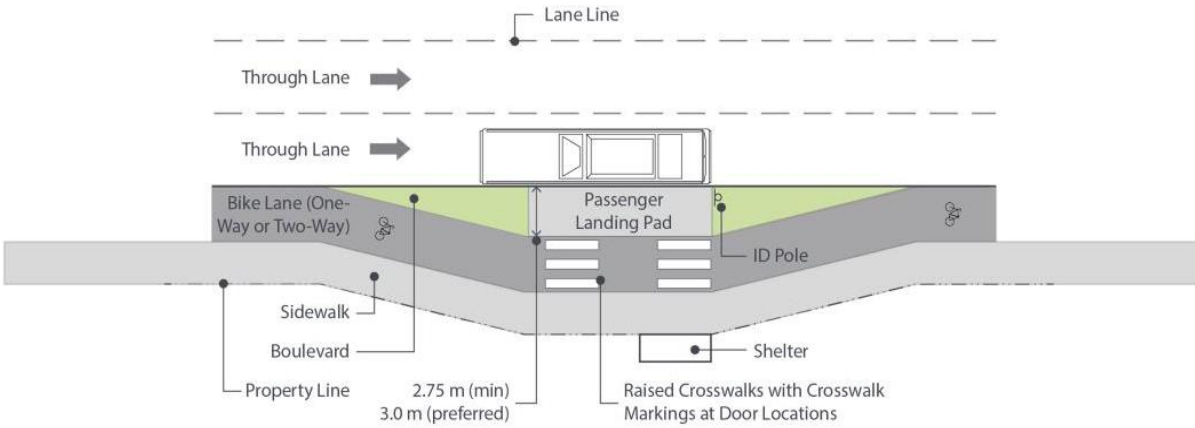
Source: [12]

Figure 3.43: Bus Stop Bypass Layout based on London's Accessible Bus Stop Design Guidance

The guidelines also suggest early engagement with possible users when proposing a bus stop bypass, particularly groups representing individuals with visual, mobility, hearing, or cognitive disabilities who may face greater dangers while crossing a cycle path to access the bus stop.

Vancouver, Canada [13]

Vancouver's TRANSLINK Bus Infrastructure Design Guidelines describe a potential design option of an "island bus stop" with a separated bike lane positioned between the sidewalk and the bus stop, given adequate available space; see Figure 3.44. This configuration can include a raised crosswalk spanning the bike path, covering both the front and rear bus door locations, along with designated crosswalk markings at the door areas. A crosswalk sign, supplemented by a sign instructing bicyclists to yield to pedestrians, is necessary to face approaching bikes. If a minimum 4m (13.12 ft)-wide island is provided, it is desirable to include a bus shelter within the island, as long as it doesn't obstruct sightlines between pedestrians and bicyclists. The platform should have a minimum width of 2.75m (9 ft).

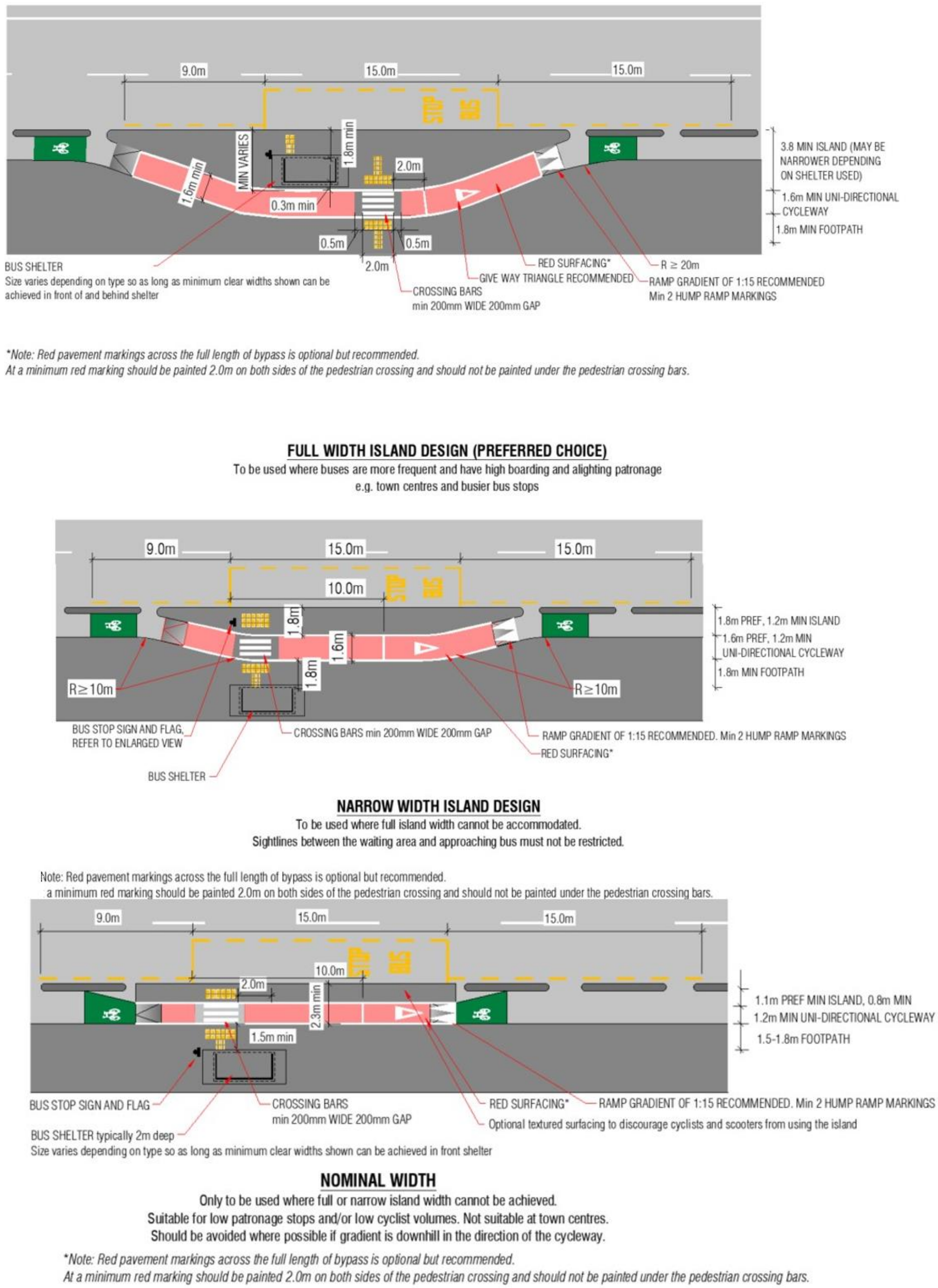


Source: [13]

Figure 3.44: Bus Stop Bypass Layout, Vancouver, Canada

Waka Kotahi, New Zealand [14]

New Zealand's Waka Kotahi Transport Agency bus stop guidelines refer to three distinct types of bus stops: full-width island bus stops, narrow-width island bus stops, and nominal-width island bus stops, as shown in Figure3.45.



Source: [14]

Figure 3.45: Waka Kotahi Transport Agency, NZ Floating Bus Stop Types

The full-width island bus stop layout in this manual offers bus passengers a dedicated waiting area that eliminates the need to cross the cycleway (i.e., bike path) when accessing the bus. The recommended minimum width for this layout is a 3.8m (12.36 ft) wide island, consisting of a 1.8m (5.9 ft) wide one-way cycleway and a 1.8m (5.9 ft) wide footpath, resulting in a total distance of 7.2m (23.62 ft) from the property boundary to the face of the island curb. Variations may occur depending on the specific circumstances. The minimum widths for a one-way separated cycleway range from 1.6m (5.25 ft) to 2.3m (7.55 ft) for a two-way separated cycleway. A cycleway behind a bus stop should have a minimum width of 1.2-1.4m (3.94-4.59 ft), depending on the presence of a curb. A limit line and give way marking are necessary before the pedestrian crossing, with the limit line set back 2m (6.56 ft). If the island allows for passenger waiting facilities such as a shelter or seat, a minimum separation of 300mm (11.81 in) is recommended, with a preferred minimum separation of 500mm (19.69 in).

In the case of a narrow-width island bus stop, the available space on the island may not be sufficient for passenger waiting facilities, which are instead provided on the footpath side of the cycleway; this is equivalent to the partial-width platform bus stop. It is crucial to ensure that the island's width allows for the deployment of an accessible ramp from buses and provides enough clearance for wheelchair users to move across the cycleway. Care must be taken to preserve accessibility for boarding and alighting at the bus stop. The preferred width for a narrow island is 1.8m (5.9 ft), but it can be reduced to 1.5m (4.9 ft) if space is limited, with an absolute minimum width of 1.2m (3.9 ft). The width of the cycleway remains the same as in the previous case.

In situations where it is not feasible to have a full-width or narrow-width island between the cycleway and the road, a nominal-width island is used, allowing bus passengers to directly access the bus through the cycleway, which is equivalent to the no platform bus stop. However, this design increases the potential conflict between bus passengers and bicyclists, as passengers must cross the cycleway, and the buffer space between the curb and cycleway is minimal. This design may hinder accessibility for individuals with disabilities or those who feel uneasy about crossing the cycleway when boarding or alighting from a bus. There is a risk that the quality of bus service could be compromised when there are high volumes of cyclists, posing accessibility challenges for wheelchair users. The one-way cycleway must have a minimum width of 1.2m (3.9 ft), with an additional 0.8m (2.62 ft) space provided between the cycleway and the bus stop to accommodate wheelchair users.

Australia [15]

Australia’s Guide to Road Design includes floating bus stops, as in New Zealand’s guidelines, which are characterized by their separation from the footpath by a cycleway and a raised median. These bus stops can be designed in two ways: a narrow median approach where passengers wait on the footpath and use a narrow median to access the bus, or a wide median approach where passengers wait at a shelter located on the median itself.

3.2.3 Summary of Existing Guidelines

This section summarizes the guidelines as documented in multiple guidebooks across the world. The summaries of overarching guidelines are presented separately for the U.S. and internationally.

In the U.S., bike lanes should be a minimum of 5 feet wide to moderate bicycle traffic speed and reduce conflicts with pedestrians. Bicyclists are expected to yield to pedestrians who are accessing the boarding island. To promote yielding behavior and ensure the safety of everyone, yield signage and pavement markings are recommended. These include "BIKES YIELD TO PEDESTRIANS" signs and yield line markings at crosswalks. Additionally, it is suggested that a YIELD stencil marking be included in the bike channel and reflective signage, or elevated components be incorporated for improved visibility.

Some guidebooks recommend using at least two crosswalks to get to the boarding area from the sidewalk but most manuals do not specify the number of crosswalks. In order to ensure the safety of pedestrians, it is imperative that shelters be strategically placed in a location that avoids obstructing or posing potential hazards in crosswalks.

To ensure accessibility for individuals with mobility impairments, it is imperative to establish a boarding area that is easily accessible. Most guidebooks, however, do not provide adequate instructions for designing accessible boarding areas to accommodate wheelchair users and blind passengers. This boarding area should measure 8 feet in width and 5 feet in length and adhere to level or near-level boarding conditions. In accordance with accessibility standards, platform access ramps should not exceed a maximum slope of 1:12. The consideration of level boarding conditions is imperative to ensure comfortable boarding for all passengers, especially those with mobility impairments. Moreover, waiting areas should be designed to minimize conflicts between bicycles and pedestrians while also being wheelchair accessible, and detectable warning strips should be installed at the edge of the sidewalk and the curb of the boarding area.

It is also recommended that contrasting materials or green color treatments be used in order to enhance visibility and designate bike lanes. These visual cues can aid in distinguishing the cycling area and promoting safety and awareness among all users. Adherence to these comprehensive guidelines can effectively prioritize accessibility, safety, and efficiency in the design and implementation of full-width, partial-width, and no platform bus stops, thereby benefiting all travelers.

In the context of international standards, certain recommendations have been put forth concerning the dimensions of various types of bus stops. Specifically, when it comes to full-width platforms, the platforms ought to be at least approximately 13 feet in width, whereas, for partial-width platforms, a width of 8-12 feet is deemed appropriate; these dimensions are higher than those recommended based on U.S. guidelines. In the case of bike lanes, the recommended minimum width is 4-5 feet and narrowing of it is allowed as a speed management strategy. When no platform is provided some of these guidelines require a minimum width of the bike path and an additional 2.7 ft to ensure enough space for wheelchair users. There is a strong preference for the bus shelter to be located within the island. Multiple crossing points are recommended based on demand or pedestrian desire lines as well as yield to pedestrians signs. Notably, London's guidelines explicitly state the need to engage with potential users, including those with disabilities, at the early stage of designing these types of bus stops.

A summary of floating bus stop guidelines in the United States and internationally can be found in Table 3.3 and Table 3.4.

It should be noted that an attempt to locate other research studies related to the design of floating bus stops and its impact on bicyclist and transit rider behavior and interactions, did not yield any results. This indicates that while guidelines have been developed by various agencies, no comprehensive behavioral study has been performed at floating bus stops with various designs. This research project is therefore essential for providing evidence on safety risk mitigation of floating bus stop design elements. The next two subsections summarize additional knowledge obtained from the professional and community outreach efforts we pursued as part of this project to supplement information related to the state-of-practice and challenges associated with floating bus stops obtained from the review of guidebooks.

Table 3.3: Summary of floating bus stop design guidelines in the U.S.

Guideline	Terminology	Classification	Minimum Bike Lane Width	Pedestrian Crossing	BIKES YIELD TO PEDESTRIANS sign	Bus Platform Width	Accessible Boarding Area	Rails/Fences
NACTO Transit Street Design Guide [1]	Side Boarding Island Stop	Full-width platform	5’	-	required	-	5’x8’	Yes (optional)
NACTO Transit Street Design Guide [1]	Shared Cycle Track Stop	No platform	-	-	-	-	-	-
MassDOT Separated Bike Lane Planning & Design Guide [2]	Floating Bus Stop	Full-width platform	4’	2	-	8’	5’x8’	yes
MassDOT Separated Bike Lane Planning & Design Guide [2]	Constrained Bus Stop	No platform	4’	-	-	-	-	-

Guideline	Terminology	Classification	Minimum Bike Lane Width	Pedestrian Crossing	BIKES YIELD TO PEDESTRIANS sign	Bus Platform Width	Accessible Boarding Area	Rails/Fences
MBTA Bus Priority Toolkit [3]	Floating Bus Stop	N/A	-	--	required	8’ (required), 10’ (recommended)	8’x10’	Required at stops with high volumes of pedestrians and bicyclists
MDOT Bus Stop Design Guide [5]	Floating Bus Stop/ Boarding Island Stop	Partial-width platform	-	-	-	-	5’x8’	-
MDOT Bus Stop Design Guide [5]	Shared Cycle Track Stop	No platform	-	-	-	-	5’x8’	-
Rhode Island Bus Stop Design Guide [6]	Floating Bus Stop/ Bus Island	N/A	-	-	required	-	5’x8’	-
AC Transit Multimodal Corridor Guidelines [7]	Floating Bus Stop	Full-width platform	-	-	optional	-	5’x8’	Yes (optional)
Street Design Guidance City of Minneapolis [8]	Floating Bus Stop	Full-width platform	5’	-	-	8’	-	-

Guideline	Terminology	Classification	Minimum Bike Lane Width	Pedestrian Crossing	BIKES YIELD TO PEDESTRIANS sign	Bus Platform Width	Accessible Boarding Area	Rails/Fences
ART Bus Stop Guidelines Update: Floating Bus stops [9]	Floating Bus Stop	Full-width platform	5’	2	required	10’	5’x8’	yes
FHWA Separated Bike Lane Planning and Design Guide [10]	Island Platform Stops	Full-width platform	-	-	optional	-	5’x8’	-
FHWA Separated Bike Lane Planning and Design Guide [10]	Island Platform Stops Without a Platform	No platform	-	-	optional	-	5’x8’	-

Table 3.4. Summary of international floating bus stop guidelines

Guideline	Terminology	Classification	Minimum Bike Lane Width	Pedestrian Crossing	BIKES YIELD TO PEDESTRIANS sign	Bus Platform Width	Accessible Boarding Area	Rails/Fences
Active Transportation Design Guide, British Columbia, Canada [11]	Floating Transit Stop	Full-width platform	4.9’	2	recommended	8.2’	9.8’x9.8’	-
Active Transportation Design Guide, British Columbia, Canada [11]	Mid-Block Floating Transit Stop	Full-width platform	3.9’	-	required	9.8’	9.8’x9.8’	
Accessible Bus Stop Design Guidance, London, UK [12]	Bus Stop Bypass	Full-width platform	-	multiple	-	8.2’	-	-
TRANSLINK Bus Infrastructure Design Guidelines, Vancouver, Canada [13]	Island Bus Stop	Full/Partial-width platform	-	-	required	9’	-	-

Guideline	Terminology	Classification	Minimum Bike Lane Width	Pedestrian Crossing	BIKES YIELD TO PEDESTRIANS sign	Bus Platform Width	Accessible Boarding Area	Rails/Fences
Design options for island bus stops-Waka Kotahi New Zealand Transport Agency, New Zealand [14]	Full-Width Island Bus Stop	Full-width platform	5.2’	-	-	12.5’	-	-
Design options for island bus stops-Waka Kotahi New Zealand Transport Agency, New Zealand [14]	Narrow Width Island Bus Stop	Partial-width platform	5.2’	-	-	3.94’	-	-
Design options for island bus stops-Waka Kotahi New Zealand Transport Agency, New Zealand [14]	Nominal Width Island Bus Stop	Partial-width platform	3.9	-	-	2.6	-	-

3.3 Professional Community Input

3.3.1 Professional Listserv

An email was shared with the Association of Pedestrian and Bicycle Professionals listserv that included the questions presented in Section 2.3.1, soliciting information on the state of practice for the design and implementation of floating bus stops. With one week, five responses were collected, three of which did not directly respond to the questions but suggested ongoing research studies related to floating bus stop guidelines, one recommending a related topic for a future webinar and only one providing detailed answers to the questions that were posed.

More specifically, one of the respondents provided information based on their experience with the implementation of floating stops in Montgomery County, MD and Austin, TX. The corresponding diagram is presented in Figure3.46. They suggested that yielding to pedestrians in a crosswalk is the law in every state and can be reinforced by supplementing crosswalks with pedestrian signs and yield (or stop) markings (①, ②, and ③ in Figure 3.46). Channelization (i.e., providing elements for wayfinding and path guidance such as fences, planters, etc.) was stated as the preferred way for guiding riders to the crossings (④ in Figure 3.46). The preference is for provision of two crossings to facilitate alignment with the bus doors (⑤ in Figure 3.46), with the exception of bus stops with low volumes or when grading or drainage issues dictate the use of a single crossing location.

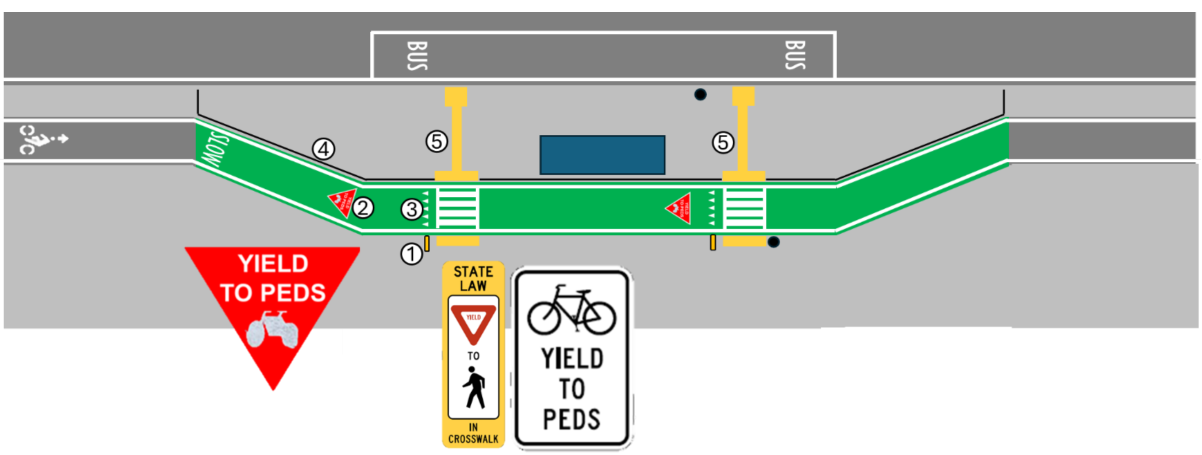


Figure 3.46: Design recommendations from professional listserv email outreach

They also discussed treatments that can be used to slow down bicyclists when approaching floating bus stops. For two-way bike lanes, bollards on the centerline can be used to slow down bicyclists, as is done in Montgomery County, MD, see Figure3.47, although these can also become a hazard for bicyclists and prevent the use of larger bicycles. Alternative ways for reducing bicycle speeds are changes in grade, which can also facilitate accessible grading. In addition, the design of these bus stops needs to ensure clear sight lines so that bicycles can detect pedestrians who are about to cross the bike lane. This can be achieved by transit shelters that are transparent and free of advertisements.

Source: [18]

Figure 3.47: Bollards on the centerline of the two-way bike lane (Montgomery County, MD)

When space is limited, it is acceptable to reduce the bike lane width for the length of the transit stop to allow for wider bus stop platforms. Intermediate-level bike lanes and sloping curbs can help make the bike lanes feel wider even when narrowed. When space is most constrained, bicyclists can be merged into a shared-use path with pedestrians, which could also be a good practice when pedestrian volumes are high and, therefore, wide sidewalks are necessary or when bicyclist volumes are low. When space is constrained, narrow shelters can also be considered, or just the placement of benches, but only when ridership is low, although these are often decisions made by transit agencies. Montgomery county, MD, suggests that shelters should be considered at all transit stops.

Wayfinding, especially for visually impaired riders, can be facilitated via audible messages on the bus, letting riders know the type of floating bus stop they are about to alight into and informing riders of the specific door to be used to access the crossing. Montgomery County, MD aims to provide floating bus stops at signalized intersections and incorporate bike lane crossings into the signal so that the rider crossing is controlled. Additional recommendations can be found in the Montgomery County, MD toolkit. Austin, TX, has also considered audible messages, but it is not clear whether they have been implemented yet.

Other responses pointed to similar studies addressing accessibility concerns in British Columbia, a second one in partnership with the Canadian National Institute for the Blind which focuses on preferences of people that are blind or have visual impairments, and lastly, a study funded by the Federal Highway Administration and performed by the UNC Highway Safety Research Center, the Accessible Design for the Blind and Kittelson and Associates.

This last study focuses on floating bus stops in addition to other quick/build facilities to develop accessibility solutions with a focus on tactile walking surface indicators. At the time of this report writing no reports or other documents associated with these studies were publicly available.

3.3.2 City Interviews

Interviews with city officials and representatives of engineering and planning firms that have worked with cities that are at the forefront of integrating bus stops and bicycle infrastructure and developing design guidelines for those in the United States and internationally were also pursued. Four interviews were completed in total with: 1) Amsterdam, Netherlands; 2) Montreal, Canada; 3) Toronto, Canada; and a combined one with Montgomery County, and representatives of engineering design firms that have been involved in floating bus stop design and development of guidelines for Montgomery County, MD, Austin, TX, and British Columbia.

Amsterdam

Cycle tracks are usually lower than the sidewalks in Amsterdam, and no cycling on sidewalks is allowed, see Figure 3.48 as an example. The primary feature for mitigating conflicts between bicyclists and riders crossing at floating bus stops is zebra crossings (i.e., a pedestrian crossing marked with white stripes). However, it is frequently observed that riders do not wait for bicyclists to stop. Rather, they wait for a sufficient gap for them to cross or adjust their path so neither the bicyclist nor the rider must stop.

Source: [16]

Figure 3.48: Cycle track that is lower than the sidewalk at a floating bus stops in Amsterdam, Netherlands

Platforms are designed with a minimum of 2.1 meters (7 ft); this has been in place since 2011. This allows for 60 cm (2 ft) for the ramp to be deployed, plus 1.5 meters (5 ft) of maneuvering space for the wheelchair user. Narrower shelters are a possibility for platforms that were designed in the past and did not have to meet the minimum platform width requirement.

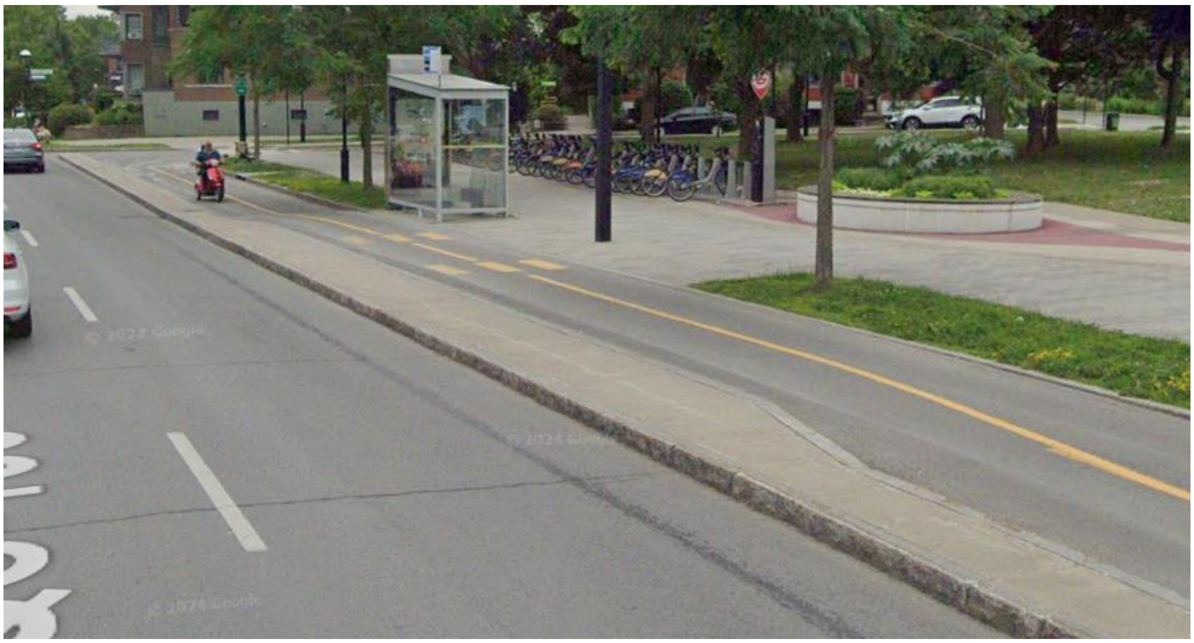
When space availability is limited at floating bus stop locations, the city of Amsterdam removes parking and combines car and tram lanes, therefore narrowing the street, implementing narrower cycle tracks (with a width down to 1.8 m (6 ft)), and in some cases, offsets bus stops so that bus stops in the two different directions are not directly across from each other. Shared use paths for bicyclists and pedestrians, conversion of the cycle track to a conventional bike lane that allows buses to stop or change of the location of the cycle track to be to the left of the lane that bus stops at are never considered in Amsterdam.

In terms of accessibility, Dutch law gives blind individuals with canes priority, and everybody else must stop. However, the introduction of electric bikes and mopeds (even if the latter are not allowed on bike lanes) challenges safe stopping so that blind people can cross due to the higher speeds they develop. While not common at floating bus stops, at tram stops, tiles are inserted into the sidewalk that create a pair of parallel raised lines perpendicular to the sidewalk's axis leading to the zebra crossing across the cycle track that features truncated domes at its edges; see Figure 3.49. They also have different types of truncated domes made from different materials to indicate where riders should be waiting placed as a large pad, which is accompanied by a button for audio information.

Figure 3.49: Wayfinding treatment at tram stops in Amsterdam, Netherlands

Montreal

The city of Montreal does not implement speed bumps to slow down bicyclists as they approach floating bus stops since they consider them dangerous. However, the cycle track is raised and narrowed, see Figure 3.50, paving materials are contrasting, crosswalks and bus stop poles are present, and there is also often a shelter. Narrowing the cycle track at the bus stop prevents the overtaking of bicyclists who slow down, allowing riders to cross the bike lane, shortening the crossing distance, and providing more space for the platform. So, they primarily rely on both bicyclists and riders yielding to each other, except for when blind passengers are present, in which case bicyclists are expected to yield. They also consider the presence of the platform as a key safety feature since it provides space for passengers getting off the bus to check whether bicyclists are coming and decide when to cross safely. Shelters are typically located on the sidewalk. The city is challenged by the decision on where to locate the bus stop sign as people typically wait next to it, so it should be on the curb or located next to the shelter since it is easier for individuals with visual impairments to find it.



Source: [16]

Figure 3.50: A raised and narrowed cycle track adjacent to a floating bus stop in Montreal

In terms of accessibility, the city of Montreal requires truncated domes on both sides of the cycle track all along it. However, this is currently implemented only on new cycle tracks, not those that are being retrofitted. The domes are not necessary when cycle tracks are implemented at elevations different from sidewalks. However, cycle tracks typically rise to sidewalk level at bus stops, so truncated domes are used to provide the delineation.

Montreal also considers a platform width of 7.8 feet to be sufficient, with a minimum of 5 ft for all users, including wheelchair users, under the assumption that the ramp will be deployed in the cycle track. This is considered acceptable as wheelchair users are allowed to use the cycle tracks. This is because wheelchairs typically have a length of 3.2 ft, and an additional 3.6 ft is needed for the ramp, leading to a preferred platform width that is slightly higher at 7.8 ft.

Toronto

Toronto has implemented these types of floating bus stops since 2011 and has supplemented these designs with various types of pavements and signage, a few of which are shown in. Figure 3.51. Their older locations do not have any signage or pavement markings. The city is still exploring which types of pavement markings and signage are most appropriate for strengthening the message around roles and responsibilities at floating bus stops.

Images: courtesy of B. Katz

Figure 3.51: Examples of pavement markings and signage used in floating bus stops in Toronto, Canada

Floating bus stops in Toronto also present clear, guiding tactile pavement that facilitates crossing for the visually impaired, as shown in Figure 3.52 for a no platform floating bus stop.

Image: courtesy of B. Katz

Figure 3.52: Floating bus stop with guiding tactile pavement in Toronto, Canada

In Toronto, a municipal law bans cars, cyclists, and any other street users from passing buses on the side where riders are boarding and alighting. More specifically, the law states: “Where a person in charge of a bicycle or a large cargo power-assisted bicycle on a cycle track approaches a Toronto Transit Commission bus which is stationary for the purpose of taking on or discharging passengers, the person on a bicycle or a large cargo power-assisted bicycle shall not pass the bus or approach nearer than 2 meters (6.6 ft) measured back from the rear or front entrance or exit, as the case may be, of the Toronto Transit Commission bus on the side on which passengers are getting on or off until the passengers have crossed the cycle track.” A similar state law exists for streetcars.

The city’s success in implementing floating bus stops is attributed to the widespread use of those in addition to an existing culture of yielding to streetcars that run on the center of the streets.

Montgomery County, MD

Montgomery County is already working on its 3rd generation of floating bus stop designs that will be part of the county’s Accessible Design Guide for the county, expected to be published in 2024. Working with the visually impaired community, they have tested various treatments at a floating bus stop in Silver Spring to find what’s most effective.

For lessening conflicts between bikes and pedestrians, their recommended treatments include:

1) Flexposts on the edges of the path and (for bidirectional bike paths) mid-path, creating a “gateway,”

2) R16A sign (State Law, Stop for Crossing Peds) on the side of the path,

3) SLOW pavement marking on the bike lane, and

4) rumble strips on the bike lane.

They also plan to install at their test site an RRFB for crossing the separated bike lane.

To improve wayfinding, they tested various forms of tactile walking surface indicators, considering three desirable properties for tactile indicators: traversability (i.e., not a barrier), detectability, and discriminability (i.e., provide an unambiguous message). They found that Tactile Directional Indicators (TDIs) developed by Beezy Benson – parallel raised bars embedded in sidewalk tiles – to be especially effective. They recommend TDIs going across the sidewalk to show people the way to the bus stop. However, they now recommend that the raised bars of the TDI be oriented parallel to the direction of travel in order to avoid being an obstacle to wheelchair users traveling along the sidewalk, unlike those shown in Figure 3.53, which are perpendicular to the sidewalk axis. They also recommend using TDIs rather than raised domes to indicate the boarding zone (i.e., where to stand as a bus approaches).

Another wayfinding aid they have piloted is a secondary bus stop pole located on the sidewalk, with information about which bus routes are served. To distinguish it from the primary bus stop pole, located next to the boarding zone, the secondary pole has a hexagonal cross section, so that people finding that pole will know that they shouldn't be waiting there.

At the planning level, Montgomery County tries to avoid split stops, i.e., where the bus stop shelter is located on the sidewalk rather than on the platform, as they create a risk of collision between pedestrians and bicyclists when transit riders leave the shelter to get to the bus. Where there isn't space for a full-width platform, they first consider moving the bus stop, and only accept a split-stop solution when there is no feasible location for the bus stop that has the needed width. They have committed to the blind community to try to locate floating bus stops at signalized intersections and have at least one signalized crosswalk for accessing the platform; that way, pedestrians can use the signal information to know when it's clear to cross the bike lane.

Source: [18]

Figure 3.53: Crosswalk at floating bus stops with tactile tiles in Montgomery County, MD

Austin, TX

Austin, TX, is currently developing guidelines that include a typology for floating bus stops. Given that the guide has not yet been published, limited information is available. The most important one is that in the case of limited space, a shared-use path for bicyclists and pedestrians should be implemented.

British Columbia

Following a Human Rights case (British Columbia Human Rights Tribunal ruling (BCHRT 197) in November 2020) that resulted in the installation of audible flashing beacons at floating bus stop crossings, British Columbia is currently engaging in a public consultation process to develop a policy framework for these types of bus stops.

3.3.3 Summary of Professional Community Input Findings

Engagement with professionals involved in the design and implementation of floating bus stops through the Association of Pedestrian and Bicycle Professionals listserv and through interviews revealed multiple ongoing projects investigating best practices for floating bus stop design. Some of these projects are particularly focused on designs to improve bus stop access and safety for visually impaired riders. Recommendations provided through the listserv came from one individual and focused primarily on their experience with the implementation of floating bus stops in Montgomery County, MD and Austin, TX they had experience with. These recommendations included channelization to facilitate wayfinding for crosswalks, which should be aligned with the bus doors. Speed mitigation strategies, such as bollards in the middle of two-way cycle tracks and changes in grade were also suggested. For constrained spaces, bike lane width can be reduced or merged into shared-use paths with pedestrians. Narrow shelters or just benches can also be used for narrow platforms, although Montgomery County, MD recommends shelters at all bus stops. To facilitate wayfinding for visually impaired riders, audible messages are recommended, which have been considered in Austin, TX. Montgomery County, MD also plans to incorporate future floating bus stops at signalized intersections so that crossings are controlled by the traffic light.

City interviews with Amsterdam, Montreal, Toronto and professionals involved in various floating bus stops designs in Montgomery County, MD, Austin, TX, and British Columbia revealed certain design strategies implemented for speed management and wayfinding as well as ongoing efforts in Austin, TX and British Columbia that are currently working on developing floating bus stops guidelines.

Platform width outside of the U.S. is between 7-7.8 ft with a minimum of 5-6 ft, which assumes implementation of a ramp for wheelchair users taking space on the cycle track. Constrained spaces are addressed by narrowing bike lanes or offsetting bus stops to allow for enough right-of-way width in Amsterdam; however, conversion of separated bike lanes to conventional bike lanes or share use paths are never considered. Wayfinding for visually impaired individuals is facilitated with the use of truncated domes along the separated bike lane (when bike lanes are at the sidewalk level), at the transit stop locations and at crosswalks, often using different materials to indicate the presence of a crosswalk versus a boarding location (often equipped with audible messages in Amsterdam). Guiding tactile pavement is used in Toronto. Dutch laws as well as laws in Canada have been implemented that improve safety at floating bus stop locations, such as yielding to blind pedestrians (Montreal and Amsterdam) and banning cars from passing stopped transit vehicles closer than 6.6 ft when passengers are boarding and alighting. Speed management is achieved in Montreal by raising and narrowing bike lanes, implementing contrasting color pavement materials, but do not install speed bumps as they are considered dangerous for bicyclists, while Toronto is still studying which pavement markings and signage are most effective for communicating expected behaviors at floating bus stops.

The interview with Montgomery County, MD revealed that the county is at the forefront of developing floating bus stop design guidelines, with them currently being in their 3rd generation of these guidelines. These new guidelines introduce the need for detectable warning surfaces for wayfinding and avoidance of placing shelter on the sidewalk when there is a platform. They are also considering accessible pedestrian signals at crossings.

3.4 Community Outreach

Community outreach involved three focus groups in August 2023, engaging with a total of 30 participants, representing individuals with visual, hearing, and mobility impairments. These individuals were recruited with the help of MBTA's System-wide Accessibility Department through email outreach to the Massachusetts Commission for the Blind and via advertisement during June 2023 RTAG's meeting. The following subsections summarize the discussion organized by floating bus stop element and conclude with recommendations as suggested by the focus group participants.

3.4.1 Findings

The full-width platform design was considered safer than the other two, and for many participants, it was considered the only acceptable option, even though it is not ideal and is still in need of improvements. However, one participant reported that none of these designs are safe and that travelers, whether with a disability or not, should not be asked to cross an actively used bike lane as it is not safe. Some visually impaired riders discussed that guided assistance or support from surrounding individuals is the only way for them to feel safe using these bus stops, and they pointed out that guide dogs are not trained to navigate these types of bus stops. The advantages and limitations of the various bus stop designs and bus stop elements are summarized in the next subsections, followed by recommendations on how to improve safety, as expressed by the focus group participants; see Figure 3.54.

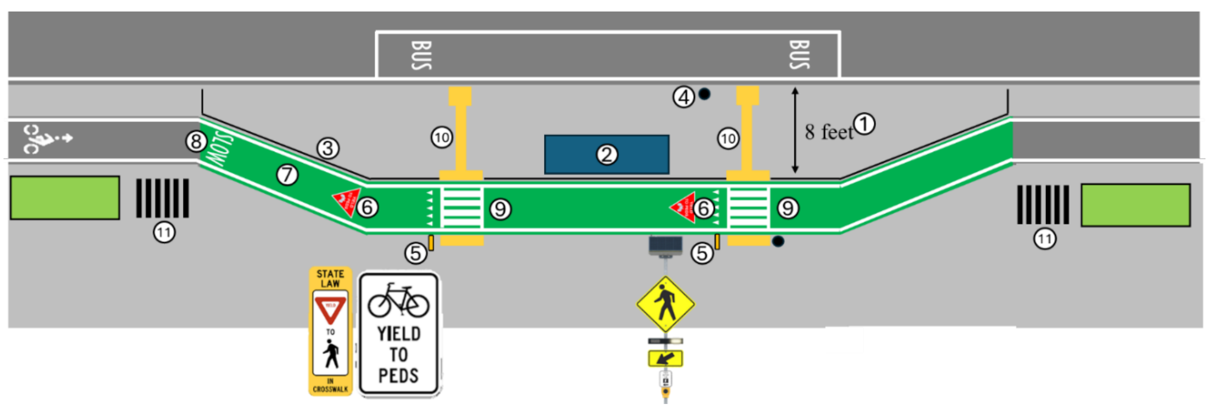


Figure 3.54: Design recommendations as expressed by focus group participants

Platform Width

Respondents that are wheelchair users expressed feeling safe waiting for the bus on full-width platforms and having enough space with platforms of 8 feet or wider to navigate their way on and off the bus; see ① in Figure 3.54. In addition to allowing enough space for wheelchair users to navigate and for ramps to be deployed to facilitate wheelchair access on and off the bus, wider platforms are also critical for wheelchair users to be visible by the bus operator at crowded bus stops. Wheelchair users also emphasized the need for enough space that will allow them to navigate the wheelchair even around the shelter and buses. This could be resolved with platforms that are wider than 8 feet or benches and shelters located away from the bus doors to facilitate ramp employment and accessibility for wheelchair users.

Concerns related to platform width include ramp deployment for wheelchair users. This is particularly problematic for the no platform bus stop design as ramps would be deployed in the bike lane, causing conflicts between bicyclists, pedestrians, and wheelchair users that may lead to injuries. Wheelchair users also reported they did not feel comfortable navigating the no platform bus stops. In addition to challenges associated with deploying the ramps at the no platform bus stops, participants reported that the lining up of bus riders to board the bus could also create risky conditions as bicyclists are approaching the bus stop location and could create collisions between bicyclists and riders, pedestrians walking on the sidewalk, and particularly between bicyclists and wheelchair users who cannot engage in avoidance maneuvers as easily.

Bus Stop Shelter

Typically, when full-width platforms are present, the bus shelter is located on the platform, making it easier for the bus operator to see if riders are waiting at the shelter and recognize them as transit riders so that they stop; see in ② in Figure 3.54. Focus group participants expressed a concern about partial-width platforms, as they could potentially be leading to riders crossing the bike lane without checking for bicyclists traveling on the bike lane. In addition, participants mentioned that partial-width platform bus stops and, in particular, placing the shelter on the sidewalk is likely encouraging more bike lane crossings of riders waiting at the bus shelter just to check whether the bus is coming.

Fencing

Fencing is helpful in directing riders to the crosswalk locations; see ③ in Figure3.54. A visually impaired rider reported benefitting from having the railing at least as low as 27 inches from the platform so it can be easily detected by a cane and that it should be accompanied by tactile pavement. The presence of two openings in the fence was considered sufficient and necessary to avoid crowding at crossings. Fencing was also seen as beneficial for partial-width platforms to prevent bus riders from stepping in the bike lane without checking for oncoming bicycling traffic. Fences were also seen as beneficial for preventing bicycle riding on the platform and, in general, providing visual cues to bicyclists and improving their situational awareness of potential pedestrian crossings at those locations.

Waiting

Participants, especially those with visual impairments or who are wheelchair users, reported that they typically wait at the bus stop sign so that they are visible to the bus operator; see ④ in Figure 3.54. In the case of partial-width platforms, this also addresses safety concerns regarding crossing the bike lane without checking for bicyclists when the bus arrives. As a result, the no platform bus stop was considered unacceptable by most participants since it required them to cross the bike lane when the bus arrived at the bus stop.

Transit Rider – Bicyclist Interactions

Crossing the bike lane is a point of concern for participants of all abilities. Scenarios where riders are rushing to get to the bus or are texting while walking were presented as of particular concern, as riders are less likely to check for bicyclists. These concerns were more severe for the partial-width platform bus stops as the likelihood of someone stepping in the bike lane without checking for oncoming bicyclists is much higher.

The lack of curb presence separating the bike lane for both the partial-width and no platform bus stops was seen as an additional issue, especially for visually impaired pedestrians who might not be aware of the presence of the bike lane and step in it while waiting to board or alighting the bus, assuming it is pedestrian-safe zone. This is a particularly big concern for the no platform bus stops when riders alighting the bus end up immediately in the bike lane with no warning and limited visibility for any bicyclists that might be coming.

Participants also commented on bike lane design elements affecting bicyclist behavior. Concerns were raised for protected bike lanes, and bike lanes being paved with colored pavement, as bicyclists could perceive these treatments as giving the right-of-way, leading to less cautious bicyclist behavior and higher speeds at bus stops. Implementation of bike lanes at grade with sidewalks can also result in bicyclists veering off to the sides, increasing the risk of collisions with pedestrians. The participants particularly pointed out the risks associated with the lack of crosswalk markings at some of these bus stops (e.g., no platform bus stops), causing bicyclists to travel through the bus stop areas without slowing down.

Visually impaired participants commented on additional concerns associated with bicyclist behavior that make navigation of such bus stops unsafe for them. Bicycles are fairly silent and the background noise from the traffic makes it harder for visually impaired pedestrians to decide on when it is safe to cross. Bicyclists riding in the opposite direction of the bike lane exaggerates this issue, as it makes crossing the bike lanes even less predictable and therefore, riskier. Lastly, visually impaired riders communicated that bicyclists might not recognize people with visual impairments since not all of them use a white cane or are accompanied by guide dogs.

Other Considerations

Rider movement, especially for wheelchair users and visually impaired individuals, can be further obstructed when trees are planted close to the bus stop shelters both due to lack of space in-between the trees and the shelter also due to tree roots that could be contributing to the unevenness of the walking/riding surface. Concerns were also expressed about the use of bricks to pave the area in front of bus stop shelters as they warp, causing potential tripping hazards and making the use of a wheelchair harder.

Additional considerations include the extra travel distance imposed on transit users, particularly those with a disability, when they must travel at the end of the platform or the end of the sidewalk to cross the traffic lanes. Wayfinding is a concern that should be addressed not only to decrease unnecessary distance traveled but also to ensure that riders do not end up on the wrong side of the platform or end up waiting in the bike lane or traffic lane.

The participants also brought up issues related to the bus not being able to stop next to the curb due to parked cars, further complicating their access to the bus doors. Lastly, participants reported that partial-width and no platform bus stops can make boarding and alighting of paratransit passengers more challenging, especially when there is not enough space for the deployment of ramps.

3.5 Recommendations

Bike Lane Design

Participants provided several suggestions for bicyclist speed management such as signage (with flashing lights, i.e., RRFB, or without; see ⑤ in Figure 3.54), or pavement markings; see ⑥ in Figure 3.54, or pavement color change; see⑦ in Figure 3.54), informing bicyclists about pedestrian crossings, and/or imposing slower speed limits to bicyclists to help mitigate potential crashes between bus riders crossing the bike lane and bicyclists.

Introducing elevation (i.e., vertical curve) in the bike lanes as they approach the bus stop and/or diverting (i.e., horizontal curve; see ⑧ in Figure 3.54 the bike lane just upstream of the bus stop location could also help reduce bicyclist speeds. Washington, DC, has some examples of bike lanes changing levels through a ramp as they approach the bus stop.

Changes in pavement surface or speed bumps on the bike lane as they approach bus stop locations, could also help reduce bicyclist speeds. Different pavement surfaces have the additional benefit of adding more noise to bicycle operations and facilitating differentiating the sidewalk from the bike lane, potentially improving the awareness of all users, especially those who are visually impaired. The addition of warning strips at the edge of the bike lane was also suggested to improve the differentiation of bike lanes, bus stop platforms, and sidewalks when they are all at the same level. Some type of bollard blocking bicyclists' right of way when the bus is located at the bus stop was also recommended.

In addition, fencing could prevent veering off on the sidewalk, which however, can also be achieved through the introduction of a curb separating the bike lanes from the sidewalk; see ③ in Figure 3.54. Participants also emphasized that two-way bike lanes or counterflow bike lanes adjacent to bus stops should be avoided as they complicate navigating the bike lane crossing, especially for people with disabilities.

Crosswalk Improvements

Participants also emphasized the need for crosswalks to be visible so that both riders know where to cross and to improve bicyclists' awareness of crossing bus riders; see ⑨ in Figure3.54. Pedestrian-activated flashing lights to improve the safety of crossings and make pedestrians more visible, especially at night, were also suggested. Specifically for visually impaired riders, tactile pavement on the curb is critical for indicating crossings and should be differentiated to communicate crossing of a bike lane versus crossing of traffic lanes; see ⑩ in Figure 3.54.

Bus Stop Shelter

Given their preference and, in many cases, advise riders with disabilities receive to wait for the bus next to the bus stop sign, participants recommended placement of bus stop shelters close to the signs (i.e., 4-5 feet from the bus stop shelter; see ② in Figure 3.54; however, this is only possible in the full-width platform bus stop. Shelter placement should not only be close to the bus stop sign and where the bus stops, but also be done such that it ensures enough space for the free movement of wheelchair users.

Bike Parking

Bike parking at bus stops should be carefully considered so that parked bicycles do not encroach upon the bike lane or constrain the movement of pedestrians and bus riders; see ⑪ in Figure3.54).

Bus Improvements

Participants also suggested improvements that could be implemented on the buses or announcements on board the buses. Buses could be equipped with stop signs, such as those on school buses, to communicate to bicyclists the need to stop when ramps are deployed or even in general when a bus stops at the bus stop. Audible messages could also be used and be particularly helpful for the no platform bus stops for informing bus riders that they would be stepping into a bike lane. Messages on board the bus saying "Beware of bikes when exiting" have been implemented on bus route 74. Bus operators could also advise bus riders to use the front door that allows them to exit on the curb in case the bus cannot fully stop parallel to the curb.

Education

Education recommendations related to riders with and without disabilities and bicyclists were also mentioned. Mobility lessons for visually impaired individuals at those types of bus stops would also be beneficial for their understanding of the bus stops and crossings at those locations. Education is also needed so that all riders do not position themselves in front of wheelchair users so that they are visible to the bus operator, who will be deploying the ramp. Lastly, but very importantly, education of bicyclists is essential to mitigate conflicts at these types of bus stops by teaching them that they do not have the right-of-way when they are approaching bus stops and that they should slow down and look out for pedestrians crossing.

Enforcement

Enforcement to ensure rule-following was also recommended. Massachusetts law requires bicycles to stop when a blind person is trying to cross a bike path. Enforcement was suggested to motivate compliance with the law and make these bus stops safer for all.

3.5.1 Summary of Community Outreach Findings

Community outreach through three focus groups that took place in August 2023 engaging a total of 30 participants, with representation from individuals with visual, hearing, and mobility impairments. These focus groups resulted to several recommendations related to floating bus stop design and education needs.

No platform bus stops were considered unacceptable due to the lack of space for wheelchair deployment and increased risk of collisions between bicyclists and transit riders as well as pedestrians. In addition, no platform bus stops require transit riders to cross the bike lane when the bus arrives at the bus stop increasing the risk of collisions with bicyclists. These no platform bus stops are concerning for alighting passengers who are stepping immediately in the bike lane when exiting the bus. Additionally, partial width platform and no platform bus stops were seen as dangerous given the lack of curb presence that would communicate the presence of a bike lane. Full-width platforms were seen as comfortable to navigate and the preferred type of bus stop both from an availability of space that facilitates navigation and ramp deployment and due to the presence of the shelter on the platform the eliminates the need for crossing the bike lane when the bus arrives and increases bus operator visibility of waiting passengers.

Fencing was perceived as helpful for wayfinding for visually impaired transit riders and for improving bicyclist situational awareness of the potential of pedestrian crossings. Participants mentioned that at grade bike lanes are introducing the potential of bicyclists encroaching upon sidewalk space, increasing the risk of collisions with pedestrians. Concerns were also raised about colored pavement bike lanes communicating right-of-way and lower yielding at crosswalks at floating bus stops. Lack of noise from bicycle operations, bicyclist wrong way riding and lack of recognition that visually impaired pedestrians are not always accompanied by guide dogs or using white canes were listed as additional concerns. Other concerns included other obstacles around bus stops that could be challenging navigation for wheelchair users, additional travel distance often imposed to them and challenges associated with buses not stopping next to the platform.

Recommendations as expressed through the focus group participants included bicycle speed management strategies, such as bike lane elevation change or deflection ③, pavement surface or color change, signage, lower speed limits, speed bumps, and bollards preventing movement of bicyclists when a bus is stopped at the stop. Pavement surface change and warning strips at the edge of the bike lane were also seen as beneficial for navigation for visually impaired riders. Visibility of crosswalks ⑥, tactile pavement, and pedestrian-activated flash lights were also seen as critical for the safe crossing of bike lanes at floating bus stops. Shelter placement should be close to the bus stop sign ensuring that there is enough space for wheelchair navigation. Additional recommendations included bus improvements to incorporate audible messages at bus stops to inform the riders of the type of bus stop they are alighting to as well as stop signs similar to those of school buses indicating to bicyclists the need to stop when buses are stopped at bus stops. Lastly, education was seen as critical for both transit riders and bicyclists to safely navigate floating bus stops in addition to enforcement for yielding to blind pedestrians at bike paths.

3.5 Behavioral Analysis

Behavioral analysis followed the gathering of information through the review of guidebooks, and the professional and user community input through data gathering using LiDAR and a 360-degree camera at five selected floating bus stops. These included two full-width platform bus stops: Washington Street at Walnut Street in Brookline and Broadway at Horizon Way in Everett, two partial-width platform bus stops: Massachusetts Ave opposite Christian Science Center in Boston and Somerville Avenue at Stone Avenue in Somerville, and one no platform bus stop: Broadway opposite Beacham Street in Everett. Video recordings were manually processed to analyze information related to transit rider glancing behavior, while trajectories extracted from the LiDAR scans were processed and utilized for statistical analysis of bicyclist speeding behavior and pedestrian crossing behavior around floating bus stops.

3.5.2 Manual Observations

Manual observations of the collected video recordings were performed to address questions related to pedestrian behavior, e.g., whether they looked before crossing the separated bike lane, and provide evidence of transit rider behavior to further inform design recommendations. In total, 36.5 hours of video were observed to extract behaviors described in this section. The number of hours of videos observed at each stop is shown in Table 3.5.

Table 3.5: Number of video hours observed by stop

Bus Stop Location	Hours captured
Massachusetts Ave opposite Christian Science Center, Boston	12.0
Somerville Ave at Stone Ave, Somerville	12.0
Broadway at Horizon Way, Everett	3.0
Washington St at Walnut St, Brookline	5.0
Broadway opposite Beacham St, Everett	4.5

Pedestrian Glancing Behavior While Crossing the Separated Bike Lane

Pedestrians crossing the separated bike lane were recorded as having looked before crossing if they turned their heads. The review of the video recordings indicated that boarding and alighting passengers at the full-width platform floating bus stops were more likely to look for oncoming bicyclists before crossing the bike lane than passengers at partial-width platform bus stops; see Figure 3.55. It should be noted that there is no corresponding data in the Figure for no platform stops due to the very small number of passengers (roughly three boarding and alighting passengers per hour) observed at the one no platform bus stop in our sample.

Possible causes for passengers not looking for bicycles before crossing the bike path are (1) the bike path may not be recognizable and (2) bicycle volume is low, therefore diminishing the situational awareness of pedestrians regarding the presence of bicyclists. Bicycle volume is very low at Broadway at Horizon Way and Broadway opposite Beacham Street, both of which are located in Everett, MA, and is low at Washington Street at Walnut Street in

Brookline, MA, and Somerville Avenue and Stone Avenue in Somerville, MA; only at the Massachusetts Avenue opposite Christian Science bus stop has a high enough bicycle volume that would make a person waiting for a bus be likely to see more than one bicycle passing by before a bus arrives. Yet the low percentage of passengers looking before crossing the separated bike lane at the Massachusetts Avenue opposite Christian Science Center bus stop (just above 50% for both boarding and alighting passengers) suggests that recognizability of the separated bike lane space as a bike lane might be the driving factor in pedestrian glancing behavior, in other words, pedestrians might not be recognizing that they are entering an active bike lane.

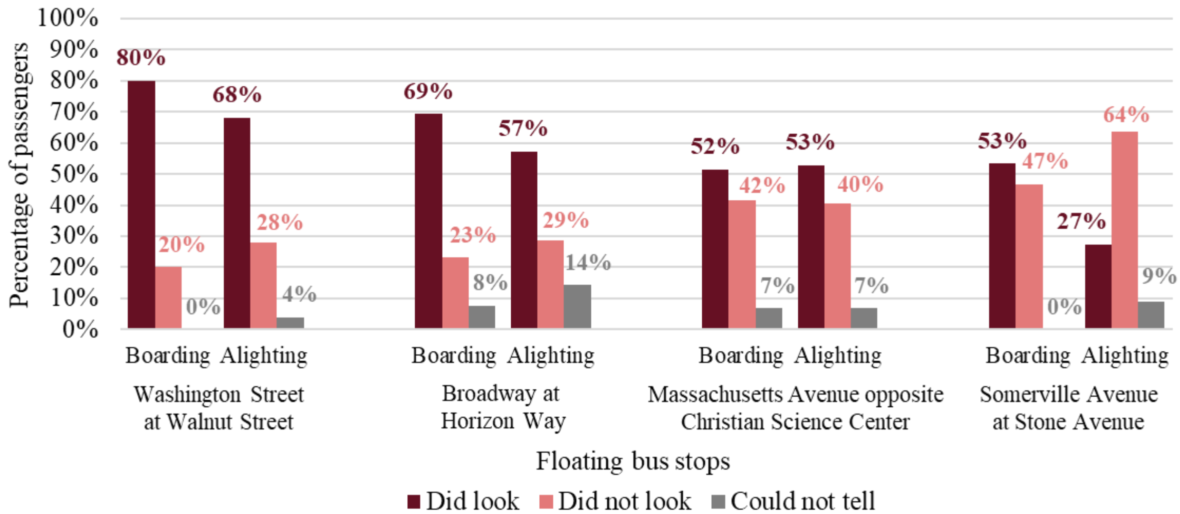
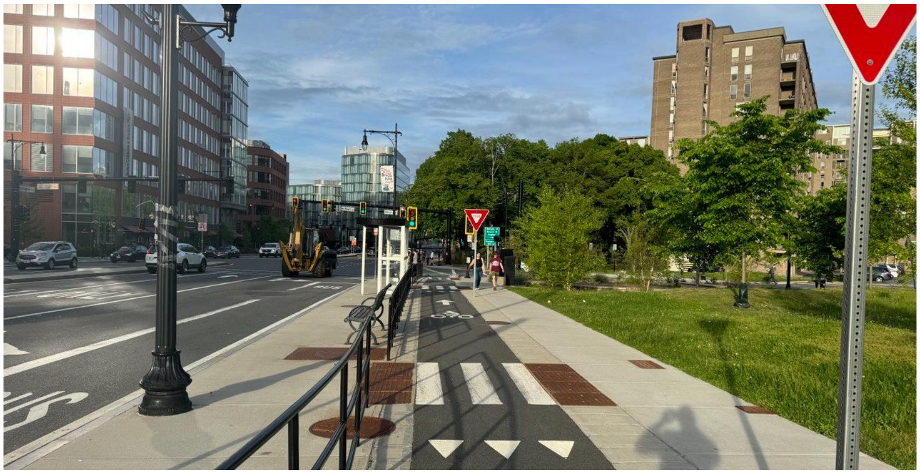


Figure 3.55: Pedestrian glancing behavior at floating bus stops

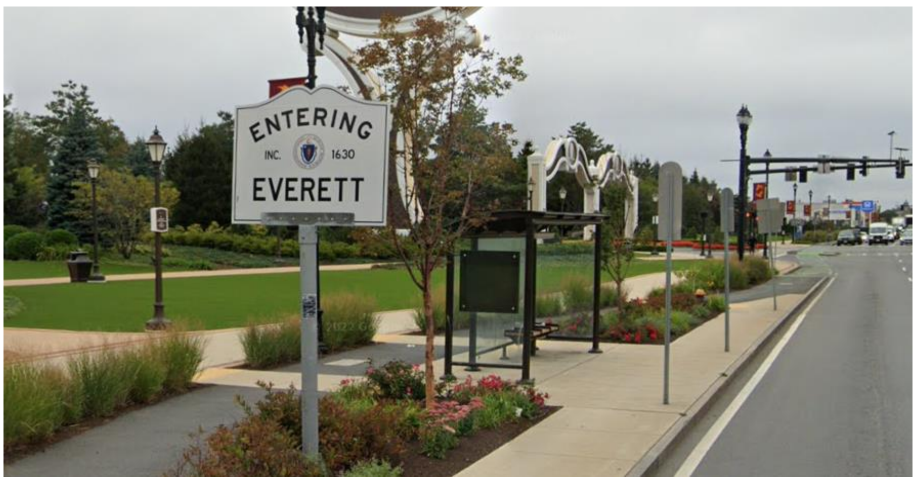
At both partial-width platform stops, the separated bike lane has a distinctly different color from the sidewalk, and there is a zebra crosswalk. At the Massachusetts Avenue opposite Christian Science Center partial-width platform bus stop, the separated bike lane is green, while the other four feature bike lanes that have a distinctly different color from the sidewalk. At the Massachusetts Avenue opposite Christian Science Center partial-width platform bus stop, the separated bike lane is green, while the other four feature bike lanes have a distinctly different color from the sidewalk. However, the green-colored bike lane does not seem to induce an increased likelihood of glancing before crossing compared to the other bus stops, indicating that pavement color might not be sufficient for increasing pedestrian situational awareness.

Glances are higher at the full-width platform stops, both of which have a barrier between the platform and the separated bike lane with distinct openings for crossing the bike lane. Between the two bus stops, performance in terms of pedestrian glances appears to be better at the one on Washington Street at Walnut Street in Brookline, MA, where there is a fence (Figure 3.56). At that location, it was observed that 70% of pedestrians glanced before crossing compared to the Broadway at Horizon Way bus stop in Everett, MA (65% glancing rate), where the barrier is a planting strip (Figure 3.57).



Source: [16]

Figure 3.56: Full-width platform bus stop at Washington Street at Walnut Street, Brookline, MA



Source: [16]

Figure 3.57: Full-width platform bus stop at Broadway at Horizon Way, Everett, MA

One reason may be that the fence at the Washington Street at Walnut Street bus stop in Brookline is higher than the vegetation used as a barrier at Broadway at Horizon Way in Everett, making the barrier more obvious without obstructing the view. Another reason is that at the Broadway at Horizon Way bus stop, the crossing zone is paved with the same material as the sidewalk, potentially making the bike lane appear as an extension of the walking path. For approaching bicyclists, paving the crossing in sidewalk material may help them recognize that they are crossing a walking path, but for pedestrians, it makes it less obvious that they are crossing a bike lane. For safety, it is desirable that both bicyclists and pedestrians recognize that they are at a crossing so that they can adjust their behavior accordingly. The Washington Street at Walnut Street bus stop in Brookline, which presents higher glances, has a more distinct crossing zone with zebra-striped crosswalk markings. Lack of recognizability is especially apparent when passengers, who after alighting from the bus, walked along the cycle track as if it was meant to be a walking route. In addition, alighting passengers were less likely to look before crossing at all bus stops.

Mopeds on Separated Bike Lanes

Despite regulations prohibiting mopeds from using separated bike lanes, observations indicate that there was an average of 0.5 mopeds per hour traveling along the Massachusetts Avenue separated bike lane on the side of the bus stop under consideration during the data collection duration.

Bus Stopping Behavior

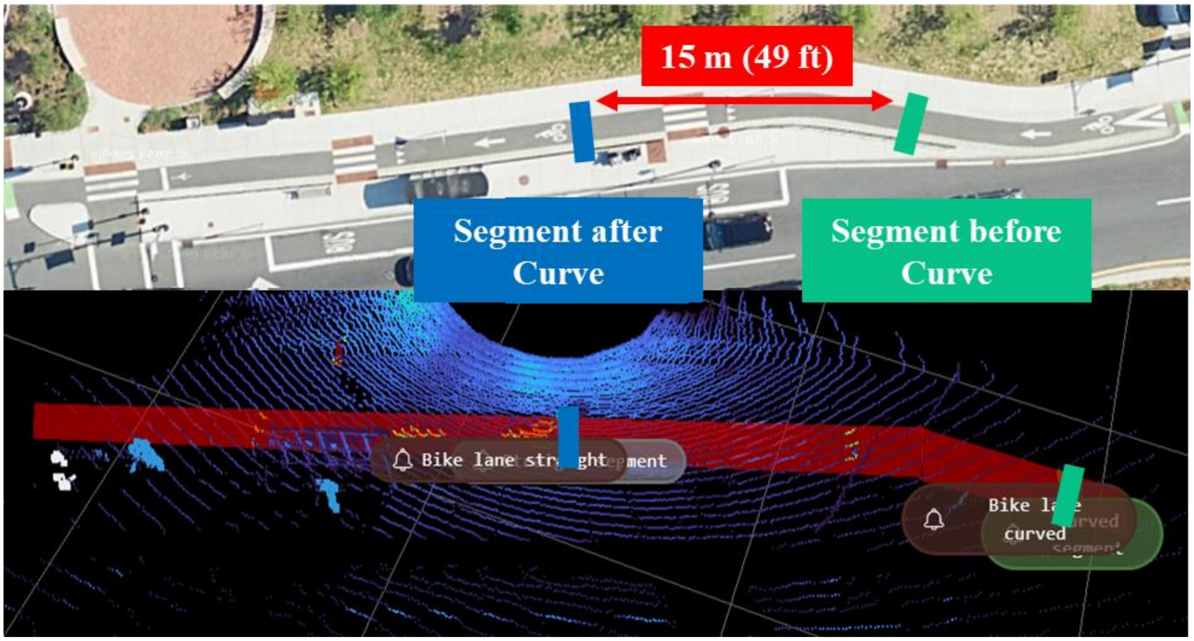
Manual observations also reveal concerns about appropriate bus stops at floating bus stops. In particular, it was observed that even when cars were parked very close to—but not directly at—the bus stop, bus drivers were generally hesitant to pull into the bus stop. Instead, they preferred to stop in the travel lane despite the bus stop being long enough to allow for maneuvering in and out. Additionally, if a car was illegally parked at the bus stop, bus drivers were unable to pull in even if they wanted to. Finally, in instances where there were no parked vehicles near the bus stop, about 30% of bus drivers did not pull in the bus stop fully. As a result, their rear wheels partially blocked the travel lane, but this usually still allowed vehicles behind the bus to maneuver around and pass.

3.5.3 Trajectory Analysis

This section presents the results of trajectory analysis based on the research questions and analysis plan discussed in Chapter 2.

Question 1: ***Do horizontal curves in the separated bike lane affect bicyclist speed*?**

This research question hypothesizes that separated bike paths featuring horizontal curves at the bus stop area, induce lower bicyclist speeds. The sample size for Question 1 is twenty-seven bicyclists, extracted from the Washington Street at Walnut Street bus stop. Since the Broadway at Horizon Way bus stop had only two bicycles detected, their trajectories and therefore that specific bus stop was dropped from this analysis. Figure 3.58 shows the two detection zones at the Washington Street at Walnut Street bus stop, with one zone on the curved segment and the other on the straight segment. Twenty-seven bicycle trajectories passed through both of these zones. Figure 3.59 displays the average speed and speed variations for the two detection zones.



Source: [17]

Figure 3.58: Detection zones for the impact of bike lane curve (Washington Street at Walnut Street)

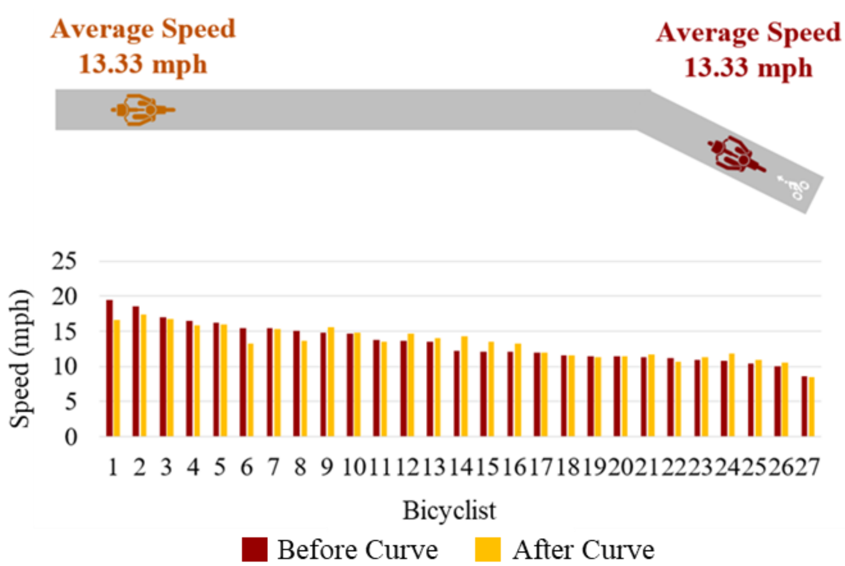


Figure 3.59: Average speed and speed distribution for the two detection zones (Question 1)

To examine whether there is a significant speed difference between the two detection zones' speeds, it is suitable to utilize a paired t-test since it can be used to compare the means of two measurements taken from the same individual. The result of the paired t-test using a 95% confidence interval is shown in Table 3.6. The research team found a p-value of 0.990, indicating no significant difference in speeds between the two detection zones.

Table 3.6: Paired t-test for the impact of curved bike lanes on bicyclist speed at floating bus stops

	Observations	Mean	Standard Deviation	Degrees of Freedom	t-statistic	p-value
Curved Segment	27	13.3296	2.721			
Straight Segment	27	13.3270	2.260			
Difference	27	0.0026	1.053	26	0.013	0.990

However, bicyclists with a higher speed at the curve segment were found to decelerate more noticeably. Another paired t-test with a 95% confidence interval was conducted to determine if there is a significant difference between the two detection zones for bicyclists with an initial speed greater than 15 mph. Table 3.7 shows that eight bicyclists had an initial speed greater than 15 mph. The p-value is 0.015, indicating a significant difference between the two zones, supporting our hypothesis.

Table 3.7: Paired t-test results for the impact of curved bike lanes on bicyclist speed at floating bus stops for higher bicyclist speeds

	Observations	Mean	Standard Deviation	Degrees of Freedom	t-statistic	p-value
Curved Segment	8	16.697	1.587			
Straight Segment	8	15.577	1.451			
Difference		1.120		7	3.214	0.015

The result for Question 1 shows that having a horizontal curve can slow down the bicyclists who have a high initial speed higher than 15 mph to ensure bicyclists pass through the bus stop area at a safer speed. However, despite being statistically significant, this speed reduction is fairly small, making it unclear whether horizontal curves are an effective strategy for speed management. Additional analysis should be performed with larger sample sizes and at more locations to make more conclusive design recommendations regarding the impact of horizontal curves on bicyclist speed reduction. One limitation of this analysis is that the LiDAR sensor was installed on a temporary tripod, limiting the sensor installation height and consequently the range for which bicyclist speeds could be obtained. As a result, it was not possible to collect bicyclist speeds on the straight part far in advance of the horizontal curve, which might have affected the findings of this statistical analysis.

Question 2: ***Does fencing along the separated bike lane affect bicyclist speed?***

The sample size for Question 2 is 134 bicyclists, extracted from the Somerville Avenue at Stone Avenue bus stop. Figure3.60 shows the two detection zones at the Washington Street at Walnut Street bus stop, with one point before the beginning of the fence and the other adjacent to the fence. 134 bicycle trajectories passed through these two detection zones. Figure 3.61 displays the average speed and Figure 3.62 the average speed distribution for the two detection zones.

Source: [17]

Figure 3.60: Detection zones for the impact of fencing at Somerville Avenue at Stone Avenue bus stop

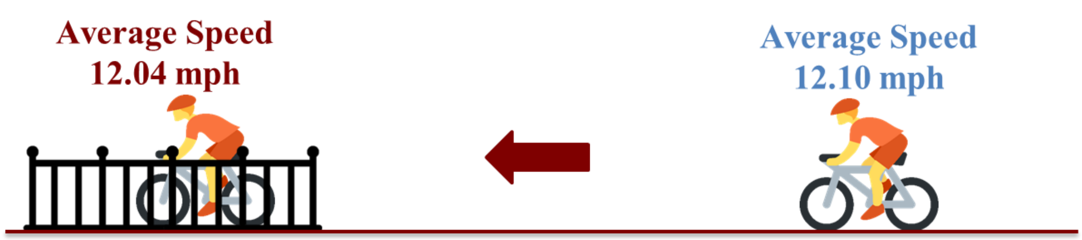


Figure 3.61: Average speed for the two detection zones (Question 2)

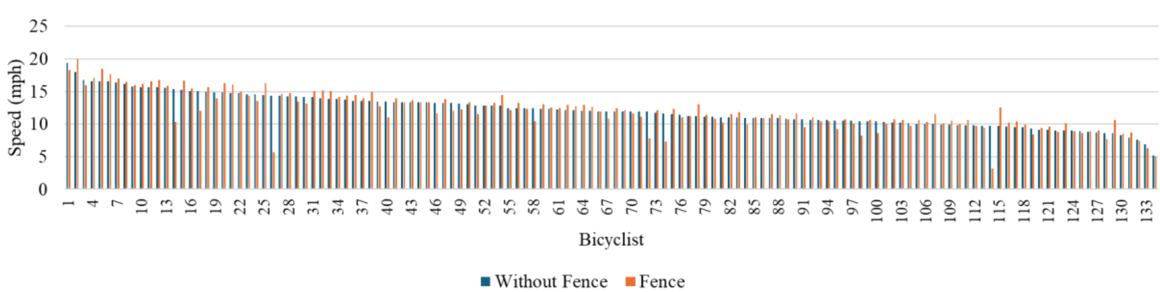


Figure 3.62: Average speed and speed distribution for the two detection zones (Question 2)

Using a paired t-test with a 95% confidence interval to examine the two average speeds, as shown in Table 3.8, resulted in a p-value of 0.631, indicating no significant difference between the two detection zones.

Table 3.8: Paired t-test for the impact of fencing on bicyclist speed at floating bus stops

	Observations	Mean	Standard Deviation	Degrees of Freedom	t-statistic	p-value
With Fence	134	12.042	2.866			
Without Fence	134	12.104	2.442			
Difference		-0.062		133	-0.482	0.631

As before, another paired t-test with a 95% confidence interval was conducted to determine if there is a significant difference between the two detection zones for bicyclists with an initial speed greater than 15 mph. Table 3.9 shows that 17 bicyclists had an initial speed greater than 15 mph. The p-value is 0.8606, indicating no significant difference between the two detection zones.

Table 3.9: Paired t-test results for the impact of curved bike lanes on bicyclist speed at floating bus stops for higher bicyclist speeds

	Observations	Mean	Standard Deviation	Degrees of Freedom	t-statistic	p-value
With Fence	17	16.265	2.232			
Without Fence	17	16.189	1.106			
Difference		0.076		16	0.178	0.861

These results indicate that having a fence does not effectively slow down bicyclists, even those traveling at higher speeds. However, this does not mean that the fence has no function at the floating bus stops. It still serves to physically separate passengers from bicycles and manage platform access.

Question 3a: ***How many and how long do waiting transit riders stand in the separated bike lane?***

The Somerville Avenue at Stone Avenue bus stop was found to have the highest number of standing pedestrians in the bike lane, and the Broadway at Horizon Way bus stop had the highest percentage of standing pedestrians in the bike lane, and the two full-width platforms showing the longest duration for those pedestrians standing in the bike lane. Table 3.10 summarizes the statistics of pedestrian standing behavior for the five selected bus stops.

Table 3.10: Pedestrian standing behavior in the bike lane

Bus Stop	Type	Number of pedestrians	Number of pedestrians standing in the bike lane	Percentage of pedestrians standing in the bike lane	Duration (secs) Mean	Standard Deviation	Duration (seconds) Min	Duration (seconds) Max
Massachusetts Avenue opp. Christian Science Center	Partial Width	2,085	49	2.35%	11.35	9.42	3.1	47.7
Somerville Avenue at Stone Avenue	Partial Width	1,595	69	4.33%	10.73	13.66	3	67
Washington Street at Walnut Street	Full Width	118	5	4.24%	26.1	20.55	3.4	59.4
Broadway at Horizon Way	Full Width	158	25	15.82%	24.06	36.27	3	134.2
Broadway opp. Beacham Street*	NoPlatform	114	6	5.26%	8.16	4.57	3.5	15.5

* Broadway opp. Beacham Street bus stop excluded an outlier of 177.4 seconds

To examine whether there is a significant difference between the percentage of standing pedestrians at the three types of floating bus stops, it is suitable to utilize a two-proportion z-test, as it can be used to compare the percentages of two measurements taken from two independent populations. The research team has conducted three pairwise two-proportion z-tests to assess the differences between the three types of floating bus stops in a pairwise manner.

Additionally, a two-sample t-test with unequal variances was used to determine whether there are significant differences between the average duration of pedestrians standing in the bike lane under different types of floating bus stop designs. These statistical tests can be used to assess whether there is a significant difference between two mean values from two independent and unpaired populations with unequal variances.

The statistical analysis shows that there is a significant difference at the 95% level of significance in the percentage of pedestrians standing in the bike lane between full-width bus stops and partial-width bus stops, as well as between full-width bus stops and no platform bus stops, i.e., there is a significantly higher portion of pedestrians standing in the bike lane at full-width platform bus stops compared to partial-width platform and no platform bus stops, as shown in Table 3.11.

Additionally, the only significant difference found across different floating bus stop types is in the average duration, showing that pedestrians stand on the bike lane for a significantly longer time at full-width bus stops compared to no platform bus stops; see Table 3.12. Other comparisons that were performed between floating bus stop types were not found to be statistically significant. This means that the percentage of pedestrians standing on the bike lane does not differ significantly between partial-width platform bus stops and no platform bus stops; yet it should be noted that there are very few pedestrians observed at the no platform bus stop for the duration of this project's data collection, which could be influencing these results.

Table 3.11: Two-proportion z-test for the impact of floating bus stop design on pedestrian standing behavior in the bike lane

	Observations	Proportion	z-statistic	p-value
Full-width platform	276	0.109		
Partial-width platform	3,680	0.032		
No platform	114	0.053		
Difference (Full-width − Partial)			6.470	0.000
Difference (Full-width – No platform)			1.740	0.819
Difference (Partial-width – No platform)			-1.216	0.224

Table 3.12: Two-sample t-test with unequal variances for the impact of floating bus stop design on pedestrian average standing duration in the bike lane

	Observations	Mean (seconds)	Standard Deviation	Welch's Degrees of Freedom	t-statistic	p-value
Full-width platform	30	237.3	340.307			
Partial-width platform	118	109.9	11.086			
No platform	5	81.6	45.660			
Difference (Full-width – Partial-width)		127.4		30.996	2.019	0.052
Difference (Full-width – No platform)		155.7		33.895	2.381	0.023
Difference (Partial-width – No platform)		28.38		8.014	1.217	0.258

This result seems counterintuitive given the fact that full-width platform bus stops offer space for transit users to wait at, and therefore, the need to traverse the bike lane and stand in it while waiting for the bus arrival should be minimized. This could be attributed to site-specific characteristics of the full-width bus stops under study. For example, the Broadway at Horizon Way full-width platform bus stop has a unique design in that it features a curved sidewalk along with a curved bike lane without any bicycle symbol markings on the bike lane at the bus stop area and with crosswalks constructed by the same material as the sidewalk indicating continuation of the walking area, as shown in Figure 3.63. It is, therefore, hypothesized that pedestrians are not necessarily aware that they travel on a bike lane, especially since the bicycle volume is relatively low, motivating a higher percentage of pedestrians to stand in the bike lane for longer periods of time while waiting for buses. In addition, no platform bus stops allow passengers to be closer to the road, and therefore, they are less likely to need to step into the bike lane to check on whether the bus is coming.

Source: [17]

Figure 3.63: Broadway at Horizon Way floating bus stop

Question 3b: ***How many pedestrians go back and forth across the separated bike lane more than two times?***

Table 3.13 shows statistics on pedestrian crossing behavior, particularly exploring the number and percentage of pedestrians that cross the bike lane more than two times. Per the results presented in the table, the Somerville Avenue at Stone Street bus stop has both the highest number and percentage of pedestrians crossing back and forth in the bike lane. One possible reason is that the shelter at that bus stop is on the sidewalk and close to the bike lane, causing passengers to cross or step into the bike lane frequently to check if the bus is coming. Conversely, the Broadway opposite Beacham Street no platform bus stop presents the lowest percentage of this phenomenon, likely due to the fact that the lack of the platform allows pedestrians to be close to the roadway and have high visibility, therefore being able to check whether the bus is coming or not, without stepping into the bike lane.

Table 3.13: Pedestrian crossing behavior

Bus Stop	Type	Number of pedestrians	Number of crossing pedestrians	Number of pedestrians crossing for more than two times	Percentage of pedestrians crossing more than two times
Massachusetts Avenue opp. Christian Science Center	Partial-width platform	2,085	168	139	82.74%
Somerville Avenue at Stone Avenue	Partial-width platform	1,595	581	519	89.33%
Wahington Street at Walnut Street	Full-width platform	118	17	13	76.47%
Broadway at Horizon Way	Full-width platform	158	79	68	86.08%
Broadway opp. Beacham Street	No platform	114	10	6	60.00%

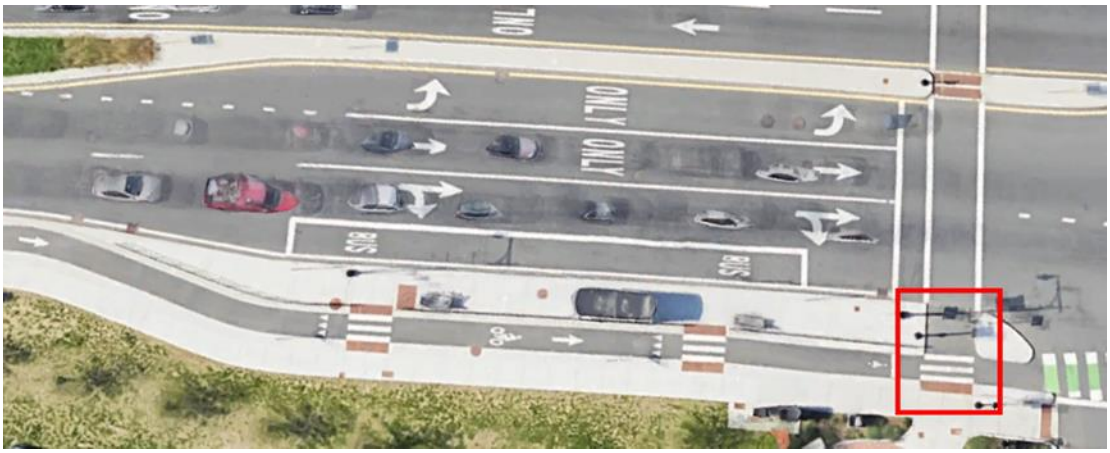
The statistical analysis shows that both partial-width and full-width platform bus stops have a significantly higher proportion of pedestrians crossing the separated bike lane more than two times compared to no platform bus stops; see Table 3.14. A possible reason for this result is that there are no other obstacles around the Broadway opposite Beacham Street no platform bus stop, allowing passengers to clearly check if the bus is arriving by standing on the sidewalk without needing to step into the bike lane. In contrast, partial-width platform bus stops, where the shelter is not located on the platform, encourage passengers to cross the bike lane multiple times to check the bus status. These results imply that even when full-width bus stops are present, many transit riders choose to wait for the bus on the sidewalk rather than the platform.

Table 3.14: Two-proportion z-test for the impact of floating bus stop design on pedestrian crossing behavior

	Observations	Proportion	z-statistic	p-value
Full-width platform	96	0.844		
Partial-width platform	749	0.879		
No platform	10	0.600		
Difference (Full-width – Partial-width)			-0.98	0.334
Difference (Full-width – No platform)			2.22	0.026
Difference (Partial-width – No platform)			2.28	0.022

Question 4: ***What percentage of transit riders use crosswalks versus crossing elsewhere?***

The highest and lowest percentage of pedestrians never stepping on the crosswalk while crossing was observed at the Washington Street at Walnut Street bus stop and Somerville Avenue at Stone Avenue bus stop, respectively; see Table 3.15 for the statistics on pedestrian crossing behavior with respect to crosswalk usage for all five floating bus stops. Note that the crosswalk that was the furthest away from the LiDAR sensor at the Washington Street at Walnut Street bus stop was not observable and was, therefore, excluded from the analysis; see Figure 3.64.



Source: [17]

Figure 3.64: Crosswalk at Washington Street at Walnut Street bus stop excluded from the analysis

A possible reason for the Washington Street at Walnut Street bus stop having the highest percentage of pedestrians who never step in the crosswalk while crossing is likely due to its layout. Transit passengers often prefer to enter/exit the platform from the side that leads to the crosswalk across the roadway rather than the marked crosswalks along the bus stop; see Figure 3.65.

Table 3.15: Pedestrian crossing behavior with respect to crosswalk usage

Bus Stop	Fence	Number of pedestrians at the bus stop	Number of crossing pedestrians	Number of pedestrians who never stepped on the crosswalk while crossing	Percentage of pedestrians who never stepped on the crosswalk while crossing
Massachusetts Avenue opp. Christian Science Center	No	2,085	168	124	73.81%
Somerville Avenue at Stone Avenue	Yes	1,595	581	237	40.79%
Washington Street at Walnut Street	Yes	118	17	12	70.59%
Broadway at Horizon Way	No	158	79	44	55.70%

Source: [17]

Figure 3.65: Typical pedestrian crossing paths at the Washington Street at Walnut Street bus stop

As for the Somerville Avenue at Stone Avenue bus stop, one of the sidewalks is much wider than typical crosswalks, as shown in Figure 3.66, resulting in a relatively low percentage of pedestrians who never stepped on the crosswalk while crossing. However, according to the video review, a lot of passengers crossed the bike line diagonally on the wide sidewalk, increasing their crossing time and, therefore, the potential for conflicts with bicyclists. As a result, even though more visible and likely to be used, wider crosswalks should be implemented with caution, recognizing that they might result in longer crossing time and, therefore, might be introducing additional interactions between pedestrians and bicyclists.

Source: [17]

Figure 3.66: Crosswalk at Somerville Avenue at Stone Avenue

Table 3.16 presents the statistical analysis results comparing the proportions of passengers crossing the bike lane outside of the crosswalk area at bus stops with and without fences. The percentage of pedestrians not using the crosswalk is significantly lower at bus stops with fences compared to those without. This suggests that bus stops equipped with fences effectively guide transit riders to use crosswalks, preventing them from crossing the bike lane at other points.

Table 3.16: Two-proportion z-test for the impact of fencing on pedestrian crossing behavior

	Observations	Proportion	z-statistic	p-value
With fence	598	0.416		
Without fence	247	0.680		
Diff (With fence – Without fence)			-6.98	0.000

Question 5: ***How many and how long do passengers walk along the separated bike lane?***

Table 3.17 shows the number, percentage, and duration of pedestrians walking along the bike lane for each of the five bus stops. The Washington Street at Walnut Street bus stop and the Broadway at Horizon Way bus stop appear to have the highest percentages of pedestrians walking along the bike lane. A possible reason for this is that passengers at the Washington Street at Walnut Street bus stop may be motivated to reduce their walking distance by walking along the bike lane. At the Broadway at Horizon Way bus stop, the bike lane has low bicycle volume, making pedestrians feel safe and/or unaware so that they walk straight into the bike lane instead of following the curved sidewalk. Figure 3.67 shows an example of a pedestrian walking route at these specific bus stop.

Table 3.17: Pedestrian walking behavior along the bike lane

Bus Stop	Fence	Number of pedestrians	Number of pedestrians walking in the bike lane	Percent of pedestrians walking in the bike lane	Duration (sec.) Mean	Std. devia-tion	Duration (sec) Min	Duration (sec.) Max
Massachusetts Avenue opp. Christian Science Center	No	2,085	48	2.78%	11.03	9.79	3	41.4
Somerville Avenue at Stone Avenue	Yes	1,595	104	6.52%	6.76	5.48	3	39.6
Washington Street at Walnut Street	Yes	118	19	16.10%	10.32	8.28	3.2	29.1
Broadway at Horizon Way	No	158	22	13.92%	8.82	6.1	3.3	29.4
Broadway opp. Beacham St	No	114	4	3.51%	8.6	9.62	3.1	23

(a) Washington Street at Walnut Street, Brookline, MA

(b) Broadway at Horizon Way, Everrett, MA

Source: [17]

Figure 3.67: Typical walking route for pedestrians at Washington Street at Walnut Street and Broadway at Horizon Way bus stop

A two-proportion z-test is used to test whether there is a significant difference in the percentage of pedestrians walking in the bike lane between bus stops with and without fences. Table 3.18 shows that the proportion of pedestrians walking in the bike lane is significantly higher at bus stops with fences compared to those without. This result might be driven by the specific layout of the Washington Street at Walnut Street, which presents the highest percentage of pedestrians walking along the bike lane, which as described earlier might be motivating that behavior to reduce walking distance. However, when we tested the average duration of pedestrians walking in the bike lane between bus stops with and without fences using a two-sample t-test with unequal variance, see Table 3.19, we found that bus stops with fences have a significantly lower average duration compared to those without fences. This indicates that while fencing might not be preventing pedestrians from walking along the bike lane, it serves as a spatial separation between the platform and the bike lane, reminding pedestrians when they step into the bike lane and encouraging them to step out.

Table 3.18: Two-proportion z-test for the impact of fencing on pedestrian walking behavior along the bike lane

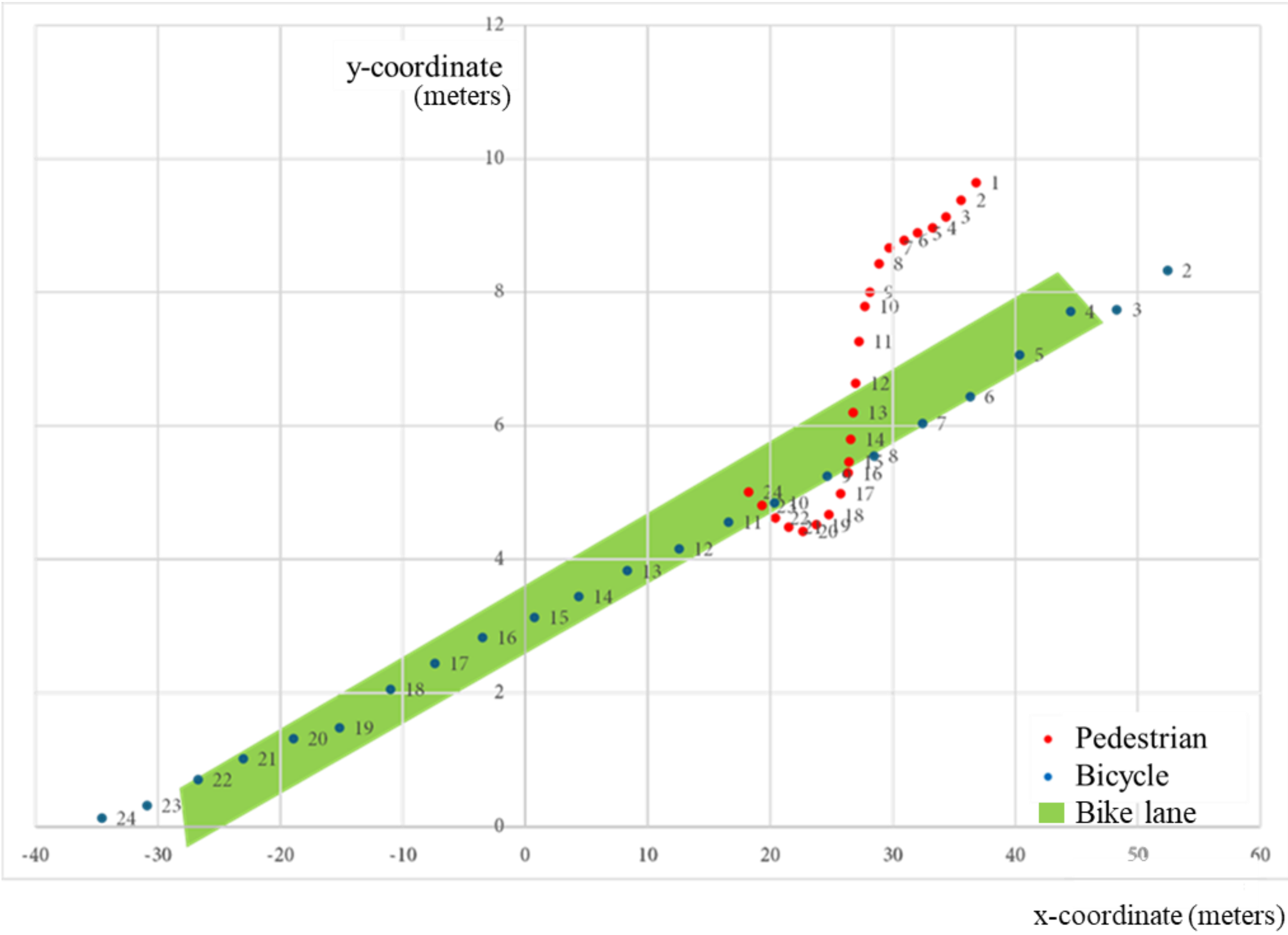
	Observations	Proportion	z-statistic	p-value
With fence	1,713	0.072		
Without fence	2,243	0.031		
Difference (With fence – Without fence)			6.007	0.000*

Table 3.19: Two-sample t-test with unequal variances for the impact of floating bus stop design on pedestrian average walking duration in the bike lane

	Observations	Mean (seconds)	Standard Deviation	Satterthwaite's Degrees of Freedom	t-statistic	p-value
With fence	123	7.311	0.550			
Without fence	74	10.238	1.022			
Difference (With fence – Without fence)				115.522	-2.522	0.013*

Question 6: ***When a pedestrian is standing in the separated bike lane, how much do approaching bicyclists slow down, and with how much clearance do they pass the pedestrian?***

Based on the definition of bicycle and pedestrian interactions described in Chapter 2, i.e., an interaction was recorded if the minimum distance between the two trajectories was less than 10 meters (~33 ft), the number of interaction cases is low. For example, in the 12-hour data collection at Massachusetts Avenue opposite Christian Science Center bus stop, there are only seven bicycle-pedestrian interaction cases. In these cases, the pedestrians were found to be actively moving to avoid collision with a bicyclist and none of the seven bicyclists were observing reducing their speeds. Figure 3.68 shows an example in which a pedestrian accelerated to cross the bike lane after a bicyclist passed through. This observation points to the challenge for visually impaired transit users when they cross the bike lane since, in a similar case, they might not have detected the bicyclist and altered their path to avoid it.



The number for each dot represents the time stamp in seconds. The bicycle started being detected from the 2nd second forward.

Figure 3.68: Example of a pedestrian-bicyclist interaction within the bike lane area along a floating bus stop (Massachusetts Avenue opp. Christian Science Center)

Question 7: ***In the absence of platforms (i.e., no platform bus stops), do bicyclists approaching the stop while a bus is there adjust their speeds?***

Question 7 only focused on no platform bus stops, namely the Broadway opposite Beacham Street bus stop. Although there were 36 bicyclists passing through the bus stop area in the three-hour data collection period, none of them happened when a bus stopped at the bus stop. Therefore, it was not possible to answer this question using the data collected in this research project.

3.5.4 Summary of Behavioral Analysis Findings

The results of the analysis using trajectory data have revealed that the design of the bike lane adjacent to a bus stop, in addition to the design and placement of other elements such as crosswalks and fences, can have a significant impact on the interactions and potential for conflict between bicyclists and transit users. More specifically, the introduction of horizontal curves for bike lanes in the bus stop proximity does not significantly reduce average bicyclist speed. While it does significantly reduce speeds for bicyclists traveling at higher than 15mph speeds, which can potentially have implications for areas with high volumes of electric bikes or other motorized micro-mobility options (e.g., e-scooters) that tend to travel at higher speeds, the results of this analysis showed very small reductions on the order of 1 mph. Fencing was found to not be significantly contributing to bicyclist speed reduction, even for the bicyclist with the highest speeds; yet it can still have a positive effect on separating bicyclists from pedestrians/transit users, managing platform access, as well as wayfinding.

The statistical analysis also revealed interesting findings, with full-width platform bus stops experiencing a statistically higher number of pedestrians that stand in the bike lanes compared to partial-width platform and no platform bus stops and significantly higher standing durations compared to the no platform bus stops. This could be a function of the specific designs and traffic conditions at the tested bus stops, such as poorly marked bike lanes and low bicycle volumes, communicating to transit users a lack of potential interactions between pedestrians and bicyclists. In terms of crossing the bike lane more than two times, full-width and partial-width platform bus stops were found to have significantly higher percentages of pedestrians engaging in this moving pattern compared to no platform bus stops, possible due to lack of visibility from their waiting location on whether the bus is coming. This also implies that many transit riders at full-width platform bus stops choose to wait on the sidewalk rather than on the platform. High percentages of pedestrians traveling along the bike lane could be attributed to low bicycling volumes and the perceived low risk of interactions with bicyclists in addition to being motivated by pedestrians' desire to reduce their walking distance at some bus stops.

Fencing is an effective countermeasure for encouraging pedestrians to use the designating crosswalks when crossing the bike lane. Statistical analysis shows that the percentage of pedestrians using crosswalks while crossing bike lanes at bus stops with fencing is significantly higher than at those without fencing. Additionally, wider crosswalks presented higher percentages of pedestrians that never stepped outside of the crosswalk compared to narrower ones, but also led to a potentially higher risk for conflicts between pedestrians and bicyclists, as they motivated some pedestrians to cross diagonally therefore, spending more time on the bike lane during their crossing. The presence of fencing was also found to be correlated with higher percentages of pedestrians walking along the bike lane, even though still fairly small percentages, but lower durations. This indicates that fences might be increasing situational awareness for pedestrians, and therefore, motivating less time in the bike lane and consequently lower risk of conflicts with bicyclists.

When attempting to study the interactions between bicyclists and pedestrians standing or walking in the bike lane, it was observed that pedestrians adjusted their positioning to avoid conflict with bicyclists not adjusting their speeds for the seven cases that were observed. This is critical to note, as it has implications on the risk visually, hearing, and mobility-impaired individuals waiting in the bike lane would face as they might not be able to detect or react fast to an oncoming bicycle. However, larger sample sizes should be analyzed to make more concrete conclusions on pedestrian and bicyclist behavior when they interact with each other.

Studying bicyclist and pedestrian behavior in relation to the bus arrival was not possible due to the lack of sufficient sample sizes, which was attributed to low detection rates of pedestrians waiting in the shelter and low numbers of bicyclists.

Manual observations reveal that boarding and alighting passengers were more likely to check for oncoming bicyclists before crossing the bike lane at full-width platform bus stops compared to partial-width platform bus stops. This lack of glances by many pedestrians can be attributed to the fact that they might not recognize that there is a bike lane due to its design or low bicyclist demand. Colored pavement does not seem to be impacting glancing behavior, while continuous barriers seem to have a stronger impact on inducing glances before crossings. A statistical analysis with data from more bus stops could help further understand the impact of various design elements on pedestrian glancing behavior before crossing. In addition, the presence of a few mopeds on the bike lanes indicates the need for signage restricting separated bike lane use by mopeds. Intensifying enforcement can also increase compliance with these regulations. Lastly, an educational campaign may be launched to inform moped users of the appropriate routes.

All these results are preliminary findings that could be strengthened with the use of larger sample sizes in terms of bicyclist and pedestrian trajectories at more floating bus stop sites. Validation of these results with video recordings could also strengthen the findings.

4.0 Implementation and Technology Transfer

This Chapter translates the knowledge that has been obtained through this project into tangible recommendations that MassDOT can use to inform: 1) design and implementation of floating bus stops, 2) network-wide assessment of safety and accessibility of existing floating bus stops, and 3) data collection processes that can contribute to this assessment.

4.1 Recommendations

Recommendations are provided in the context of design guidelines that improve floating bus stop safety and accessibility, as well as policy recommendations. Safety and accessibility involve protecting pedestrians of all abilities, including passengers and bicyclists, from danger when boarding, alighting, waiting, or passing through the bus stop area. A basic principle of Sustainable Safety, the Dutch Vision Zero program, is to avoid differences in speed. This means slowing bicycles and/or separating them from pedestrians, e.g., with fencing. Another Sustainable Safety principle is recognizability and predictability, which means making physical changes to the bike path that help cyclists recognize that they're passing through a bus stop – changes such as an S-curve, a change in elevation, or flexposts in the middle of the path or on the sides of path. These standard principles of safety, when applied to this context, point to two main objectives: 1) maximize separation between bicyclists and pedestrians, and 2) manage the speed of bicyclists and raise their situational awareness when entering a bus stop area. Accessibility can be achieved through improved safety and wayfinding.

4.1.1 Maximize Separation Between Bicyclists and Pedestrians

Based on these concepts and principles, there is a strong preference for a full-width platform bus stop. A full-width platform provides sufficient space to implement shelters and benches, encouraging passengers to wait on the platform and eliminating the need to cross the bike lane to check if the bus is arriving. In addition, full-width platforms allow bus passengers who use a ramp to not interfere with passing bicyclists. In several ways, then, full-width platforms maximize the separation between bicyclists and pedestrians, as shown in Figure 4.1.

Source:[16]

Figure 4.1: Full-with platform bus stop

If there are space restrictions for building a full-width platform, then partial-width platform bus stops are recommended; an example is shown in Figure 4.2. Although shelters and benches are not implemented on the platform, there is still a dedicated area for passengers to alight instead of stepping into the bike lane directly (as in the no platform bus stop design) and likewise to stand when awaiting an arriving bus. However, partial-width platforms provide far weaker separation of users, as passengers have to cross the separated bike lane to get between the waiting area and the bus; therefore, there should be stronger bicyclist speed management efforts at partial-width platform bus stops. Narrower shelters can also be implemented in partial-width platform bus stops to eliminate transit riders crossing the bike lane when a bus is approaching or to check whether a bus is approaching.

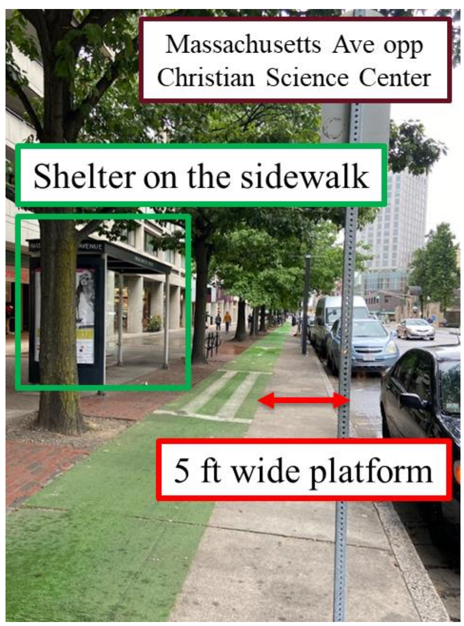


Figure 4.2: Partial-width platform bus stop

Sometimes, space to implement full-width platform bus stops can be obtained by narrowing or diverting the adjacent bike lane. With this kind of change, some partial-width platforms can be converted to full-width, as shown in Figure 4.3. For example, at the Somerville Avenue at Stone Street bus stop, the platform is more than 7 ft wide; by making the bike lane

1 ft narrower, the platform width would exceed 8 ft, and the shelter could be moved onto the platform. At the stop on Massachusetts Avenue opposite the Christian Science Center, there is ample space for the sidewalk to be diverted away from the street near the bus stop, leaving space for a full-width platform. As an added benefit, narrowing a bike lane or adding a horizontal curve to divert the bike lane will also enhance situational awareness for bicyclists, possibly increasing their yielding rates and reducing their speeds.

Figure 4.3: Conversion example of partial-width platform to full-width platform

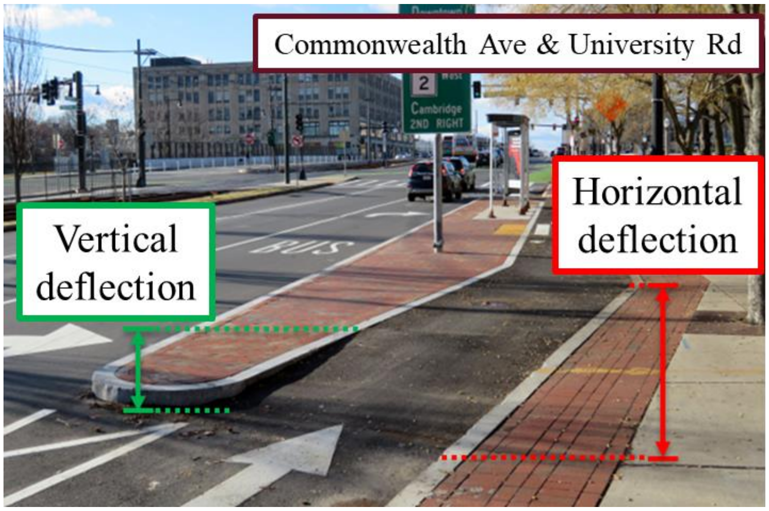
At no platform bus stops, the bike lane is adjacent to the curb, meaning passengers must board from the bike lane and alight into the bike lane. This alighting maneuver is particularly problematic – alighting passengers face a blind corner, unable to see approaching bikes. Instead of adding speed management strategies to the adjacent bike lane, it is more important to get bicyclists to stop when the bus door is opened or to divert the bike lane away from the bus.

Fences can be implemented to reinforce separation among users. The statistical analysis showed that floating bus stops with fences presented significantly higher percentages of pedestrians using the designated crosswalks and lower durations of pedestrians walking along bike lanes. Fences can also prevent bicyclist veering off to the sidewalk or platform as they pass along the bus stop, which could increase conflicts between bicyclists and transit riders.

Using different pavement materials for the separated bike lane versus pedestrian areas (crosswalk, platform, and sidewalk) is recommended to establish and communicate the presence of dedicated spaces for bicyclists and pedestrians, and therefore, the separation. While this statistical analysis did not include any testing of the impact of pavement material and color on bicycle speed or transit rider crossing and walking behavior, it did discuss that transit rider behavior in terms of walking along the bike lane could be attributed to the lack of situational awareness of the presence of the bike lanes and the potential of interactions with bicyclists. Situational awareness for both bicyclists and transit riders can be improved by variability in the pavement color or surface type. In addition, detectable surfaces are recommended so that visually impaired individuals can distinguish transitions from one area to another. Lastly, crosswalk dimensions should be carefully designed to avoid encouraging diagonal crossings, which can increase pedestrians' time on the bike lane and, therefore, exposure to potential conflict with bicyclists.

4.1.2 Bicyclist Speed Management

Along with separation treatments, treatments that raise the situational awareness of bicyclists and/or slow them down are crucial for improving safety and accessibility, especially at partial-width platform stops and no platform bus stops. Vertical and horizontal deflection of the bike lane upstream of the bus stop, as shown in Figure 4.4, can help get bicyclists' attention and horizontal curves will slow the fastest bicyclists, although just by a small amount, as indicated by the statistical analysis performed in this study for horizontal curves. Horizontal deflection should be sited so that it ends at least 30 ft before the pedestrian crossing because when bicyclists are turning, their attention is drawn to the ground. Changing the color of the bike lane to green (a color often used to denote a conflict zone), as shown in Figure 4.5, is probably not effective because bicyclists don't treat green pavement as a warning aimed at them. However, pavement color or surface can be used to increase bicyclist situational awareness of them approaching a bus stop in addition to high visibility of crosswalks to encourage speed reduction and yielding to crossing riders. Fencing could also contribute to situational awareness, although statistical analysis performed as part of this study indicated that it does not significantly reduce bicyclist speeds at the locations under study. Vibration feedback from rumble strips has been used at some bus stops, but they are not specific to bus stops (i.e., they don't make bicyclists aware that they are approaching a bus stop) and pose an unacceptable danger to bike path users with small wheels (those with roller blades or skateboards).



Source: [20]

Figure 4.4: Vertical and horizontal deflection

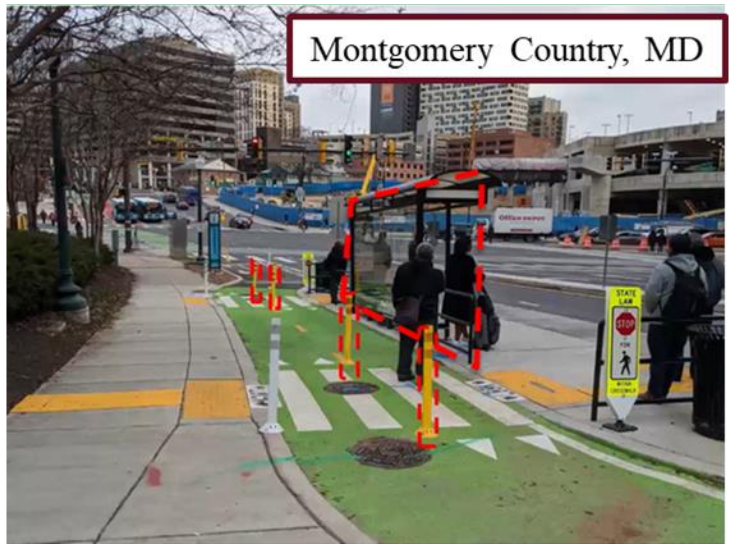
Source: [18]

Figure 4.5: Change in pavement surface

Two treatments that have been used in the Washington DC area appear to be very effective in slowing bicyclists and getting their attention. One is using vertical elements to create a "gateway" through which bicyclists must pass, as shown in Figure 4.6 and Figure 4.7. The vertical elements can be yellow flexposts or narrow "Yield to Pedestrian" signs. On a two-way path, a flexpost in the middle of the path, as well as on the sides, creates a narrow gate for cyclists in both directions; on a one-way path, the vertical elements should be on the sides only. The second one is where a pre-fab platform is placed on the street, and the separated bike lane is at street level. The platform has built-in ramps for bicyclists, which tend to be noisy as well as steep,effectively slowing bicyclists while also making them aware of entering a bus stop area. The noisy ramps also provide an audible warning of a bicyclist passing through, a benefit to bus passengers with visual impairments.

Narrowing the separated bike lane as it approaches the bus stop is another way to manage bicyclist speeds and it has been used in Montreal. One reason this treatment is successful is that it is that it discourages bicyclists from passing or riding side by side, thus reducing the risk of a multiple-threat crossing. Even where bicyclists are riding alone or single file, making the separated bike lane narrower – even if just with painted lines – is always noticeable, raising awareness of an approaching bus stop and encouraging slower bicyclist speeds.

Source: [19]
Figure 4.6: Unsignalized pedestrian crosswalk sign



Source: [18]
Figure 4.7:Restricted-space bike lane using fencing, shelter walls, and flexposts

Changes in traffic supplementary signage and pavement markings to communicate restrictions and even signalization of bike lane crossings can be used to manage bicyclist speeds and yielding/stopping behavior. In Massachusetts, there is a state law about vehicles stopping when a streetcar opens its door (one may pass only with 8 ft clearance), and there are laws about not passing a school bus when stopped, but there is no such law for transit buses because the law did not anticipate buses stopping where traffic might be passing on the right. In Copenhagen, Denmark, there is a regulation requiring bicyclists to stop upstream of the crosswalk when the bus door is opened, as shown in Figure 4.8. In Toronto, Canada, the law about not passing streetcars with open doors was recently extended to apply to buses; at no platform stops, there are markings in the bike lane reminding bicyclists to stop when the bus door is opened, as shown in Figure 4.9. Buses in Taipei, Taiwan, are equipped with a stop sign on their doors (aimed at motorcycles that might be passing on the right), which automatically appears when the bus door is opened, similar to school buses in the U.S., as shown in Figure4.10. As mentioned earlier, Montgomery County is planning to signalize such crossings wherever possible, which will also facilitate crossings for visually impaired transit riders.

Image: courtesy of Vincent B.

Figure 4.8: Bicyclists stopping when the bus door is opened in Copenhagen, Denmark

Image: courtesy of B. Katz

Figure 4.9: Bike lane markings to remind bicyclists not to pass when the bus door is opened in Toronto, Canada

Image: courtesy of K. Huang

Figure 4.10: Motorcycle stop sign on the bus door in Taipei, Taiwan

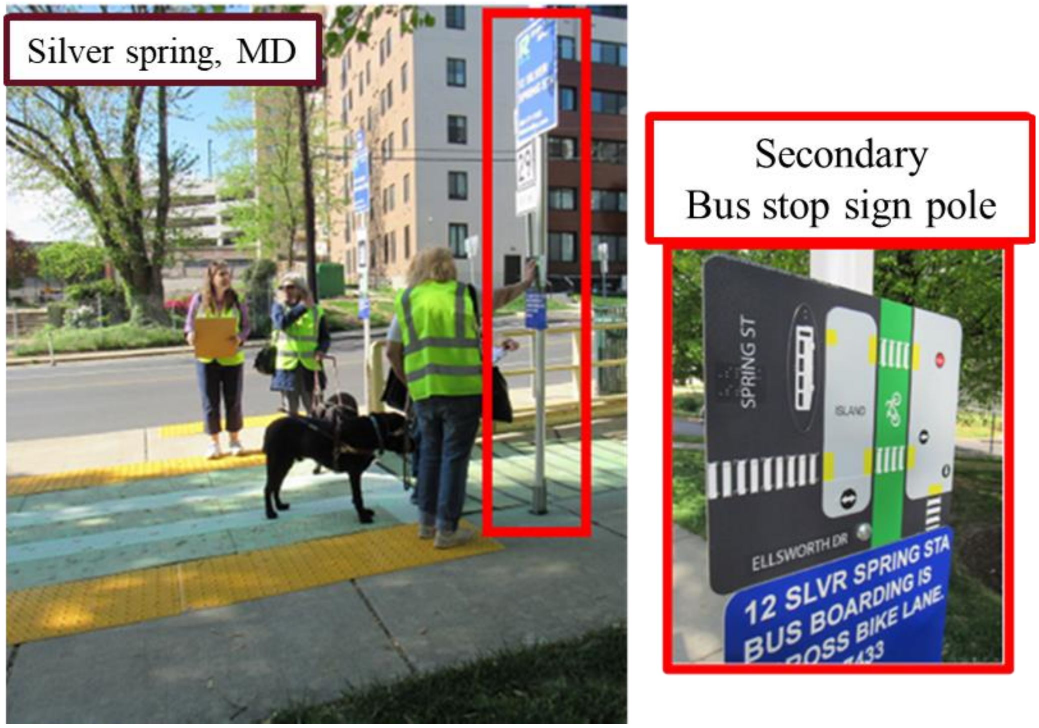
4.1.3 Wayfinding and Other Accessibility Considerations

Visually impaired individuals need some specially designed for them wayfinding to get information about certain infrastructure and the direction of their way. Crosswalks should be visible and equipped with tactile pavement to facilitate wayfinding. Fencing serves as a wayfinding aid by positioning crosswalks at fence openings, and per focus group participant recommendations, fences should include a rail that is low enough to be detected with a cane.

To assist visually impaired individuals in locating the crosswalk, it is advisable to use secondary bus stop signs on the sidewalk to mark the entrance to the bus stop, as shown in Figure 4.11. They should have a special shape, such as the octagon-shaped poles used in Montgomery County, MD to distinguish them from the primary bus stop poles. The secondary sign should also have a unique shape, as shown in Figure4.12, and provide information about bus route services, including in Braille so that would-be passengers can determine whether it’s the right bus stop for them. This setup helps passengers avoid crossing the bike lane repeatedly to check for information.

Source: [18]

Figure 4.11: White flexpost for marking the crosswalk location



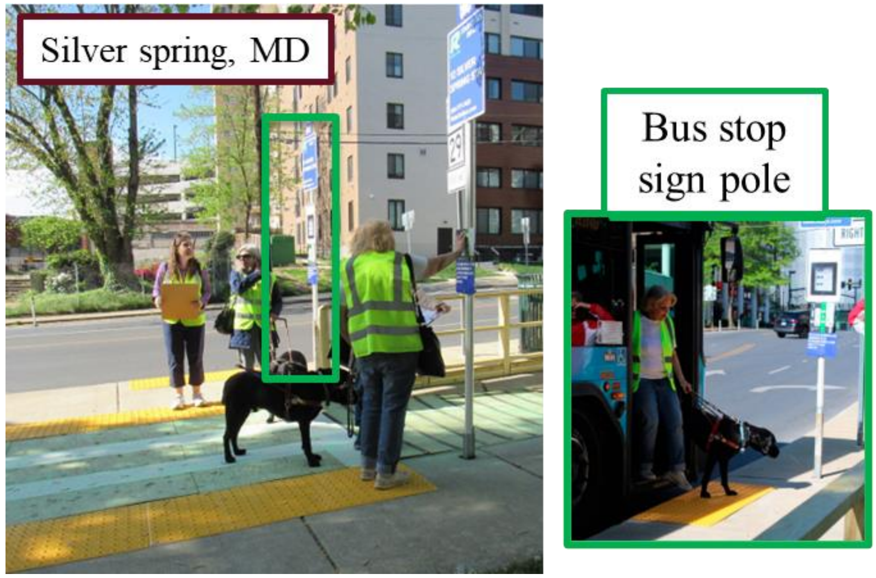
Source: [21]

Figure 4.12: Secondary bus stop sign pole with bus route information in Braille

Based on feedback from focus groups, visually impaired passengers often wait next to the bus stop sign pole on the platform to ensure the bus driver sees them. To accommodate this behavior, it is recommended to place the bus stop sign pole near where the front door of the bus will stop but offset a bit so as not to obstruct the path to/from the door, as shown in Figure 4.13 and Figure4.14. At the same time, the shelter should be located near the bus stop sign so that approaching bus drivers can see both the bus stop sign and the shelter or boarding area simultaneously.

Source: [16]

Figure 4.13: Bus stop sign pole beside the shelter (130 Western Ave, Boston, MA)



Source: [21]

Figure 4.14: Bus stop sign pole by the boarding area (Source: [21])

When considering bus stop accessibility, it is critical to also focus on accommodating the needs of users of mobility-assisting devices and ensure that there is adequate space, i.e., wide enough platforms and ramps to access bus stops using wheelchairs. In addition, it is important to ensure that the path from the shelter to the bus is clear of obstructions, and the pavement is frequently maintained to ensure smooth riding surfaces. Additionally, it is advisable to align the crosswalk and boarding area in a straight line, as shown in Figure 4.15. This design helps prevent wheelchairs from having to navigate turns on the platform and facilitates wayfinding for visually impaired riders. Audible announcements on board buses related to stepping off onto or having to cross a bike lane could also improve alighting passengers' situational awareness and, therefore, safety.

Source: [18]

Figure 4.15: Crosswalk, tactile pavement, and boarding area aligned in a straight line

Two-way bike lanes or counterflow bike lanes adjacent to bus stops should be avoided as they create additional crossing challenges, especially for visually impaired transit riders.

Finally, while not specific to floating bus stops, it is critical for accessibility that buses stop at the curb and bus drivers are trained to look out for waiting passengers that might be at the shelter or secondary pole and not necessarily next to the bus stop sign. Manual observations revealed that buses not pulling into the bus stop and stopping parallel to the platform is a frequent phenomenon. Additional parking restrictions around the bus stop and driver training could address this issue, which is critical for ensuring accessibility and safety for all users.

4.2 Step-by-Step Assessment Procedure

This step-by-step assessment procedure is intended to assist the MBTA and any other transit agency or jurisdiction on how to assess the safety and accessibility of their existing floating bus stops. In addition, it provides concrete recommendations on how to improve these bus stops for improved safety and accessibility for all.

1. **Are stopping buses often failing to get both doors, especially the front door, tight next to the curb?**
   If not, in addition to traditional remedies (remove more parking, strengthening enforcement, and training drivers), consider adding a bus bulb, with buses stopping in the travel lane. An added bus bulb, which can be pre-fab or made of permanent materials, will not only solve the curb access problem but will also create more space for a full-width platform
2. **If the stop does not have a full-width platform, can the platform be expanded to a width of 8 ft or more?**
   - Consider narrowing the bike path to 5 ft if it immediately abuts a fence or other vertical obstruction, such as the back of a shelter, and to 4 ft if there is no vertical obstruction within 1 ft of the separated bike lane. Note that flexposts are not an obstruction if they are at least 3 inches from the bike lane edge; detectable boundary tiles are not a vertical obstruction if they are less than 2 inches high.
   - If the sidewalk area is wide enough, consider rerouting the path further away from the curb.
   - If the platform can be expanded to 8 ft, reconfigure it as a full-width platform, with the shelter/bench of the platform.

3. **If the stop has a full-width platform, is the platform separated from the bike path by a fence?**
   - If not, consider adding a fence with an opening in line with each bus door. Even if there is a landscaped area separating the platform from the separated bike lane path, a fence will make separation clearer.
   - Where the separated bike lane path abuts either the sidewalk or platform without a fence, add detectable boundary tiles.
4. **Does the stop have a partial-width platform, i.e., a platform less than 8 ft wide but at least 5 ft wide?**
   - If yes, consider shelter/bench configurations that would still allow the shelter and/or bench to be located on the platform (i.e., narrower platforms). There may be shelter configurations that don't require a walking accessible path around the shelter.
5. **Is it a no platform stop, i.e., a stop in which people step out of the bus directly into the bike path or into a buffer between the curb and bike path less than 5 ft wide?**
   If yes:
   - Is it possible to create a 5-ft wide buffer between the curb and separated bike lane, making this a partial-width platform stop, by relocating the bike path or making it narrower? (See earlier guidance about narrowing the bike path.)
     - If not, consider converting the entire sidewalk area at the curb – i.e., sidewalk, bike path, and buffer/platform – into a shared-use path by making it all a uniform paving material and suspending any bike lane lines. Examples of this treatment include the Southwest Corridor path at the Green Street station (pavement is brick) and at the Roxbury Crossing Station (uses typical sidewalk pavement). Add signs to the effect of "Bikes: do not pass within 5 ft of a stopped bus." Upstream of the bus stop, add signs to the effect of "Go slow – shared bus stop area ahead."
6. **Is there a full-width or partial-width platform?**
   If yes, where the separated bike lane meets the walking path between sidewalk and platform, in addition to a zebra crosswalk, consider the following treatments:
   - Yellow flexposts and/or a vertical "State Law: Yield to Pedestrians" sign on either side of the path to create a gateway for bicyclists. If it's a two-way bike path, add a flexpost in the middle of the path as well. Consider using two sets of flexposts on the bike lane approach, one set at the pedestrian crossing and another set 10 ft upstream, to create a stronger sense of confinement to slow down bicyclists and get their attention.
   - Painted white lines that narrow the (visible) bike path to 4 ft per direction.
7. **Is there a partial-width platform in which bus passengers using a ramp have to use part of the separated bike lane as their loading area (out to 8 ft from the curb)?**
   If yes, consider changing the surface of that portion of the separated bike lane that will be part of the loading area, either by paving it with a different material or X-hatching it with white lines. The goal is that pedestrians standing in this area (e.g., as they prepare for the bus ramp to be deployed) will not have the appearance of obstructing the separated bike lane but rather of standing in an area that has been designated for pedestrians.
8. **Is there a partial-width platform or a no platform bus stop?**
   If yes, stay abreast of research to see whether it might be possible to add moped speed humps on the separated bike lane approach. Moped speed humps are speed humps that are comfortable at conventional bike speeds (e.g., up to 14 mph) and do not pose a hazard to the bike lane users with small wheels (roller blades, skateboards) but are uncomfortable at

speeds greater than 15 mph whether the vehicle is a moped or an electric bike (e-bike). In the Netherlands, moped speed humps are trapezoidal dips in the path; in the U.S., this design has not yet been tried, partly because it presents a challenge for drainage and snow clearance. However, because bike-specific speed humps is a topic of concern in many U.S. cities, especially with the growth in e-bike use, there is a good chance that research on this topic will appear in the next few years. If research develops speed control devices for separated bike lanes that will not be a hazard to small-wheel bike lane users, consider applying them where pedestrians are expected to be in the bike lane because the bus stop has a partial-width platform or no platform.

9. **At every bus stop with a bike path between the sidewalk and the curb:**
   Update wayfinding treatments to the latest guidelines. A recent Transit Cooperative Research Project (TCRP) B51: Floating Transit Stops and Passengers with Vision Disabilities is beginning shortly and should be completed by the end of 2026. This project will create recommendations for guidelines regarding wayfinding and minimizing conflicts between bikes and bus passengers at floating bus stops.

4.3 Field Data Collection Recommendations

In this study, the quality of the field data collection is critical for investigating bicyclists' and pedestrians' (including transit passengers) behaviors with adequate accuracy and without distracting and interfering with their active behaviors. Through the extensive data collection effort with the LiDAR sensor and a 360-video camera, the following suggestions for future field data collection efforts for this study's future phases or other geographic locations are made.

Sensor Selection and Configuration: Investigating the interactions between passengers and bicyclists using a LiDAR sensor solution requires two key sensor characteristics, including the sensor's range and density. For the range selection, experiments were designed at the testing bus stop within the proximity of 100 ft. to capture the upstream behaviors of bicyclists and the up/downstream behaviors of alighting and onboarding passengers. For the density selection, it was assumed that the traffic extraction algorithm could distinguish pedestrians, bicyclists, and vehicles with sufficient point density at a 100 ft. distance. Figure 4.16 shows the difference among different sensors at different distances scanning a pedestrian (6 ft. tall). In this study, the 128-line, long-range LiDAR sensor was selected and demonstrated reasonably good performance for trajectory extraction. It can be seen that around 120 ft. distance, the selected sensor can still capture enough point density for a pedestrian (more than 100 points for the scanning object required by the algorithm in this study).

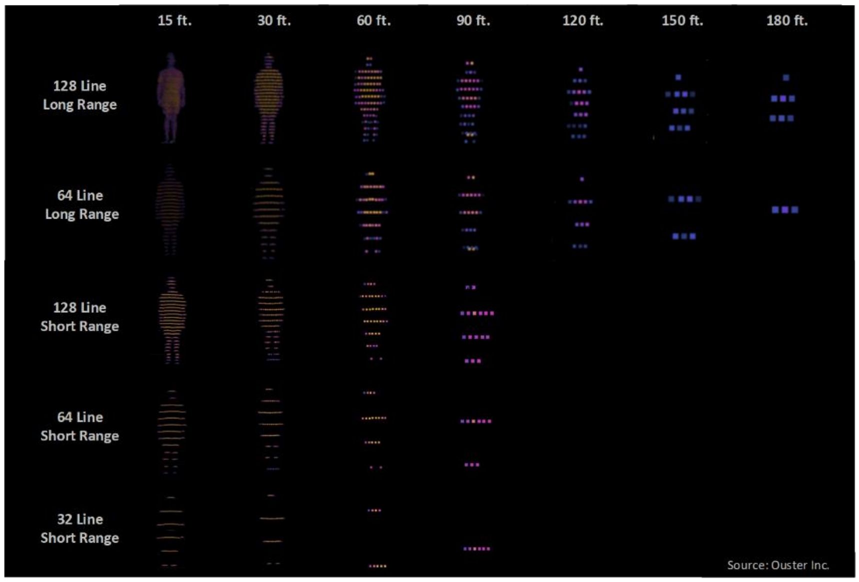


Figure 4.16: Sensor sensitivity to scanning distance

Occlusion Avoidance: Because LiDARs are line-of-sight sensors, voiding occlusion is crucial for accurate LiDAR data collection at bus stops, especially at locations with dense populations, heavy traffic, and complex streetscapes. Strategic sensor placement is critical, with sensors positioned at elevated heights and angled downward to provide a clear line of sight over potential obstructions. As tested in this study, an example setup includes a LiDAR sensor (i.e., Ouster OS1-128) mounted on a tripod pole at a 2.5m (8.2 ft) elevation, positioned slightly forward, with a pitch angle of 10 degrees, and from the bus stop shelter with a 360-degree horizontal and 45-degree vertical field of view. While the collected data was of reasonably good quality (thanks to the elevated sensor configuration) for extracting the trajectories at the studied bus stops, occlusions still occurred (for example, passengers were blocked by the bus shelter, and the subsequent trajectories were interrupted). In future studies, deploying multiple sensors will also help cover different angles and perspectives, ensuring overlapping fields of view to compensate for occlusions from large structures, e.g., bus shelters. Figure 4.17 shows an example of two LiDAR sensor configurations, with each sensor configured at a different end of the bus stop and on a different side of the road. Even when a large bus is in the shelter area, primary or both sensors can capture the passengers. It should be noted that installing multiple sensors is not always feasible, as the presence of the sensors might distract the true behavior of the road users. In addition, processing multi-sensor data will require more computational power, and the synchronization error might affect the overall trajectory analysis performance. Therefore, in this study, only a single LiDAR sensor was used and the multi-sensor configuration is recommended for future research.

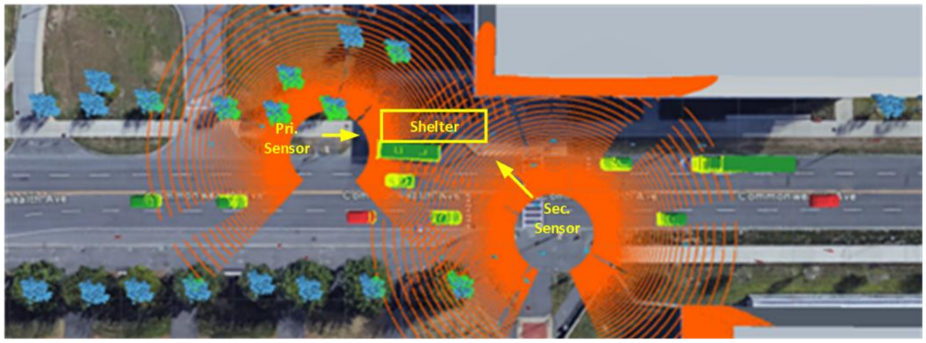


Figure 4.17: LiDAR sensor configurations at two bus stops

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5.0 Conclusions

This research study used multiple methods, including community outreach, both user and professional and a field study, to:

1) Develop an inventory of floating bus stops and their design characteristics within MBTA's service area,

2) provide a clear understanding of the challenges encountered by visually, hearing, and mobility-impaired transit riders at floating bus stops,

3) summarize best practices across the world on the integration of separated bike lanes and bus stop infrastructure,

4) analyze bicyclist and transit rider behavior at various types of floating bus stops to further understand bicyclist-transit rider interactions and inform design guidelines, and

5) develop design guidelines and policy recommendations that improve safety and accessibility of floating bus stops.

Through these contributions, this study not only allows for a more precise understanding of the interaction behaviors between bicyclists and bus passengers at floating bus stop areas but also helps the MBTA assess whether the design of its floating bus stops meets safety and accessibility standards and inform decision making for retrofitting these bus stops. Additionally, it provides the MBTA with design recommendations to use as a reference when designing new floating bus stops, thereby improving the safety and accessibility of these stops and encouraging travelers of all abilities to use public transportation more easily and safely.

5.1 Summary of Findings

To maintain the maximum separation between bicyclists and passengers, this research project strongly recommends that city officials and representatives consider using full-width bus stop designs. For existing partial-width bus stops, space can be created by narrowing or diverting the adjacent bike lane to convert partial-width bus stops to full-width bus stops and relocating shelters and benches from the sidewalk to the platform. Partial-width platform bus stops should be accommodated by stronger speed management strategies. For no platform bus stops, when they cannot be avoided, efforts should be made to ensure that bicycles stop or divert away from the bus when it is stopped.

In addition to ensuring the separation between bicyclists and bus passengers, it is also necessary to raise the situational awareness of bicyclists and slow them down. Implementing horizontal or vertical deflections upstream of the bike lane can help get bicyclists attention and possible slow them down. Bicyclist speed management can also be achieved with narrowing the bike lane. Setting up flexposts and signage on the bike lane, as well as fences, can create a channel crossing situation, making bicyclists aware that they are entering a bus stop area, thereby increasing their situational awareness, reducing their riding speed, and preparing them to stop at any time. Fences to encourage crosswalk usage, support way finding, and decrease bicyclist veering off to the sidewalk in addition to overall increasing situational awareness. Situational awareness can also be increased with the use of different pavement materials. Finally, regulatory signage, pavement markings, regulations (e.g., laws for stopping for crossing pedestrians), as well as signalization of crossings can be considered for speed management.

To improve accessibility, there needs to be a focus on designing facilities for passengers of all abilities. The crosswalk, tactile pavement, and boarding area (the place where the bus door is located) should be in a straight line so passengers can board and alight the bus without having to turn, directly accessing the bus door or sidewalk via the tactile pavement. Additionally, based on feedback from focus groups, the bus stop sign pole should be placed close to the shelter or bus door stopping location to facilitate boarding for visually impaired or mobility impaired passengers. The path from the shelter to the bus boarding area should be clear of obstructions and the pavement should be providing a smooth riding surface. Audible messages on board of buses could also be helpful for communicating the need to step in a bike lane. An octagon-shaped flexpost or secondary bus stop sign pole can be set at the edge of the sidewalk to mark the crosswalk, helping visually impaired passengers know that they are entering the bike lane and providing information on bus routes.

Figure 5.1 presents the elements of an ideal floating bus stop based on the findings of this study.

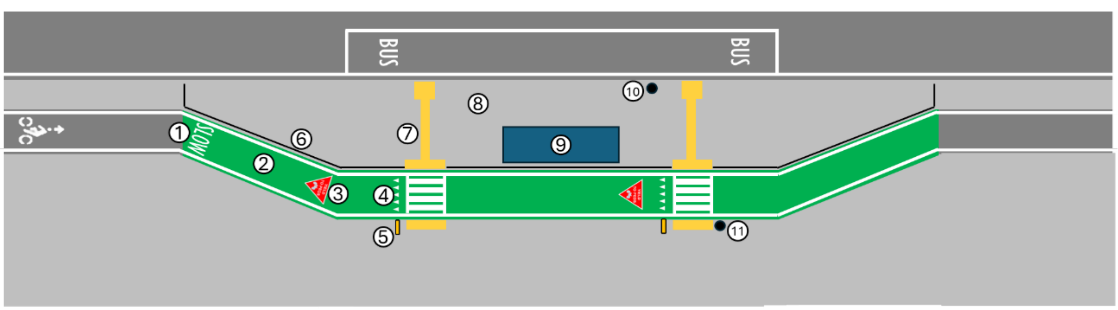


Figure 5.1: Ideal floating bus stop elements

An ideally designed floating bus stop includes:

1. A "SLOW" stencil with colored pavement on the bike lane section approaching the bus stop area.
2. Vertical and horizontal deflection for the bike lane when approaching the bus stop area.

3. A "YIELD TO PEDS" pavement marking before each crosswalk; see Figure 5.2.

Figure 5.2: Yield to Pedestrians pavement marking

4. Yield markings before crosswalks; see Figure 5.3.

Figure 5.3: Yield lines pavement marking

5. An "In Street Crossing" sign or a "Bicycle Yield to Peds" sign on the sidewalk side of each crosswalk; see Figure 5.4.

Figure 5.4: "In Street Crossing" and "Bicycle Yield to Peds" signs

6. Fences with openings only at crosswalks.
7. Crosswalks that are aligned with boarding areas and equipped with tactile pavement.
8. Platforms that are at least 8 feet wide.
9. Shelters/benches that are located on the platform.
10. A bus stop sign pole near the shelter/bench and boarding area.
11. A secondary bus stop sign pole at the sidewalk side of a crosswalk to indicate the crosswalk location for visual impaired riders and provide bus route information.

Furthermore, based on these findings, a step-by-step assessment procedure was developed that provides recommendations for improving accessibility and safety based on their existing design and conditions. Suggestions for using LiDAR sensors to collect inventory and behavior data were also provided. By implementing the recommendations, assessments, and suggestions proposed in this project, city officials and representatives can ensure the accessibility and safety of new bus stops, evaluate whether their existing bus stops meet accessibility and safety objectives, and use sensing technology to collect inventory and behavior data. This approach allows for an in-depth analysis of each bus stop's conditions, ultimately enhancing the accessibility and safety of floating bus stops.

5.2 Limitations and Future Work

Several limitations were identified related to the accuracy of LiDAR scan speed and position data, the accuracy of road user classification algorithm, the limited sample size at only five floating bus stops, the use of only LiDAR and 360-degree video camera data, and the reliance of the study results on only video and trajectory data. These limitations are described next along with related suggestions for future work:

LiDAR scanning data accuracy: The accuracy of LiDAR data is subject to noise and trajectory drift issues, leading to unreasonable fluctuations in the speed and position of moving objects. Speed outliers were removed in this study using a median filter, but the position fluctuations were not adjusted. In the future, unreasonable position data can be removed, and research can be conducted on the most effective methods to eliminate unreasonable outliers while ensuring the remaining data reflects the reasonable behavior of road users.

1. Algorithm for Classifying Road Users: The accuracy of the algorithm for classifying road users is relatively low. The algorithm distinguishes moving objects as a person, two-wheeler, car, or truck/bus based on their shape. However, noise or special situations can affect the algorithm's accuracy. For example, when multiple pedestrians walk side by side, they may be misclassified as a two-wheeler or even a car. Future research could focus on adjusting the current algorithm or developing new algorithms to improve classification accuracy.
2. Sample Size: This study conducted data collection and behavioral analysis at a limited number of bus stops in MBTA’s service area. It is recommended that longer-term data collection at different bus stops be conducted in the future to increase the sample size and improve the statistical power of the findings.
3. Sensing Technology: This study used LiDAR sensors to collect behavior data and 360-degree video cameras to simultaneously record images, allowing for a more detailed analysis of interactions and key events. Future studies could consider using other sensing technologies to enhance data accuracy. For example, fusing LiDAR data with computer-visioned video data can improve classification accuracy using the high resolution of video and the ability of LiDAR sensors to collect data in adverse weather or lighting conditions, thereby enhancing data quality and the accuracy of analysis results.
4. Behavioral Analysis: This study analyzed the behavior of bicyclists and pedestrians using only trajectory and video data. Future research could also use surveys in combination with simulation to analyze the perception and behavior of bicyclists when navigating different bus stop designs and the corresponding infrastructure. This would help understand how various bus stop designs and related facilities impact the perceptions and behavior of bicyclists and pedestrians.

6.0 References

1. National Association of City Transportation Officials (NACTO). “Transit Street Design Guide” Accessed: Jun. 26, 2023. [Online]. Available at: https://nacto.org/publication/transit-street-design-guide/
2. MassDOT, “Separated Bike Lane Planning & Design Guide,” 2015. Accessed: Jun. 26, 2023. [Online]. Available: https://www.mass.gov/doc/chapter-5-curbside-activity-design/download
3. MBTA, “Bus Priority Toolkit”, 2023. Accessed: Jan. 29, 2024. [Online]. Available: https://cdn.mbta.com/sites/default/files/2023-05/2023-05-Bus_Policy_Toolkit_Chapter_Five.pdf
4. MBTA. Bus Stop Planning & Design Guide. 2018. [Online]. Available: https://cdn.mbta.com/sites/default/files/engineering/001-design-standards-and-guidelines/2018-04-01-bus-stop-planning-and-design-guide.pdf
5. MDOT, “Bus Stop Design Guide,” 2019. Accessed: Jun. 26, 2023. [Online]. Available: https://s3.amazonaws.com/mta-website-staging/mta-website-staging/files/Service%20Development/MDOT_MTA_Bus_Stop_Design_Guide_2019_Edition.pdf
6. RIDOT, “Rhode Island Bus Stop Design Guide,” 2017. Accessed: Jun. 25, 2023. [Online]. Available: https://www.ripta.com/wp-content/uploads/2020/07/ribsdg___final___web_version.pdf
7. AC Transit, “Multimodal Corridor Guidelines,” 2018. Accessed: Jun. 26, 2023. [Online]. Available: https://www.actransit.org/website/uploads/AC_Transit_Multimodal_Corridor_Guidelines_Final.pdf
8. City of Minneapolis, “Street Design Guidance.” Accessed: Jun. 26, 2023. [Online]. Available: https://sdg.minneapolismn.gov/design-guidance/transit-stops/bus-stops-and-bikeways
9. Arlington Transit, “Bus Stop Guidelines Update: Floating Bus stops,” 2022. Accessed: Jun. 25, 2023. [Online]. Available: https://www.arlingtonva.us/files/b5abe773-0087-4f46-93c7-79a578fd48c7/2022-05-10-TAC-FloatingBusStops_GuidelinesUpdate.pdf
10. FHWA, “Separated Bike Lane Planning and Design Guide,” 2015. Accessed: Jun. 25, 2023. [Online]. Available: https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/separated_bikelane_pdg/separatedbikelane_pdg.pdf
11. British Columbia Ministry of Transportation and Infrastructure, “British Columbia Active Transportation Design Guide,” Law Courts Education Society of BC, 2019.
12. Transport for London, “Accessible Bus Stop Design Guidance,” 2017. Accessed: Jun. 26, 2023. [Online]. Available: https://content.tfl.gov.uk/bus-stop-design-guidance.pdf

13. TransLink, “Bus Infrastructure Design Guidelines,” 2018.

14. “Design options for island bus stops | Waka Kotahi NZ Transport Agency.” Accessed: Jun. 25, 2023. https://www.nzta.govt.nz/walking-cycling-and-public-transport/public-transport/public-transport-design-guidance/bus-stop/bus-stop-design/integrating-bus-stops-with-cycling/bus-stops-with-separated-cycleways/design-options-for-island-bus-stops.

15. Austroads, Guide to Road Design Part 3: Geometric Design. Austroads, 2021. Accessed: Jun. 26, 2023. [Online]. Available: https://austroads.com.au/publications/road-design/agrd03

16. Google Map. Available: https://www.google.com/maps

17. Google Earth. Available: https://earth.google.com/web/

18. Matt Johnson, 2023, *Bus Boarding Islands & Accessibility Lessons Learned from Montgomery County, Maryland* [Presentation Slides]. TRB Webinar: Accessible Floating Bus Stops

19. MUTCD, 11th Edition, 2023, Federal Highway Administration, Available: https://mutcd.fhwa.dot.gov/kno_11th_Edition.htm

20. Wikimedia Commons. Available: https://commons.wikimedia.org/wiki/File:Bus_boarding_island_at_University_Road,_December_2018.JPG

21. Jim Elliott, 2023, *Spring/Ellsworth Pilot Engaging people with vision disabilities in floating bus stop design* [Presentation Slides], TRB Webinar: Accessible Floating Bus Stops

7.0 Appendices

7.1 Appendix A: Focus Group Presentation Slides

UMassAmherst

Accessible Bus Stop Design in the Presence of Bike Lanes

Focus Group

August 10, 2023

Agenda

1. Introductions

2. Housekeeping

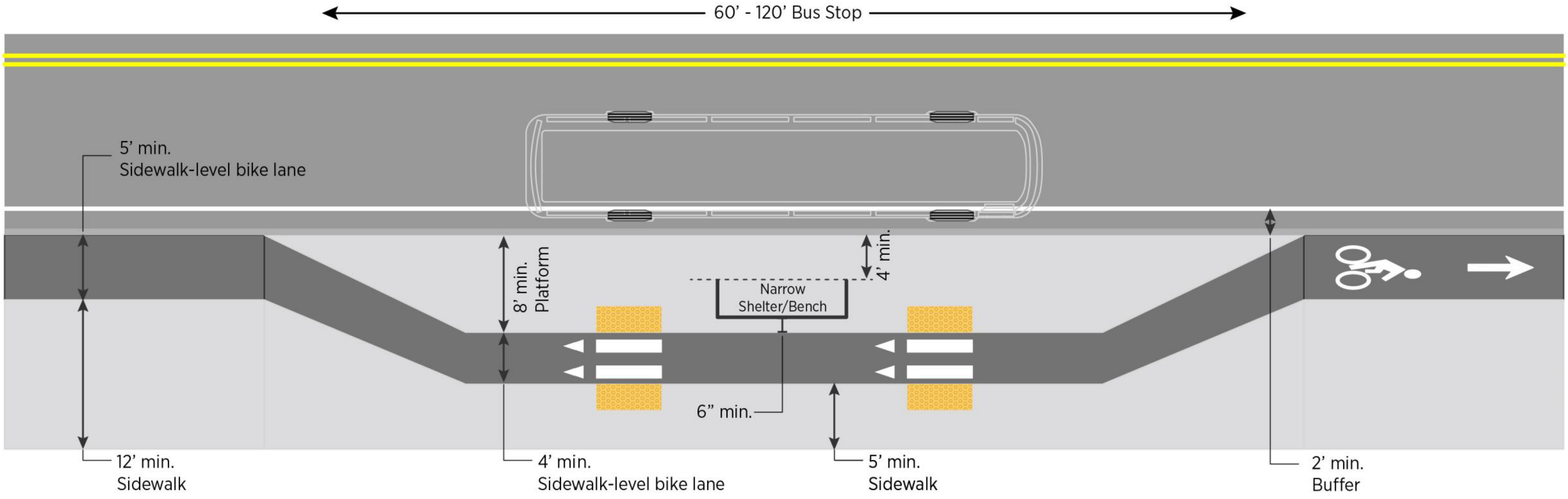
3. Types of bus stops
    1. Detailed description of bus stops and their elements
    2. Questions/Discussion

4. Other thoughts?

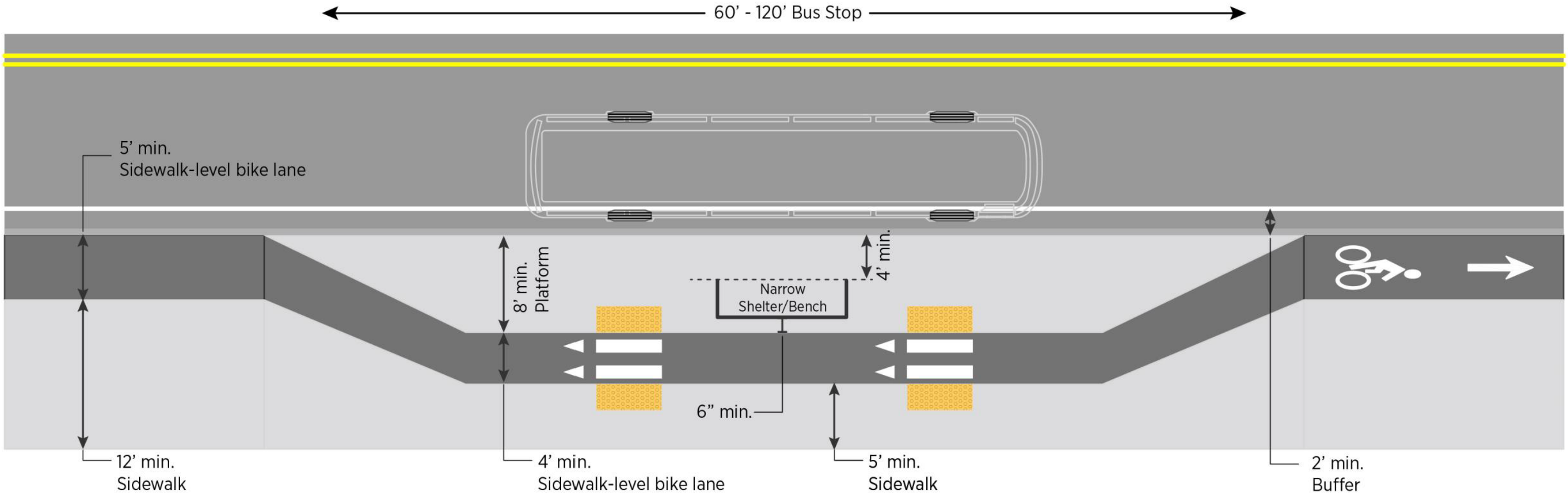
Housekeeping

1. The meeting will be recorded for transcription purposes
2. Feel free to have your camera turned off if not comfortable
3. Please keep your microphone muted until you are ready to speak
4. When a question is posed, use the zoom function to raise your hand

Bus Stop Elements



Bus Stop Elements



Full-width Platform

Washington St. and Walnut St., Brookline

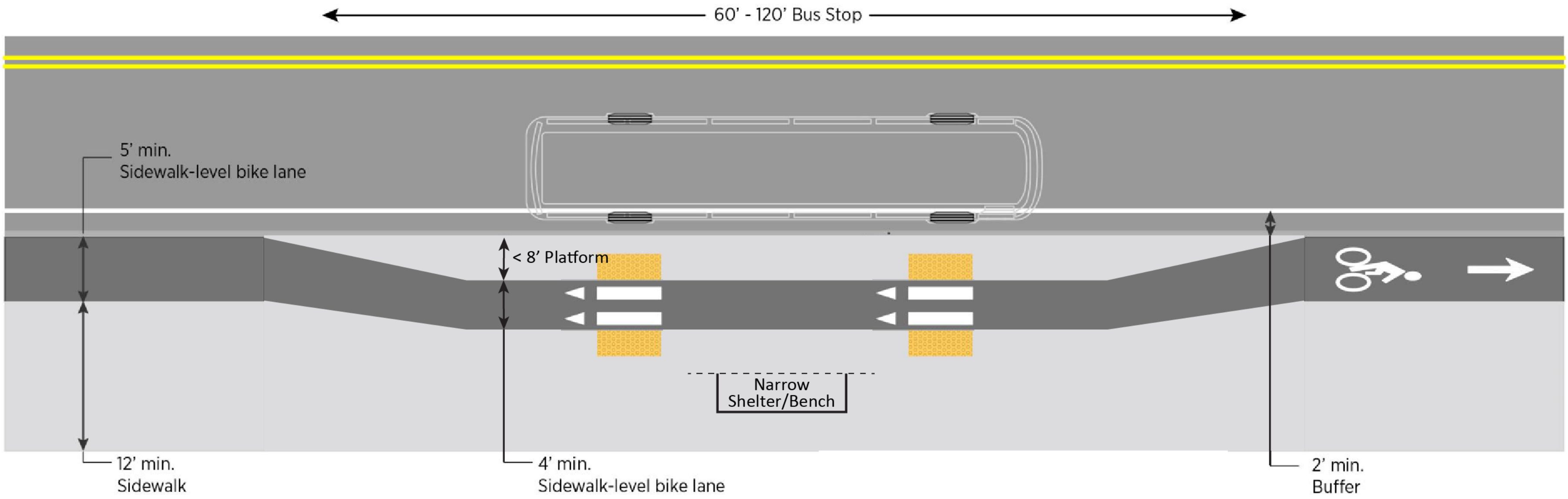
Full-width Platform

1. What are the design elements that make you feel safe or unsafe in this bus stop design?

2. Does the railing work to guide you to the crossings?

3. What is your experience with bicyclists at this type of bus stop?

Full-width Platform



Partial-width Platform

Massachusetts Ave opp Christian Science Center

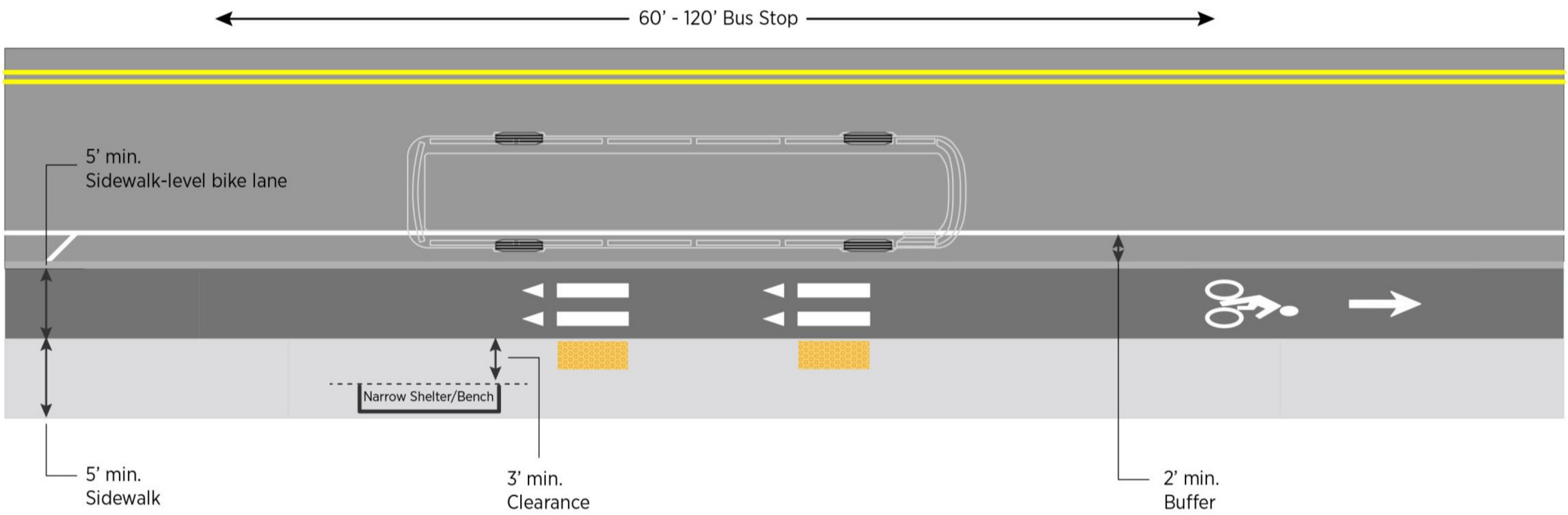
Partial-width Platform

1. What are the design elements that make you feel safe or unsafe in this bus stop design?

2. Where do you wait for the bus (shelter on the curb side, or on the platform)?

3. What is your experience with bicyclists at these types of bus stops?

No Platform


60' - 120' Bus Stop
5' min.
Sidewalk-level bike lane
Narrow Shelter/Bench
5' min.
Sidewalk
3' min.
Clearance
2' min.
Buffer

No Platform

Broadway and Beacham St., Everett

No Platform

1. What are the design elements that make you feel safe or unsafe in this bus stop design?

2. What is your experience with bicyclists at this type of bus stop?

In closing...

- What other treatments do you think would be helpful in improving safety at these types of bus stops?

- Any other recommendations? Thoughts?

Thank you for your participation!