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Effectiveness of Two-stage Turn Queue Boxes in Massachusetts: A Comparison with Bike Boxes

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Two-stage turn queue boxes (TSTQBs) are designated for bicyclist spaces that are installed to improve the safety of left turns at intersections. This project studied the effectiveness of TSTQBs in Massachusetts by investigating left-turning bicyclist behavior at TSTQBs and correlating it with design elements. A comprehensive inventory of 88 TSTQBs was developed and a field study that allowed for capturing left-turning bicyclist behavior at six intersections in Massachusetts, including 14 TSTQB and 6 control (no TSTQB) approaches was performed. The results indicate a much lower TSTQB bicyclist utilization rate compared to other studies and no statistically significant difference in utilization at approaches that also feature bike boxes. The findings also suggest the need to install TSTQBs when crosswalk usage for bicyclists’ left-turning is high, and when approaches lack protected left-turn phasing or dedicated left-turn lanes. Future work should focus on understanding bicyclists’ and motorists’ perceptions, comprehension, and familiarity with TSTQBs as well as the impact of TSTQB dimensions and bicyclists demand to further inform design recommendations.</td></tr>
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Effectiveness of Two-stage Turn Queue Boxes in Massachusetts: A Comparison with Bike Boxes

Final Report

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Executive Summary

Introduction

Two-stage turn queue boxes (TSTQB), often referred to as Copenhagen lefts, Melbourne lefts, hook turns, and box turns, are areas designated for bicyclists, placed downstream of intersection stop lines, outside the traveled path of through moving vehicles and bicycles, and in front of cross-street traffic. These areas, which are typically paved in green colored pavement, are intended for facilitating bicyclist left-turning maneuvers through intersections.

TSTQBs present multiple advantages, such as

- Reduction of conflicts between motor vehicles and bicycles.
- Improved bicyclist visibility.
- Provision of space for formal queueing of bicyclists.
- Reduction of conflicts between bicyclists and pedestrians at crosswalk and sidewalks.
- Separation of through moving and turning bicyclists.
- Improved bicyclist comfort in making left turns.
- Safer crossing of streetcar tracks.

Disadvantages associated with TSTQBs include

- Increased delay for bicyclists
- Bicyclist discomfort from waiting within the intersection.
- Higher maintenance costs compared to alternatives, especially in areas with snow and ice.

Implementation of TSTQBs has only recently started to become more common, and few studies have been completed in North America to assess their effectiveness. In addition, no studies have explored left-turning bicyclist behavior in the presence of both TSTQBs and bike boxes. More specifically, the research objectives of this project are

1. Create an inventory of two-stage turn queue boxes in Massachusetts that includes TSTQB design as well as design characteristics of the intersection approaches that they are located at.
2. Characterize left-turning bicyclist behavior at intersections with two-stage turn queue bike boxes and compare TSTQB utilization when bike boxes are also present vs when not.
3. Recommend guidelines on the design and implementation of two-stage turn queue boxes to improve safety.

Research Methodology

The research methodology consists of three components:

1. A review of existing publications that includes design guidebooks from the United States and peer-reviewed journal and conference publications related to the effectiveness of TSTQBs.
2. Creation of a TSTQB inventory using surveys to obtain the locations of interest and subsequent light detection and ranging (LiDAR) technology and manual observations of online resources to obtain their design characteristics.

3. A field study on bicyclist behavior at 14 TSTQB box locations at 6 intersections in Massachusetts, analyzing bicyclist left turning behavior and specifically, TSTQB utilization.

Results

Inventory

- At least 88 TSTQBs are currently installed in Massachusetts.
- All of them have colored pavement, and with the exception of one, all have a bicyclist stencil.
- Based on the detailed measurement from the LiDAR point cloud, the depths and widths of the TSTQBs in Massachusetts range between 8.8 ft. and 14.0 ft., and 7.3 ft. and 14.0 ft., respectively, which are not always consistent with existing guidance.
- The most common TSTQB configuration in Massachusetts is the crosswalk setback one (68.18%).
- The vast majority of TSTQBs are accompanied by bike lanes upstream (conventional or protected) (75%).
- The type of bicycle facilities downstream of TSTQBs varies.
- At this time, very few TSTQBs feature an MUTCD-compliant TSTQB guide sign.
- The majority of the TSTQB approaches feature a no turn on red sign (68.18%).
- A large percentage implements intersection crossings that could help with TSTQB awareness (71.59%).

Left-Turning Bicyclist Behavior

- TSTQB utilization by left-turning bicyclists is very low (11.91%) for the 14 TSTQTBs studied compared to existing studies.
- A similar percentage of left-turning bicyclists performed a two-stage maneuver without using the TSTQB.
- The most common ways left turns at intersections were completed were by either utilizing a conventional left turn (46.03%) or the crosswalk (28.49%).
- Bicyclists from other approaches were observed to use adjacent TSTQBs as bike boxes
- The presence of bike boxes and bike lanes (protected or conventional) and the size of the intersection were not found to significantly affect TSTQB utilization.
- The bike lane type (whether conventional or protected) and TSTQB configuration type (specifically, crosswalk setback versus parking lane configuration) did not result in a statistically significant difference in the TSTQB utilization.
- TSTQBs receive significantly higher utilization in the absence of protected left-turn phasing and dedicated left turns lanes and result in significantly lower crosswalk utilization for bicyclists’ left turns.
- The frequency of two-stage maneuvers is statistically higher at TSTQB approaches.

Recommendations

The recommendations have been obtained through both the thorough review of guidebooks and published research and primarily through the detailed exploraton of left-turning bicyclist behavior at 14 TSTQBs and an additional six control sites.

Design:

- Ensure future TSTQB implementations comply with the newly published MUTCD (*1*).
- Implement regulatory or guidance TSTQB signs (see Figure 3.2) to increase bicyclist awareness of TSTQB presence.
- Position TSTQBs near corner curbs of intersections to enhance bicyclist comfort and reduce potential conflicts with motor vehicles.
- Consider implementation of two-stage turn queue boxes in the absence of dedicated left-turn lanes to facilicate left-turning maneuvers for bicyclists.
- Position TSTQBs near the through moving path of bicyclists to improve utilization.
- Implement TSTQBs at locations with high crosswalk use for bicyclists' left-turning maneuvers.

Education:

- Educate bicyclists on the proper use of TSTQBs, emphasizing the advantages of using TSTQBs and correct positioning within the box.
- Implement educational campaigns to enhance driver awareness of bicyclists and the function of TSTQBs.

Data Collection:

- Develop and administer surveys to supplement existing data, correlating bicyclists' comprehension and familiarity with TSTQBs with their behavior at these locations.
- Expand data collection to cover a more diverse range of intersection designs and layouts, as well as demands and seasons.
- Collect and analyze bicyclist and motorist trajectories at intersections with TSTQBs for conflict analysis to further understand safety risks associated with their implementation.
- Investigate alternative bike infrastructure usage at intersections where TSTQBs are not used; trajectory analysis may be helpful for this study.

Conclusions

Overall, this study contributes by

1. offering evidence of much lower TSTQB utilization in the Greater Boston area than what has been reported in the literature,
2. revealing the most common ways bicyclists complete left turns at signalized intersections,
3. offering evidence for TSTQB implementation at locations with high crosswalk use by left-turning bicyclists and those that lack protected left-turn phasing or dedicated left-turn lanes,
4. suggesting the need for additional elements accompanying TSTQBs, such as guide and regulatory signage to increase TSTQB utilization, and
5. reiterating the need for education of bicyclists and motorists to improve comprehension and awareness of such infrastructure treatments with the goal of improving safety for all.

Future work should focus on

- continuously updating the TSTQB inventory for Massachusetts,
- expanding data collection and behavioral analysis to more locations with higher bicyclist and motorist activiting to further understand bicyclist left-turning behavior,

- assessing the impact of the TSTQB guide sign, the age of the TSTQB, and intersection crossing markings on TSTQB utilization,
- understanding the impact of TSTQB dimensions on bicyclist left-turning behavior and TSTQB utilization using data collected through LiDAR scans,
- studying the impact of bicycle infrastructure and design features affect motorist behavior around TSTQBs,
- exploring motorist and bicyclist behavior in response to the presence and number of bicyclists near or within TSTQBs,
- performing a crash/conflict analysis at TSTQB locations to assess safety improvements before and after implementation,
- conducting surveys to collect data on bicyclists' and motorists' perceptions, comprehension, and familiarity with TSTQBs and their behaviors at these specific locations to further enhance design recommendations, and
- further exploring correlations between design elements and motorist and bicyclist behavior in the presence of TSTQBs using human-in-the-loop simulation.

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List of Acronyms

Acronym	Expansion
AASHTO	American Association of Transportation Officials
DDOT	District Department of Transportation
EB	Eastbound
FHWA	Federal Highway Administration
LiDAR	Light Detection and Ranging
MassDOT	Massachusetts Department of Transportation
MBTA	Massachusetts Bay Transportation Authority
MUTCD	Manual for Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
NB	Northbound
NEB	Northeast bound
NWB	Northwest bound
SB	Southbound
SEB	Southeast bound
SWB	Southwest bound
TSTQB	Two-Stage Turn Queue Box
US	United States
VDOT	Virginia Department of Transportation
WB	Westbound

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1.0 Introduction

Intersection crashes are an important concern for bicyclists, with recent data for Massachusetts revealing that over half (55%) of fatal and serious injury bicycle crashes took place at intersections (*2*). Multilane intersections heighten crash risk especially for left turning bicyclists. Negotiating left turns on multilane roads is complicated by the need to scan for suitable gaps in opposing traffic; because larger gaps are often required, the difficulty of identifying safe opportunities for completing left turns is increased (*3*). Intersection bicycle treatments can help mitigate safety risks by increasing bicyclist visibility and facilitating safe turning maneuvers.

Two-Stage Turn Queue Boxes (TSTQB) are intersection treatments that improve bicyclist safety by designating bicyclist areas downstream of intersection stop lines, outside the traveled path of through moving vehicles and bicycles, and in front of cross-street traffic (*1*) that can be used while bicyclists are completing a two-stage turn at the intersection. TSTQBs are also referred to as Copenhagen lefts, Melbourne lefts, hook turns, jug-handle turns, pedestrian-style turns, and box turns, and they are very popular in Europe. Figure 1.1 shows a TSTQB in Amherst, MA.

Figure 1.1: Two-stage turn queue box example, Amherst, MA

TSTQBs are typically implemented to facilitate safe left-turning maneuvers for bicyclists coming from a bike lane or cycle track at multilane intersections that are not protected (*4*–*6*). TSTQBs are critical when cycle tracks are present since they prevent bicyclists from merging with the rest of the traffic at intersections (*6*, *7*). They can also facilitate right turns from left side cycle tracks or bike lanes, although that is less common. While typically implemented at signalized intersections, TSTQBs can also be used at unsignalized intersections to guide bicycle traffic turning onto major bicycle routes such as bicycle boulevards and to facilitate safe crossings for bicyclists at midblock crossings while preventing conflicts with pedestrians at crosswalks (*6*).

While navigating an intersection with a TSTQB, a left-turning bicyclist is expected to proceed through the intersection (at the green light indication or as soon as there is an acceptable gap for signalized and unsignalized intersections respectively) and locate themselves within the TSTQB area while waiting for a signal indication (in the case of a signalized intersection) or acceptable gap (in the case of an unsignalized intersection) that will allow them to complete the conflicting direction movement, essentially completing their intended turn; see Figure 1.2 a for a bicyclist utilizing at TSTQB at Somerville, MA and Figure 1.2b for the expected bicyclist path through the intersection.

(a) TSTQB in Somerville, MA

(b) Two-stage turn maneuver using the TSTQB (Image source: Google)

Figure 1.2: Two-stage turn queue box utilization

The exact placement of TSTQBs within an intersection varies depending on the specific intersection design, such as presence and placement of on-street parking upstream of the intersection, presence of a cycle track, and the type of intersection, e.g., T-intersection (*4*). TSTQBs are typically delineated by pavement markings that include a white line outlining the box and colored pavement, usually green. A bicycle stencil and arrow improve the visibility of this treatment and guide bicyclists in the appropriate direction for their turn.

The main advantages of TSTQB implementations are improved safety and comfort (*4*, *8*) as well as reduced complexity by separating turning movements from through traffic (*5*). In addition to facilitating safer turns across multilane intersections by reducing conflicts between bicycles and motor vehicles (*5*, *8*, *9*) and improving visibility, TSTQBs encourage the use of bicycle facilities over pedestrian facilities such as sidewalks and crosswalks, thereby mitigating pedestrian-bicyclist conflicts as well (*5*, *8*, *10*). TSTQBs also provide a designated queueing space for bicyclists that can contribute to increased visibility in addition to providing separation between turning and through moving bicyclists (*5*). Lastly, they encourage safer crossing angles of streetcar tracks (*4*, *11*).

The main disadvantage of TSTQBs is that they increase delay for bicyclists at both signalized and unsignalized intersections as bicyclists must wait for an additional green signal or identify an appropriate gap twice before crossing the intersection (*4*, *5*, *8*, *12*). In addition, bicyclists might feel uncomfortable waiting within the intersection (*5*). Furthermore, as with many facilities that feature colored pavement, additional maintenance costs might be incurred especially in climates with severe winters (*5*, *12*).

TSTQBs were recently added in the newest version of the Manual for Uniform Traffic Control Devices (MUTCD) (*1*). Although some studies on TSTQBs have been conducted in North America in recent years, there is still a lack of comprehensive understanding regarding how TSTQB design impacts bicyclist behavior and, consequently, safety. Additionally, despite the installation of several TSTQBs in Massachusetts, no studies on bicyclist behavior in relation to these facilities have been conducted in the state.

There is a pressing need to examine bicyclist behavior at signalized intersections that feature TSTQBs. Studying how the presence and design of TSTQBs affects left-turning bicyclist behavior will improve the understanding of the effectiveness of TSTQBs in enhancing safety. Furthermore, it is important to compare bicyclist left-turning behavior in the presence of TSTQBs when bike boxes are also present so that guidelines on the implementation of such intersection treatments can be developed. A prior MassDOT-funded study evaluated bike box effectiveness (*13*). This project conducted a field study examining motorist and bicyclist behavior at 11 bike boxes in Boston and Somerville, Massachusetts. However, it primarily focused on motorist compliance with stopping behind the bike box stop line and bicyclist positioning when stopped during red signals in the presence of bike boxes. No attempt was made to compare left-turning bicyclist behavior in the presence of both TSTQBs and bike boxes.

The objectives of this research project are to

- Create an inventory of two-stage turn queue boxes in Massachusetts that includes the TSTQB design as well as the design characteristics of the intersection approaches that they are located at.
- Characterize left-turning bicyclists’ behavior at intersections with two-stage turn queue bike boxes and compare TSTQB utilization when bike boxes are also present vs when not.
- Recommend guidelines on the design and implementation of two-stage turn queue boxes to improve safety.

The findings from this study can inform TSTQB design guidelines, in particular those related to placement and design of these intersection treatments as well as their supplementary design features, e.g., intersection crossing markings and signage that can improve TSTQB utilization and ultimately, safety. Ultimately, this research will assist the Massachusetts Department of Transportation (MassDOT) and other agencies in decision-making.

The rest of the report is structured as follows. Chapter 2 outlines the research methodology used to address the stated objectives. Chapter 3 reviews existing research on bicyclist behavior at TSTQBs, along with related safety outcomes and design guidelines in the United States. Chapter 4, presents and discusses the research results, including the development of a TSTQB inventory in Massachusetts and the analysis of bicyclist behavior using field data. Recommendations for TSTQB implementations are also provided. Finally, Chapter 5 presents a summary of the study's findings and offers suggestions for future research.

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2.0 Research Methodology

The research methodology constitutes of three parts. First, a comprehensive literature review of journal and conference publications as well as design guidelines from the US is performed. Next, an inventory of TSTQBs in Massachusetts is created with the use of a survey to identify pertinent locations, manual observations of online resources and LiDAR scans at selected locations to obtain their design specifications. Lastly, field data on bicyclists' left turning behavior is collected and analyzed to determine the impact of TSTQB and intersection design characteristics on bicyclist behavior.

2.1 Literature Review

The review of existing publications focused on 1) design guidebooks from the US to allow for summarizing existing guidance on the implementation and design of TSTQB in practice, and 2) peer-reviewed journal and conference papers that assess bicyclist behavior, with an emphasis on studies that were performed in the US Guidelines from various entities were reviewed, including the “Bikeway Design Guide” by National Association of City Transportation Officials (NACTO) (*4*); “Separated Bike Lane Planning and Design Guide” by Federal Highway Administration (FHWA) (*6*); and the “Manual of Uniform Traffic Control Devices” (MUTCD) (*1*) by Federal Highway Administration (FHWA), as well as TSTQB guidelines documented by states and cities.

2.2 TSTQB Inventory

2.2.1 Survey

A Google Forms survey was developed and distributed to all 351 cities/towns in the Commonwealth to pinpoint the locations of TSTQBs. A contact list maintained by the University of Massachusetts Transportation Center was used for distribution. Six distinct surveys were developed for the six MassDOT districts to help improve directness and limit the city/town options for each respondent. Upon selection of a city/town, the survey displayed only the TSTQBs located within that city/town.

The first page of the survey, shown in Figure 2.1, outlined the study's scope and communicated the anticipated survey duration. In addition, it presented images of TSTQBs and provided contact details for the study. In this page, the respondents were also prompted to provide their name, affiliation, title, and email address.

Massachusetts Two-Stage Left-Turn Queue Box Installations - District 1

The UMass Transportation Center has partnered with MassDOT to conduct a research study evaluating the implementation of Two-Stage Left-Turn (or TSLT) Queue Boxes at intersections across the Commonwealth of Massachusetts (see image below).

The research team would greatly appreciate your cooperation and assistance in providing us with the known TSLT Queue Boxes in your town/city/area. The following survey will take no more than 5 minutes of your time. Please fill in the following information, and attach and comments you have in the appropriate boxes below.

Note: This survey is for town/city/areas in MassDOT District 1. If you need another district, please refer back to the links in the email that you received.

If you have any additional questions or would prefer to submit your responses via email, please contact:

Francis Tainter

Research Assistant Professor
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Examples of a Two Stage Left-Turn Queue Box

Figure 2.1: Survey screenshot

On the next page, respondents were requested to select the city/town they were reporting for using a drop-down menu, as shown in Figure 2.2. Upon selection, the form displayed a list of TSTQBs in that specific city/town. Respondents were then asked to confirm those locations and list any additional TSTQBs, if applicable. The survey concluded with a thank-you message and provided an additional comment box for respondents to include any further information.

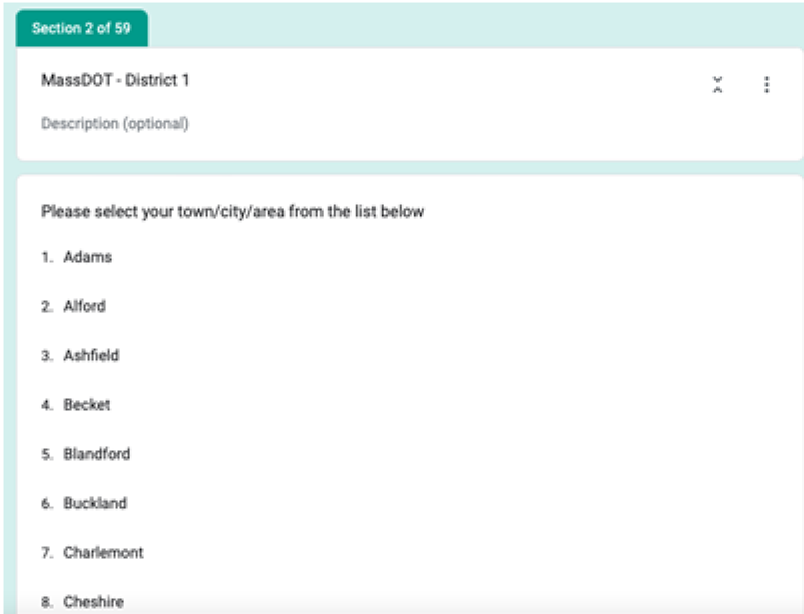


Figure 2.2: Survey district and city/town selection

2.2.2 LiDAR Data Collection

The TSTQB inventory aimed to gather comprehensive details about the TSTQBs, including their location, presence, geometry, associated bicycle facilities, and traffic control devices for both motorized and non-motorized vehicles. The selection of TSTQBs was based on diversity, geographical location, and design, guided by the inventory survey described in Section 2.2.1.

Field data included mobile LiDAR, and street video imagery collected using an integrated sensing vehicle and a handheld device developed at the University of Massachusetts. Figure 2.3 shows the sensing vehicle and examples of the captured LiDAR point cloud data and video imagery.

Figure 2.3: LiDAR sensing vehicle (left), LiDAR scan through backpack (right), and the collected point cloud data with geometry measurements (bottom)

In this study, the integrated sensing vehicle was instrumented with Inertial Labs Remote Sensing Payload Instrument (RESEPI) mobile LiDAR. The mobile LiDAR has a color video camera to capture the contextual information that is tightly calibrated and integrated with the LiDAR sensor. The mobile LiDAR system was used to acquire the point cloud data of the TSTQBs and the surrounding intersection for TSTQB positioning and geometry measurement, while the video camera was used to obtain the detailed color and texture information of the TSTQBs and the surrounding intersection for visual reference.

Thanks to the accurate positioning capability (<10 cm position accuracy) and dense point cloud (>640,000 points/sec), the research team was able to take advantage of the collected mobile LiDAR data and extract the accurate TSTQB locations and the corresponding geometry measurements. The LiDAR sensor used in this study is similar to the one previously used for the previous MassDOT's bike box study (*13*), with comparable quality and data density. Thanks to the dimension of the LiDAR sensor, it was flexibly used in two modes, including on a survey vehicle to cover larger areas of the intersections and through a customized handheld backpack to navigate through tight locations where car maneuvering is constrained. The data from both modes were then later merged into a single dataset for each intersection. Due to time and resource constraints, the research team focused on the field inventory data collection for 16 testing sites where later the subsequent video recording took place. However, the research team was able to take advantage of Google Street View data and populate the information (except for the geometry measurements) of the records without LiDAR data.

With the integrated measurement tools in the LiDAR point cloud data viewer, detailed geometry measurements were conducted and verified by the research team and MassDOT. Figure 2.4 shows an illustration of the geometry measurements for one TSTQB captured from the point cloud data, and Table 2.1explains in detail how geometries were defined and measured. It should be noted that the TSTQB may be painted with irregular shapes (i.e., trapezoid as shown in Figure 2.4). Therefore, the depth and width of the TSTQB may be defined differently. In this study, they were defined by the rectangular bounding boxes.

Figure 2.4: Illustration of TSTQB dimensions using LiDAR point cloud

Table 2.1: Definition and extraction method of geometries for TSTQBs

Geometry	Definition	Method
Location	Coordinates of the TSTQB	The latitude and longitude coordinates measured at the centroid of the TSTQB
Depth (ft.)	TSTQB depth	The length along the longitudinal direction of the TSTQB (i.e., along the traveling direction)
Width (ft.)	TSTQB width	The width along the transversal direction of the TSTQB (i.e., the arrow direction)
Distance to curb (ft.)	Distance between the TSTQB and the edge of the curb	The distance between the centroid and the edge of the curb (along the normal direction of the curb)
Edge Thickness (ft.)	Thickness of the edge line	The thickness of the white marking around the TSTQB that highlights its presence

2.2.3 Google Maps Data Collection

Manual observations of the identified TSTQBs were conducted via Google Maps to capture various characteristics. In addition to design elements specific to the TSTQBs, these included information on the lane assignment and signal phasing for left-turning traffic, and the presence of other bicycle infrastructure at the intersection as well as downstream and upstream of the intersection. In particular, the Google Maps data collection aimed to address the following questions:

1. *Is the TSTQB colored?* Yes, if the TSTQB pavement is colored green, No otherwise.
2. *Is there a turn arrow stencil?* Yes, if there is a turn arrow stencil within the TSTQB, No otherwise.
3. *Is there a bicyclist stencil?* Yes, if there is a bicyclist stencil within the TSTQB, No otherwise.
4. *What is the TSTQB configuration?* There are 5 configurations to choose from as detailed in the NACTO Urban Bikeway Design Guide (*4*), namely Cycle Track Buffer, Parking Lane, Crosswalk Setback, T-Intersection Parking Lane, T-Intersection "Jughandle" Sidewalk, and Bike Box Configuration; see Figure 2.5.

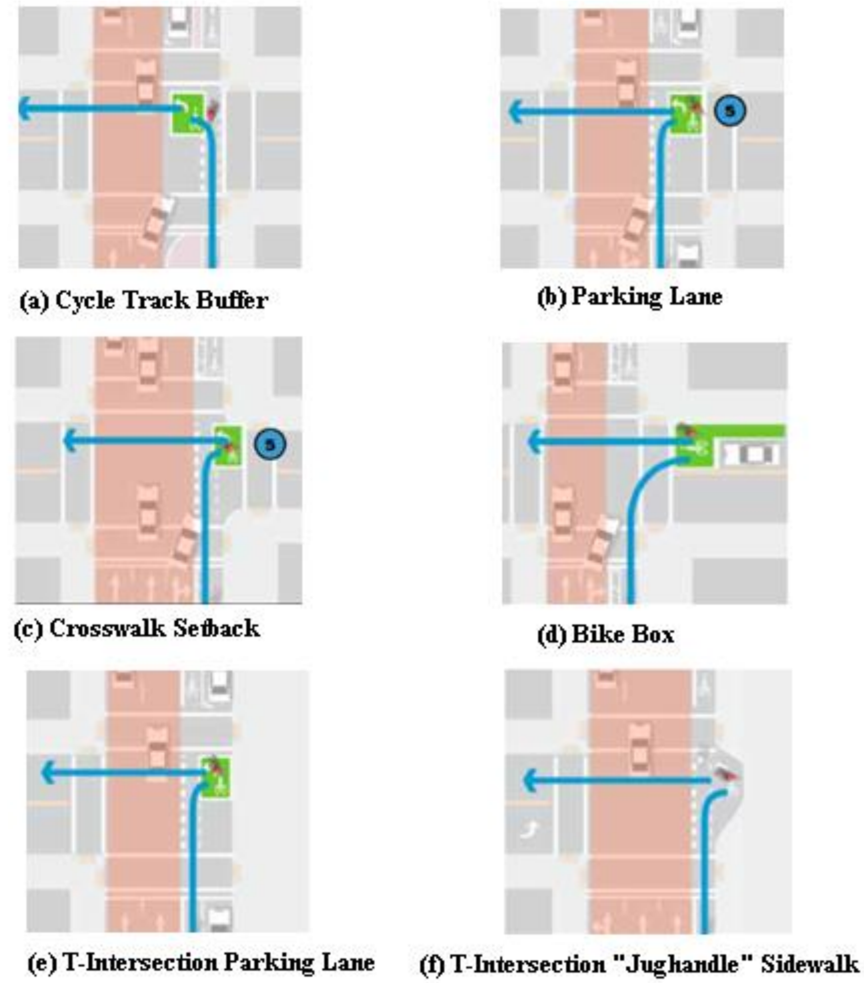


Figure 2.5: TSTQB configurations according to the National Association of City Transportation Officials (NACTO) Urban Bikeway Design Guide (*4*)

5. *Is there a bike lane upstream?* Yes, if a bike lane exists upstream of the approach feeding bicyclists to the TSTQB, regardless of the type of bike lane, No if otherwise.
6. *If a bike lane exists upstream, is it colored*? Yes, if the bike lane has green-colored pavement, No if it does not, and N/A if no bike lane exists upstream.
7. *If a bike lane exists upstream, is it separated*? Yes, if the bike lane is protected, No if it is not, and N/A if no bike lane exists upstream.
8. *Is there a bike lane downstream?* Yes, if a bike lane exists downstream for the left-turning bicyclists using the TSTQB of interest, No if otherwise.
9. *If a bike lane exists downstream, is it colored*? Yes, if the bike lane has green-colored pavement, No if it does not, and N/A if no bike lane exists downstream for those left-turning bicycles.
10. *If a bike lane exists downstream, is it separated*? Yes, if the bike lane is protected, No if it is not, and N/A if no bike lane exists downstream for those left-turning bicycles.
11. *Does the approach where bicyclists that could be using the TSTQB for their left-turning maneuvers arrive from (referred to as TSTQB approach in subsequent questions), feature a bike signal*? Yes, if it does, No if it doesn't.
12. *Does the TSTQB approach feature a bike box*? Yes, if it does, No if it doesn't.

13. *Does the TSTQB approach feature a TSTQB guide sign*? Yes, if it does, No if it doesn't; see Figure 2.6 for an image of the TSTQB guide sign.
14. *Does a No Turn on Red Sign exist on the TSTQB approach*? Yes, if it does, No if it doesn't.
15. *Are there intersection crossing markings*? Yes, if it does, No if it doesn't. Two types of intersection crossing markings are recorded here: green-colored intersection crossing markings and intersection crossing markings with no color.
16. *Does the TSTQB approach have a protected left turn phase*? Yes, if it does, No if it doesn't.
17. *Does the TSTQB approach have dedicated left turn lane(s)*? Yes, if it does, No if it doesn't.
18. *Any additional comments*? Anything irregular to note, including if the view on Google Maps was obstructed in any way (e.g. construction).

Figure 2.6: Left turn box sign from MUTCD (D11-20aL) (*1*)

2.3 Field Data Collection

2.3.1 Installation

In this study, a total of six intersections were chosen for field data collection that was performed with the use of video cameras for a duration of approximately 24 hours at each location. The primary criterion for the selection of these intersections was that each of them has at least one TSTQB.

2.3.2 Study Sites

The six selected intersections were located in the Greater Boston area, and in particular, in Boston, Somerville, and Brookline in Massachusetts. Figure 2.7 shows the locations of those six intersections and this subsection provides a detailed description of them. In total, 14 TSTQBs were captured in addition to four bike boxes. Data from an additional six approaches was also collected as part of capturing video recordings at those six intersections. These approaches were used as control sites for comparing left-turning bicyclist behavior in the presence and absence of TSTQBs and bike boxes.

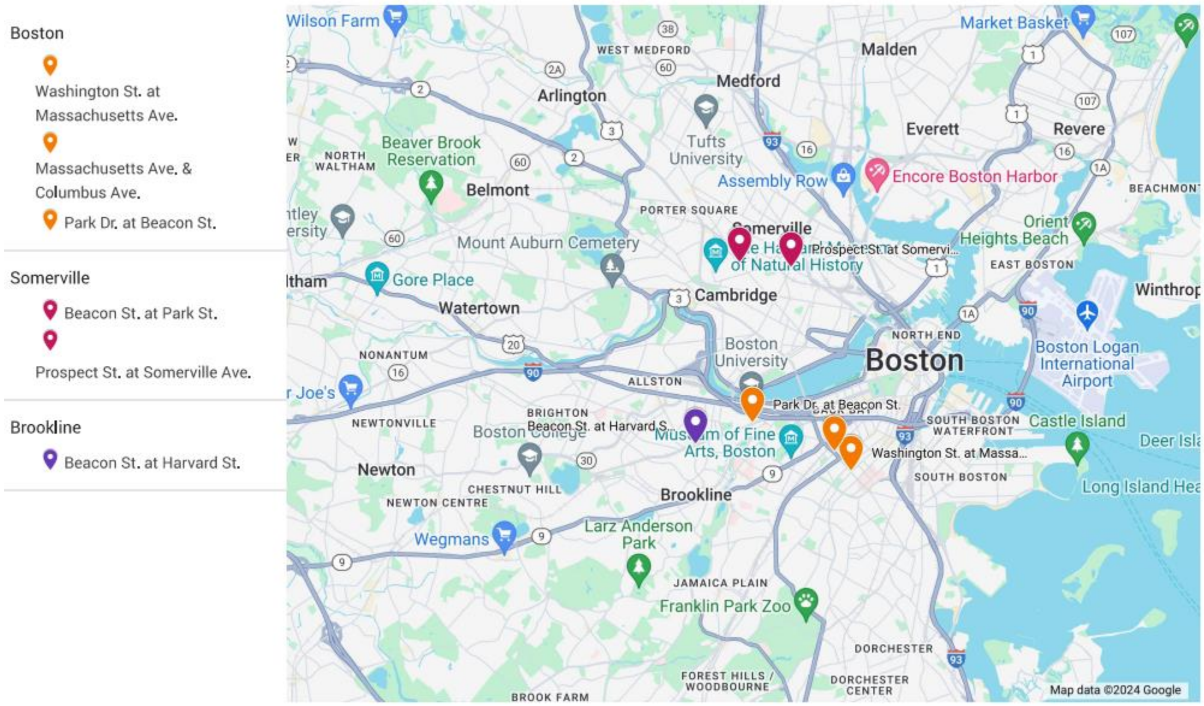


Figure 2.7: Study sites in Greater Boston Area, MA

Boston

1. Massachusetts Ave. at Columbus Ave. (Installed Thursday, 12/1/22)

The Massachusetts Avenue at Columbus Avenue intersection is a four-way signalized intersection, and two cameras were set up to capture this intersection. Massachusetts Avenue approaches from the northwest and southeast, while Columbus Avenue approaches from the northeast and southwest. At this intersection, two TSTQBs are present, one serving left-turning bicycles from the northeast-bound approach, and the other serving those from the southwest-bound approach. Both TSTQBs feature green-colored pavement, turn arrows, and bicycle stencils. One TSTQB follows the crosswalk setback configuration, while the other follows the parking lane configuration according to the NACTO classification (*4*). Additionally, intersection crossing markings are present for all directions. The southwest-bound approach comprises of one through lane, one dedicated left-turn lane, and a conventional bike lane. The northeast-bound approach includes one shared through and right-turn lane, one dedicated left-turn lane, and a conventional bike lane. Both approaches are equipped with protected left-turn phasing. Figure 2.8 shows the intersection layout and one of the camera views for this intersection.

Figure 2.8: Intersection layout and a camera view, Massachusetts Ave. at Columbus Ave

2. Massachusetts Ave. at Washington St. (Installed Monday, 11/14/22)

The Massachusetts Avenue at Washington Street intersection is a four-way signalized intersection, and four cameras were set up to capture data for this intersection. Massachusetts Avenue approaches from the northwest and southeast, while Washington Street approaches from the northeast and southwest. At this intersection, two TSTQBs are present, one serving left-turning bicycles from the northwest-bound approach, and the other serving those from the southeast-bound approach. Both TSTQBs feature green-colored pavement, turn arrows, and bicycle stencils, and follow the crosswalk setback configuration according to the NACTO classification (*4*). The intersection also features intersection crossing markings for southeast bound and northwest bound directions. Both the northwest-bound and southeast-bound approaches feature two through lanes, one dedicated left-turn lane, and a conventional bike lane. Additionally, both approaches are equipped with protected left-turn phasing. Figure 2.9 shows the intersection layout and one of the camera views for this intersection.

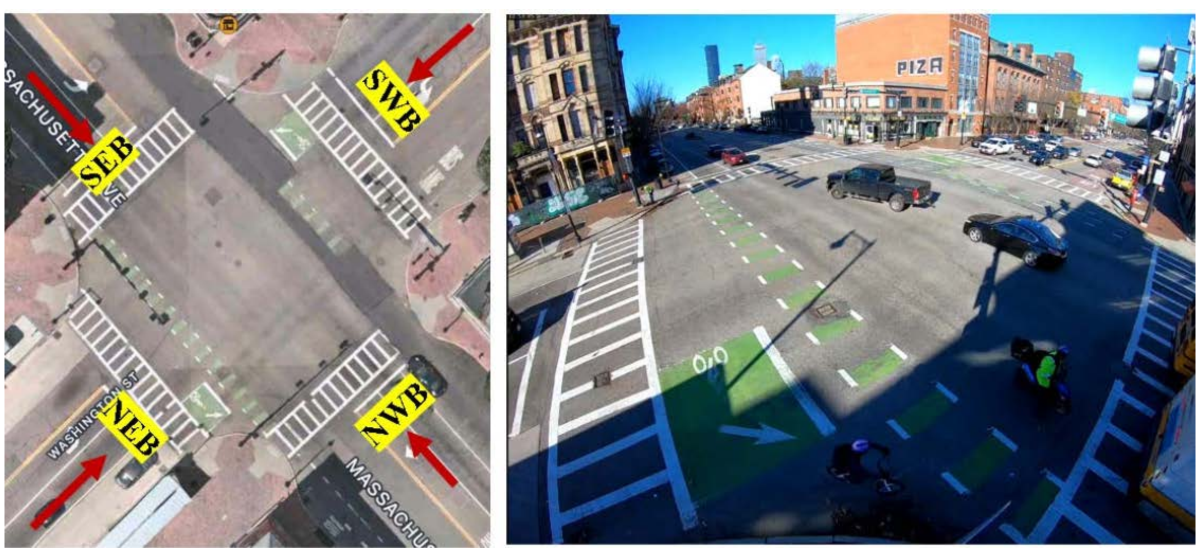


Figure 2.9: Intersection layout and a camera view, Massachusetts Ave. at Washington St.

3. Park Dr. at Beacon St. (Installed Thursday, 11/10/22)

The Beacon Street at Park Drive intersection is a four-way signalized intersection and four cameras were set up to capture data for this intersection. Beacon Street approaches from the east and west, while Park Drive approaches from the north and south. At this intersection, four TSTQBs serve left-turning bicycles from all approaches. All TSTQBs feature green-colored pavement, with three of them also having turn arrows and bicycle stencils, and one not including those markings. All TSTQBs follow the crosswalk setback configuration according to the NACTO classification (*4*). Additionally, the intersection includes intersection crossing markings for all directions. Both the west-bound and north-bound approaches have two through lanes, one dedicated left-turn lane, and a conventional bike lane, all equipped with protected left-turn phasing and bike boxes. The east-bound approach has two through lanes, one shared bike and right-turn lane, and one conventional, green-colored bike lane, with no permissible left-turn option. The south-bound approach features two through lanes and one conventional bike lane. None of these approaches facilitates protected left turn phasing. Figure 2.10 illustrates this intersection's layout and one of the camera views.

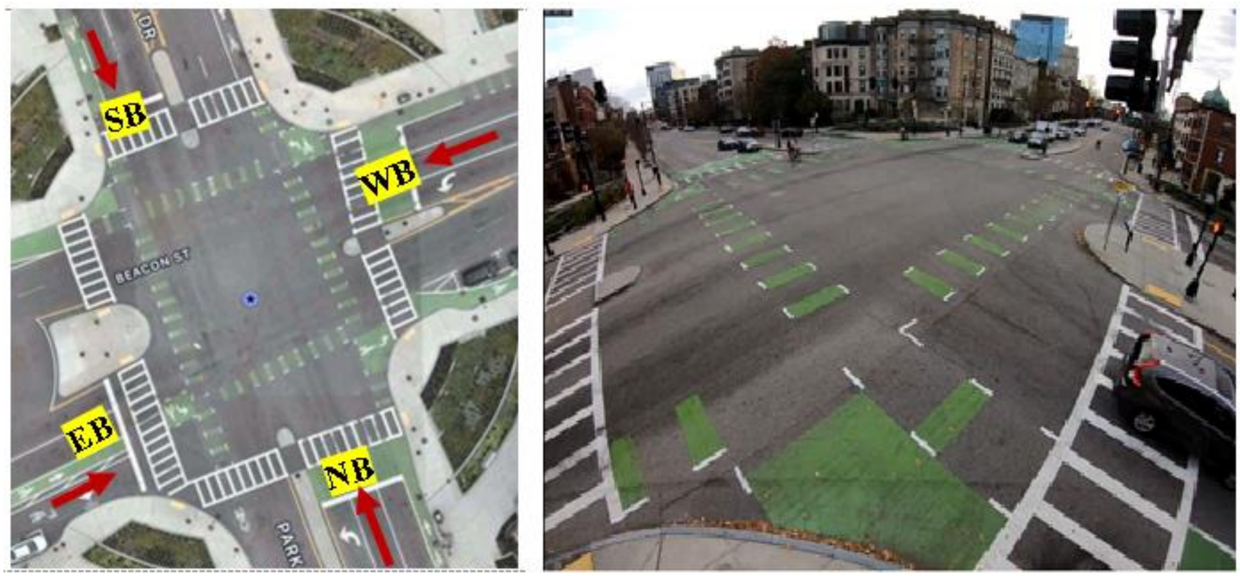


Figure 2.10: Intersection layout and a camera view, Park Dr. at Beacon St.

Brookline

4. Beacon St. at Harvard St. (Installed Tuesday, 8/22/23)

The intersection of Beacon Street at Harvard Street is a four-way signalized intersection. Four cameras were set up to capture data at this intersection. Beacon Street approaches from the east and west, while Harvard Street approaches from the north and south. At this intersection, four TSTQBs serve left-turning bicycles from all approaches. All TSTQBs feature green-colored pavement, turn arrows, and bicycle stencils. In addition, all of them follow the parking lane configuration according to the NACTO classification (*4*). No intersection crossing markings are present at this intersection. Both the east-bound and west-bound approaches of Beacon Street have one through lane and two right-turn lanes, which are also marked with sharrows. The north-bound and south-bound approaches of Harvard Street each have one through lane and one shared through and right-turning lane that are also marked with sharrows. No left turn is allowed from any of the approaches. There are also Massachusetts Bay Transportation Authority (MBTA) T tracks traversing in the east-west direction. Figure 2.11 illustrates the intersection layout and one of the camera views. As a result of certain technical complications, data was collected for only two of the TSTQBs: the northbound-westbound and the eastbound-northbound ones.

Figure 2.11: Intersection layout and a camera view, Beacon St. at Harvard St.

Somerville

5. Beacon St. at Park St. (Installed Tuesday, 6/27/23)

The Beacon Street at Park Street intersection is a four-way signalized intersection. Four cameras were set up to capture data from it. Beacon Street approaches from the southeast and northwest, while Park Street approaches from the northeast and southwest. At this intersection, only one TSTQB serves left-turning bicycles from the southeast bound approach of Beacon Street. The TSTQB features green-colored pavement, turn arrows, and bicycle stencils, following the crosswalk setback configuration according to the NACTO classification (*4*). Additionally, the intersection also has intersection crossing markings for bicyclists for northwest bound and southeast bound directions. Both the southeast and northwest bound approaches of Beacon Street have one through lane with a green-colored conventional bike lane. Additionally, both approaches have bike boxes. The southwest bound approach of Park Street has one through lane with a conventional bike lane and features a bike box. The northeast bound approach of Park Street has one through lane and parking lanes on both sides, constituting a one-way road. On the other hand, the southwest bound approach of Park Street has one through lane with a conventional bike lane and a bike box at the intersection. Figure 2.12 illustrates the intersection layout and a camera view.

Figure 2.12: Intersection layout and a camera view, Beacon St. at Park St.

6. Somerville Ave. at Prospect St. (Installed Thursday, 10/26/23)

The intersection at Somerville Avenue at Prospect Street is a four-way signalized intersection, and four cameras were set up to capture data at that intersection. Somerville Avenue approaches from the southeast and northwest, while Prospect Street approaches from the northeast and southwest. At this intersection, there are three TSTQBs that serve left-turning bicycles from the southeast bound approach of Somerville Avenue, and the northeast and southwest bound approaches of Prospect Street. All TSTQBs feature green-colored pavement, turn arrows, and bicycle stencils, and follow the crosswalk setback configuration for the northeast bound approach and cycle track configuration for the other two, according to the NACTO classification (*4*). Additionally, the intersection includes intersection crossing markings. The southeast bound approach of Somerville Avenue has one shared through and right-turn lane, along with one dedicated left-turn lane featuring a protected bike lane. The southwest bound approach of Prospect Street has one through lane and one right-turn lane, with a protected bike lane. This approach does not allow any left turns. The northeast bound approach of Prospect Street features one shared through and right-turn lane and a dedicated left-turn lane, with a conventional bike lane. Figure 2.13 illustrates the intersection layout and one of the camera views.

Figure 2.13: Intersection layout and a camera view, Somerville Ave. at Prospect St.

Table 2.2 shows the timeframe during which data was collected for the six selected intersections.

Table 2.2: Data collection timetable

Intersection	Start Time	End Time
Beacon St. at Harvard St.	Tuesday, August 22, 2023, 8:45 PM	Wednesday, August 23, 2023, 8:45 PM
Park Dr. at Beacon St.	Thursday, November 10, 2022, 8:45 AM	Friday, November 11, 2022, 9:15 AM
Massachusetts Ave. at Columbus Ave.	Thursday, December 1, 2022, 8:30 AM	Friday, December 2, 2022, 8:15 AM
Washington St. at Massachusetts Ave.	Monday, November 14, 2022, 1:15 PM	Tuesday, November 15, 2022, 12:15 PM
Somerville Ave. at Prospect St.	Thursday, October 26, 2023, 5:15 PM	Friday, October 27, 2023, 8:45 PM
Beacon St. at Park St.	Tuesday, June 27, 2023, 2:30 PM	Wednesday, June 28, 2023, 5:30 PM

2.4 Left-Turning Bicyclist Behavior at TSTQBs

2.4.1 Data recording

Bicyclist behavior, in particular recording how bicyclists were completing left turns at the selected intersections, was documented manually using the Behavioral Observation Research Interactive Software (BORIS) tool (*14*). This software offers an interface enabling users to record specific events while viewing a video recording. The interface, shown in Figure 2.14, displays the video on the left side along with video controls, while recorded observations appear on the right. The behavior of each left-turning bicyclist was recorded by assigning individual keys for different purposes. More specifically data recorded included their way that bicyclists used to complete their left-turning movement (e.g., via a conventional left turn maneuver, via a two-stage maneuver but no use of a TSTQB, by using the TSTQB or a crosswalk), the infrastructure/lane (bike lane, right/through lane, sidewalk, etc.) they used when they were approaching the intersection, as well as the downstream infrastructure type/lane used after the completion of their left turn.

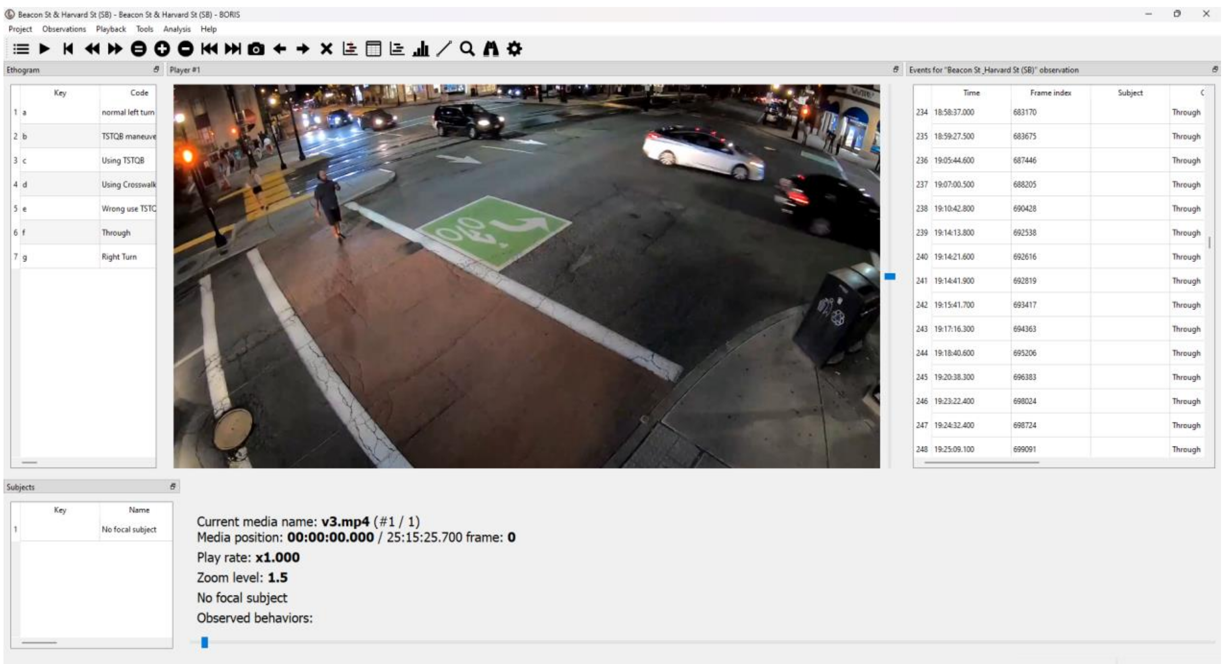
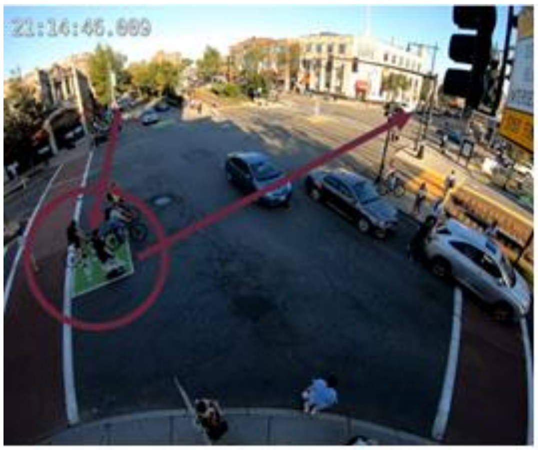


Figure 2.14: BORIS Interface

Bicyclist behavior at TSTQB focused on which lane bicyclists are coming from upstream, as well as the type of left-turning movements they perform and which lane they are traveling on after they complete the left turn. In this study, five distinct left-turning movements by bicyclists were observed and recorded. When a bicyclist uses the TSTQB, indicating standing and waiting at the TSTQB, the movement is labeled as "TSTQB." If the bicyclist performs a two-stage maneuver, waiting near the TSTQB before making the turn, it is recorded as "Two-Stage Maneuver." Utilizing the crosswalk for a left turn is denoted as "Crosswalk." If the bicyclist waits in the bike box before completing the left turn, it is labeled as "Bike Box." Finally, the conventional parabolic left turn is categorized as "Conventional Left Turn." Figure 2.15 illustrates these five left turning movement types.



(a) TSTQB

(b) Two-Stage Maneuver

(c) Crosswalk

(d) Bike Box

(e) Conventional Left Turn

Figure 2.15: Bicyclist left turning movement types

The TSTQB naming is based on the first and second leg of a bicyclist's left-turning maneuver. For instance, at the Beacon St. and Harvard St. intersection (Figure 2.16d), if a bicyclist is traveling from the eastbound (EB) approach to the northbound (NB) approach, the TSTQB will be referred to as the EB-NB TSTQB. Figure 2.16 shows the naming convention adopted for the selected TSTQBs in this study.

(a) Massachusetts Ave. at Columbus Ave., Boston, MA

(b) Massachusetts Ave. at Washington St., Boston, MA

(c) Park Dr. at Beacon St., Boston, MA

(d) Beacon St. at Harvard St., Brookline, MA

(e) Beacon St. at Park St., Somerville, MA

(f) Somerville Ave. at Prospect St., Somerville, MA

Figure 2.16: Selected TSTQBs for the study

2.4.2 Hypotheses

Various hypotheses are developed to test the impact of design elements on the utilization of TSTQBs and overall, left turning behavior of bicyclists at intersections. Different sets of TSTQB and control approaches are considered when testing each of these hypotheses, as outlined next. For a summary of the TSTQB approach characteristics, you can refer to Table 4.3-Table 4.5.

Hypothesis 1. ***The presence of a bike box at an approach reduces TSTQB utilization for bicyclists coming from that approach.***
This hypothesis assumes that when a bike box is present, left-turning bicyclists might be less inclined to use the TSTQB. That is because bike boxes offer a safe space for bicyclist to stop while at signalized intersections and then proceed to the left of the approach to complete their turn without having to encounter delay due to the signals twice. The TSTQBs at Park Dr. at Beacon St. (WB-SB & NB-WB) and Washington St. at Massachusetts Ave. (NWB-SWB & SEB-NEB) were chosen for this test to maintain consistency across all parameters with only the presence of bike boxes differing between Park Dr. at Beacon St. (WB-SB & NB-WB), which feature bike boxes, and Washington St. at Massachusetts Ave. (NWB-SWB & SEB-NEB), which do not have bike boxes.

Hypothesis 2. ***The presence of a bike lane at an approach increases TSTQB utilization for bicyclists coming from that approach.***
The hypothesis suggests that the presence of a bike lane upstream of an approach increases the likelihood of a left-turning bicyclists utilizing the TSTQBs. This is because proceeding through the intersection to use a TSTQBs might appears to be the most comfortable and safe path after exiting the bike lane, especially for approaches lacking protected or permissive left-turning phasing and dedicated left-turn lanes. The TSTQBs at Beacon St. at Harvard St. (EB-NB), and Beacon St. at Harvard St. (NB-WB), are the only TSTQBs with no bike lanes upstream and no dedicated left-turn lanes or protected/permissive left-turn phasing. Notably, they both feature sharrows upstream. The other approaches whose data was used for testing this hypothesis, feature either conventional, specifically, Park Dr. at Beacon St. (SB-EB), Park Dr. at Beacon St. (EB-NB), and Beacon St. at Park St. (SEB-NEB) or protected bike lanes, namely Somerville Ave. at Prospect St. (SB-EB).

Hypothesis 3. ***The presence of a protected bike lane at an approach increases TSTQB utilization for bicyclists coming from that approach compared to the presence of conventional bike lanes.***
The hypothesis suggests that the presence of a protected bike lane upstream of an approach encourages use of TSTQBs for left-turning bicyclists compared to conventional bike lanes. This is because protected bike lanes maintain the separation until the intersection, therefore, making it harder for bicyclists to exit the bike lane and complete the maneuver in an alternative way. The TSTQBs at Park Dr. at Beacon St. (WB-SB), Somerville Ave. at Prospect St. (SB-EB) and Somerville Ave. at Prospect St. (EB-NB) approaches have protected bike lanes upstream, while at Park Dr. at Beacon St. (SB-EB), Park Dr. at Beacon St. (EB-NB), Beacon St. at Park St. (SEB-NEB),Massachusetts Ave. at Columbus Ave. (NEB-NWB),Massachusetts Ave. at Columbus Ave. (SWB-SEB), Washington St. at Massachusetts Ave. (NWB-SWB), Washington St. at Massachusetts Ave. (SEB-NEB), and Somerville Ave. at Prospect St. (NB-WB) approaches have conventional bike lanes.

Hypothesis 4. ***The existence of protected left-turn phasing decreases TSTQB utilization for bicyclists coming from that approach***

The hypothesis suggests that left-turning bicyclists are less inclined to utilize TSTQBs when the approach they are coming from has a protected left turn phase. This assumes that when an alternative, safe way is offered for completing a left turn at an intersection, bicyclists are expected to opt for not using the TSTQB which will add delay. The intersections selected for this study were chosen based on the presence or absence of protected left-turn phasing. Specifically, Park Dr. at Beacon St. (WB-SB), Park Dr. at Beacon St. (NB-WB), Massachusetts Ave. at Columbus Ave. (NEB-NWB), Massachusetts Ave. at Columbus Ave. (SWB-SEB), Washington St. at Massachusetts Ave. (NWB-SWB), Washington St. at Massachusetts Ave. (SEB-NEB) approaches have protected left-turn phasing, while Beacon St. at Harvard St. (EB-NB), Beacon St. at Harvard St. (NB-WB), Beacon St. at Park St. (SEB-NEB), Somerville Ave. at Prospect St. (NB-WB), Somerville Ave. at Prospect St. (SB-EB), Park Dr. at Beacon St. (SB-EB), Park Dr. at Beacon St. (EB-NB), Somerville Ave. at Prospect St. (EB-NB) approaches do not.

Hypothesis 5. ***The presence of dedicated left turn lanes decreases TSTQB utilization for bicyclists coming from that approach***

The hypothesis suggests that bicyclists are less inclined to make left turns using the TSTQB at intersections where dedicated left turn lanes are present, compared to intersections that do not feature dedicated left turn lanes. Similarly, to Hypothesis 4, this assumes that when left turns are expected and are prevalent as indicated through the presence of dedicated left turn lanes, left-turning bicyclists are more likely to use those left turn lanes rather than complete a two-stage left turn by using the TSTQB. The intersections selected for this study were chosen depending on whether they featured dedicated left turn lanes. Specifically, the Park Dr. at Beacon St. (WB-SB), Park Dr. at Beacon St. (NB-WB), Massachusetts Ave. at Columbus Ave. (NEB-NWB), Massachusetts Ave. at Columbus Ave. (SWB-SEB), Washington St. at Massachusetts Ave. (NWB-SWB), Washington St. at Massachusetts Ave. (SEB-NEB), Somerville Ave. at Prospect St. (NB-WB), Somerville Ave. at Prospect St. (EB-NB) approaches feature dedicated left turn lanes. In contrast, the Beacon St. at Harvard St. (EB-NB), Beacon St. at Harvard St. (NB-WB), Beacon St. at Park St. (SEB-NEB), Somerville Ave. at Prospect St. (SB-EB), Park Dr. at Beacon St. (SB-EB), Park Dr. at Beacon St. (EB-NB) approaches lack such dedicated left turn lanes.

Hypothesis 6. ***The presence of TSTQBs at intersections increases the occurrence of two-stage maneuvers compared to control approaches without TSTQBs***

The hypothesis suggests that the presence of a TSTQB at an approach increases the likelihood of all bicyclist two-stage turn maneuvers, whether they utilize the TSTQB or not. This hypothesis assumes that TSTQBs and/or related features of intersections where they are implemented, are motivating left-turning bicyclists to complete their left turns in two stages. To test this hypothesis, all approaches with and without TSTQBs were selected. For approaches with TSTQBs, both the usage of the TSTQB and the two-stage maneuver without using the TSTQB were recorded as part of the completed two-stage maneuvers.

Hypothesis 7. ***TSTQB utilization is greater at larger compared to smaller intersections***

The hypothesis suggests that larger intersections motivate a higher utilization of TSTQBs from left-turning bicyclists. This could be due to the fact that two-stage turn maneuvers might be perceived as safer and more comfortable for completing left turns at large intersections. The size of the intersection is defined in this study based on the total number of travel lanes at the intersection. Washington St. at Massachusetts Ave. (NWB-SWB) and Washington St. at

Massachusetts Ave. (SEB-NEB) have 3 travel lane whereas Massachusetts Ave. & Columbus Ave. (NEB-NWB) and Massachusetts Ave. & Columbus Ave. (SWB-SEB) have two travel lanes. These four approaches were chosen for this test due to their similar characteristics, with the exception of the number of travel lanes.

Hypothesis 8. *Crosswalk utilization for left-turning bicyclist maneuvers is greater when there is no TSTQB to accommodate those left-turning bicyclists*

The hypothesis suggests that if an approach lacks TSTQBs, bicyclists tend to use the crosswalk more for completing left turns compared to approaches with TSTQBs. As with other hypotheses this might be due to the perception that the use of crosswalk is a safer way and therefore, more comfortable for many bicyclists for completing their left turns. All selected approaches with available data were used for testing this hypothesis, both those with TSTQBs, namely Washington St. at Massachusetts Ave. (NWB-SWB), Washington St. at Massachusetts Ave. (SEB-NEB), Massachusetts Ave. at Columbus Ave. (NEB-NWB), and Massachusetts Ave. at Columbus Ave. (SWB-SEB) and those without TSTQBs, specifically the Washington St. at Massachusetts Ave. (SWB-SEB), Washington St. at Massachusetts Ave. (NEB-NWB), Massachusetts Ave. at Columbus Ave. (NWB-SWB), Massachusetts Ave. at Columbus Ave. (SEB-NEB) ones.

Hypothesis 9. *The presence of a TSTQB sign increases TSTQB utilization*

The hypothesis suggests that left-turning bicyclists are more likely to use a TSTQB to complete their left turns at intersections, when MUTCD (*1*) TSTQB signs are present upstream of their approach. This is because the TSTQB sign at the upstream approach raises awareness about the presence of a TSTQB downstream, which can be motivating for left-turning bicyclists to use the TSTQB. Unfortunately, none of the intersections analyzed displayed a TSTQB sign during the data collection period.

Hypothesis 10. *The TSTQB parking lane configuration increases its utilization compared to the crosswalk TSTQB configuration*

The hypothesis suggests that left-turning bicyclists are more likely to use a TSTQB to complete their left turns at intersections, if the TSTQB follows a parking lane configuration. The assumption behind this hypothesis is that the parking lane configuration provides a wider bikeway space compared to the crosswalk setback configuration, which may make it more visible and allow more bicyclists to queue in the TSTQB. Park Dr. at Beacon St. (WB-SB), Park Dr. at Beacon St. (NB-WB), Park Dr. at Beacon St. (SB-EB), Park Dr. at Beacon St. (EB-NB), Massachusetts Ave. at Columbus Ave. (SWB-SEB), Washington St. at Massachusetts Ave. (NWB-SWB), Washington St. at Massachusetts Ave. (SEB-NEB), Somerville Ave. at Prospect St. (NB-WB), and Beacon St. at Park St. (SEB-NEB) approaches featured crosswalk setback configurations. In contrast, the Beacon St. at Harvard St. (EB-NB), Beacon St. at Harvard St. (NB-WB), and Massachusetts Ave. at Columbus Ave. (NEB-NWB) approaches featured parking lane configuration of TSTQB.

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3.0 Literature Review

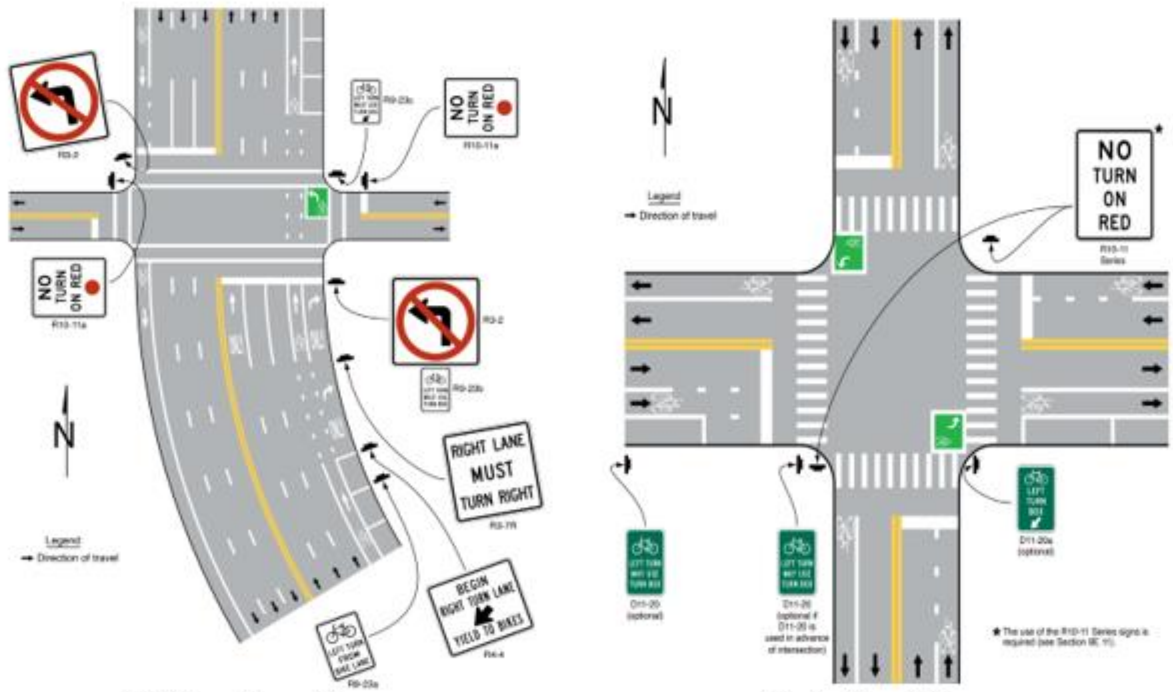
This Chapter primarily documents guidelines for implementing and designing TSTQBs in the US, along with summarizing research findings on their effectiveness. Initially, national-level design guidelines from the MUTCD, NACTO, and FHWA are presented. Subsequently, guidelines from various states and cities are discussed. Finally, research findings regarding TSTQBs are summarized.

3.1 Two-stage Turn Queue Boxes Design Guidelines across the United States

3.1.1 National Level Design Guidelines

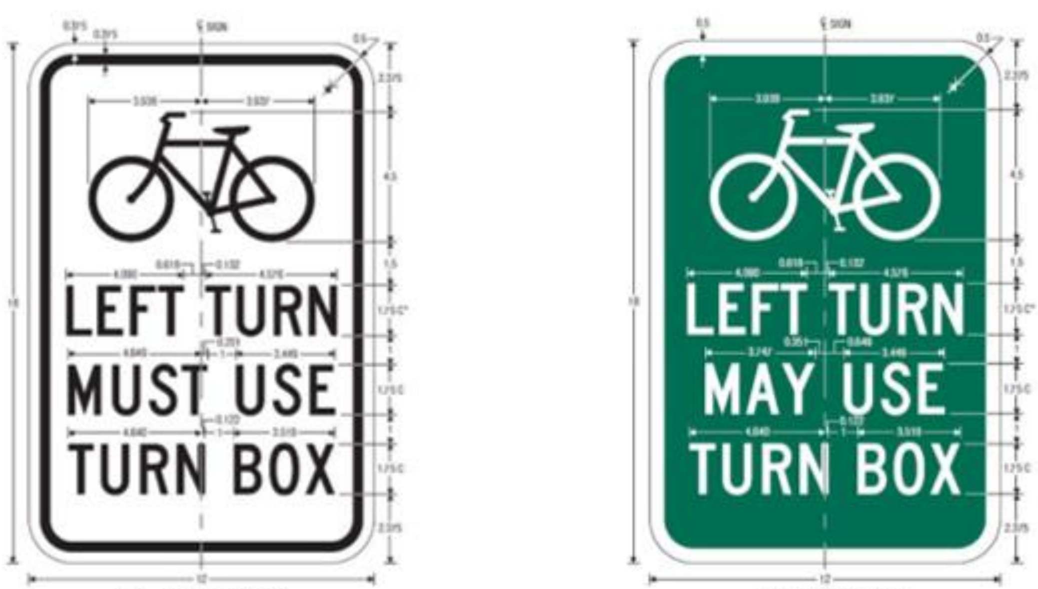
While TSTQBs have only been recently gaining popularity in the United States (US), they have been included in guidebooks since the 1970's. More specifically, references to TSTQBs exist in the University of California, Los Angeles's Institute for Transportation and Traffic Engineering's 1972 Bikeway Planning Criteria and Guidelines and the American Association of Transportation Officials (AASHTO) 1974 Guide for Bicycle Routes (*10*). Most guidebooks on bicycle facilities provide only general information such as recommendations for the type of materials to be used for pavement markings or lack guidelines altogether. AASHTO does not mention TSTQBs in their *A Policy on Geometric Design of Highways and Streets* manual (*15*) but hinted the potential of such a treatment in facilitating left turns in their Guide for the Development of Bicycle Facilities manual (*16*).

The TSTQB is a traffic control device, which was just added in the newest 11th edition of *Manual on Uniform Traffic Control Devices (MUTCD)* (*1*). Two scenarios govern the implementation and design of TSTQBs based on the MUTCD: mandatory use and optional use (Figure 3.1). When bicyclists are required to use a TSTQB, the corresponding TSTQB regulatory sign (R9-23b and R9-23c) series should be utilized (Figure 3.2(a)). In areas where TSTQBs are mandatory, regulatory signs such as "Bicycles All Turns from Bike Lane" (R9-23) or "Bicycle Left Turn from Bike Lane" (R9-23a) should be installed before the intersection. Additionally, at least one "Bicycle Turn Must Use Turn Box" (R9-23b or R9-23c) sign must be placed at the intersection. If the R9-23b sign is used, it should be placed on the near side of the intersection. Conversely, if the R9-23c sign is used, it should be placed on the far side of the intersection. Alternatively, if the use of a TSTQB is optional, directional information may be provided using the TSTQB guide sign (D11-20 and D11-20a) series (Figure 3.2(b)).



(a) Mandatory Usages (b) Optional Usages

Figure 3.1: TSTQB usages according to MUTCD (*1*)



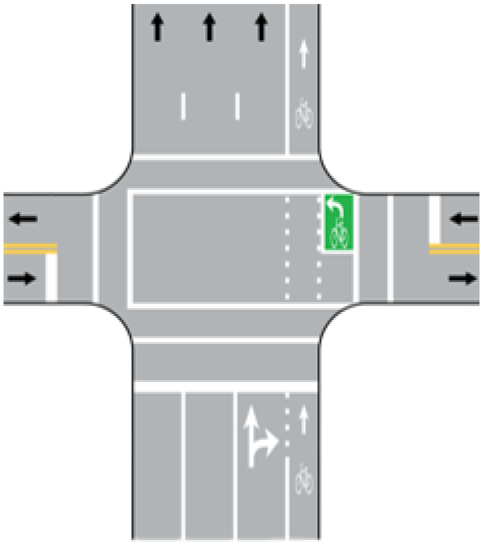
(a) R29-23aL (b) D11-20L

Figure 3.2: Regulatory and guide signage for TSTQBs (*1*)

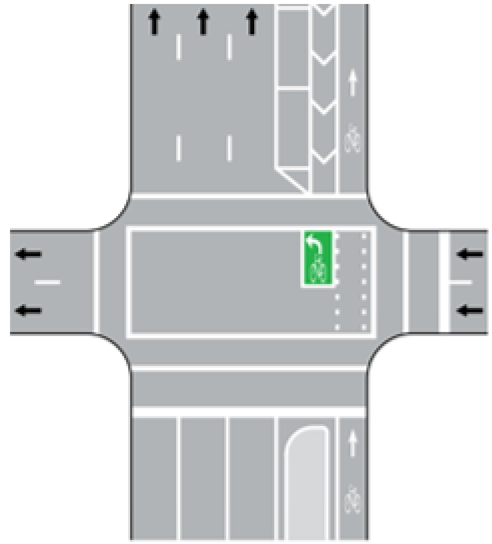
The MUTCD also provides guidelines on the pavement markings associated with the implementation of a TSTQB stating that a TSTQB must include at least one bicycle symbol pavement marking and one pavement marking arrow (*1*). If used with a one-way bicycle lane, a turn arrow in the appropriate direction is required, while a through arrow shall be used with a two-way bikeway. The TSTQB should be bounded by a solid white line on all sides. When facilitating turns from a one-way bikeway, the bicycle symbol should precede the pavement marking turn arrow. Optionally, the TSTQB may be green-colored. If implemented, the green-colored pavement should cover the entire area of the TSTQB.

Additionally, passive detection of bicycles in the TSTQB should be provided if the signal phase allowing bicycles to enter during the second stage of their turn is actuated. Lastly, if the path of vehicles making right turns on red intersects with the TSTQB, a permanent no-turn-on-red rule must be enforced for the approaching crossroad.

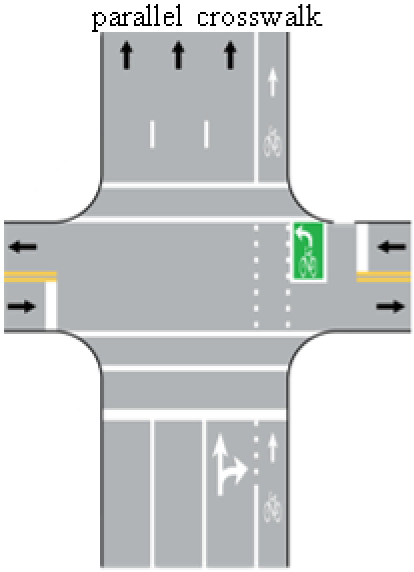
The 11th edition of the MUTCD (*1*) delineates four configurations; see Figure 3.3. According to the guidebook, TSTQBs should be placed in specific areas within the intersection. These include, the area between the through bicycle or closest motor vehicle movement and the parallel crosswalk (Figure 3.3(a)), or between the through bicycle movement and the parallel pedestrian crossing if no crosswalk exists (Figure 3.3(b)). Alternatively, they can be positioned on the innermost side of the bicycle facility in areas where parallel motor vehicle traffic does not traverse, such as islands or parking lanes (Figure 3.3(c)). For T-intersections, TSTQBs should be located between the through bicycle movement and a pedestrian facility; see Figure 3.3(d).



(a) Between the through bicycle lane and the parallel crosswalk



(b) Between the through bicycle lane and the parallel pedestrian movement



(c) On the inside of the through bicycle lane

(d) Between the through bicycle lane and the sidewalk at a T-intersection

Figure 3.3: TSTQB locations according to the MUTCD (*1*)

The *NACTO Urban Bikeway Design Guide* (*4*) provides extensive guidelines for TSTQB implementations, including detailed instructions on design elements, benefits, applications, and maintenance. NACTO suggests the use of TSTQBs at signalized intersections, on multilane roads with high traffic speed and volume, and where a significant number of bicyclists are making left turns from a right-side facility. According to NACTO, “Bicycle Hook Turn Storage Areas” (another name of TSTQB) should be 3-4 feet wide and up to 10 feet long. A bicycle symbol and turn arrow must be displayed to show the correct direction, and a "No Turn on Red" sign should be placed to prevent vehicles from entering the queue area in cities that permit right turns on red signal indications. Colored pavement inside the queue area and markings across intersections are recommended for visibility. Signs may also be used to improve visibility and clarify proper positioning. A bicycle signal with leading bicycle interval may also be installed.

To establish the positioning of bicyclists through intersections, it is recommended to utilize markings. These markings can include intersection crossing markings, pavement symbols, and/or colored pavement to direct bicyclists towards the TSTQB. The *NACTO Urban Bikeway Design Guide* (*4*) outlines six configurations in its guidelines; see Figure 2.5. According to the NACTO guidebook, the TSTQB box should be positioned within a protected area, typically situated within an on-street parking lane or between the bicycle lane and the pedestrian crossing.

FHWA's Separated Bike Lane Planning and Design Guide (*6*) recommends a depth of 10 feet depth and a width of 6.5 feet for TSTQBs, to roughly equate to the area needed by four cyclists standing side by side. It suggests placing the box between the bike lane and crosswalk to avoid disruption to through bicyclists, except for when on-street parking is present, when it can be located between the bike lane and vehicle travel lane. The guide includes pavement marking and signage guidelines that can also be found on MUTCD's 11th edition (*1*).

Table 3.1 provides a summary of these guidelines. It is important to note that some of these guidebooks are more than five to six years old and are currently being updated (such as the AASHTO Bike Guide (*16*)).

Table 3.1: Summary of two stage turn queue box design guidelines of national level in the US

Guidebook	Two Stage Turn Queue Box Depth [ft]	Two Stage Turn Queue Box Width [ft]	Bicycle Stencil and Turn Arrow	Green colored Pavement	White Line Boundary	Guide Signs[1]	Regulatory Signs[1]	"No Turn on Red" Sign
MUTCD (*1*)			Required	Optional	Required	Optional	Required	Required
NACTO - Urban Bikeway Design Guide (*4*)	10	3-4	Required	Recommended		Optional	Recommended	Required
FHWA - Separated Bike Lane Planning and Design Guide (*6*)	6.5	10	Required					Required

[1]: see Figure 3.2

3.1.2 State, County, and City Level Design Guidelines

States, counties, and cities have developed their own bicycle facility guidelines, with the following being examples that also include guidelines specific to TSTQBs: Massachusetts Department of Transportation (*17*); District Department of Transportation (DDOT) (*18*); Virginia Department of Transportation (VDOT) (*19*); Washington County, Oregon (*8*); Boston, MA (*20*); Colorado Springs, Colorado (*21*); Denver, Colorado (*9*); Berkeley, California (*22*); City of Columbia, South Carolina (*12*); and Portland, Oregon (*5*). Table 3.2 summarizes the main guidelines provided by these documents.

The *MassDOT Separated Bike Lane Planning & Design Guide* (*17*) suggests using a TSTQB when a separated bike lane extends to an intersection that is not a protected intersection. The guide recommends including a bicycle stencil with an arrow sign and paving the box with green colored pavement, with a depth of 6.5 feet. Additionally, a "No Turn on Red" sign is required to prevent right-turn movements during the red signal indication.

The *District Department of Transportation Bicycle Facility Design Guide* (*18*) recommends that TSTQBs are located outside the path of through going bicyclists and vehicular traffic, usually in the protected space created by parking lanes or the space between the crosswalk and the curb line. It also requires the use of green colored pavement with a bicyclist stencil along with an arrow in the direction of travel. The suggested outside dimensions of these boxes are 48 by 48 inches with a 4-inch solid white line outside the perimeter of the box and a 6-inch solid white line when next to a travel path. The guide also requires the use of “Two-stage Bicycle Turn Box Advance (R9-23)” and “Two-stage Bicycle Turn Box (R9-23a, R9-23b)” regulatory signs as well as signs restricting right turns on red in those cases that vehicular traffic would conflict with the TSTQB, which can also be found in the recent MUTCD edition (*1*).

The *Virginia Department of Transportation (VDOT) Bicycle and Pedestrian Treatments* (*19*) document shares the same standards as MUTCD’s 11th edition (*1*) for TSTQBs, except for guiding and regulatory signage, which are not included in VDOT’s guidelines.

The Washington County Bicycle Facility Design Toolkit (*8*) suggests following the NACTO (*4*) guidelines for implementing TSTQBs. It additionally indicates that TSTQBs can be utilized in urban, suburban, and rural areas.

The City of Columbia Engineering Regulations Part 9: Pedestrian, Bicycle (*12*) follows VDOT Bicycle and Pedestrian Treatment's (*19*) guidelines but does not provide any information about green-colored boxes, while it suggests a bicycle storage area depth of 6 feet. Limited information is provided in the Boston Complete Streets guide (*20*), which refers the reader to the NACTO Urban Bikeway Design Guide (*4*) for design guidelines. Limited information is also included in the 2020 Cambridge Bicycle Plan (*23*), which presents a high-level overview of TSTQB implementation and does not discuss specific design guidelines.

The *Colorado Spring’s Bicycle Facility Toolbox* (*21*) offers detailed guidelines for the design and placement of TSTQBs. Per the toolbox, these boxes can be placed in various locations, such as in front of pedestrian crossings, in a "jug-handle" configuration on a sidewalk, or at the end of a parking lane or median island. The minimum dimensions of the box should be 10 feet wide and 6.5 feet deep, and it should include a “No Turn on Red” sign, a green box outlined with solid white lines with a bicycle symbol and a turn arrow, as well as intersection crossing markings to indicate the travel path across the intersection.

The *Denver Bikeway Design Guidelines* (*9*) offer some guidance on the design of TSTQBs. These guidelines recommend a depth and width of 6 feet each with minimum dimensions of 3 by 6 feet and the box outlined by 4-inch white stripes around three edges, leaving the entrance direction open. These guidelines also suggest using a green colored box with pavement markings of a bicycle stencil and turn arrow, along with a "No Turn on Red" sign, as also recommended by the MUTCD 11th edition (*1*).

The *Berkeley Bicycle Facility Design Toolbox* (*22*) provides cost information for constructing TSTQBs in addition to design recommendations. More specifically, the manual recommends boxes that are 6-8 feet wide and 3-6 feet deep. It also requires features like bicycle stencils, turn arrow pavement markings, and a "No Turn on Red" sign, which align with NACTO (*4*) and MUTCD (*1*) guidelines.

Portland's Bikeway Facility Design: Survey of Best Practices (*5*) recommends a queuing area width of more than 4 feet, the use of pavement markings to guide bicycle movements and define queuing space, and the consideration of a physical refuge such as a curb extension or jug handle for queuing bicyclists. Additionally, motorists on cross streets are not permitted to turn right on red, which is in alignment with NACTO (*4*) and MUTCD (*1*) guidelines.

The *Street Design Guide of Minneapolis* (*24*) recommends that TSTQBs be placed outside of motorized traffic paths, adjacent to the intended bicycle travel path, and downstream of crosswalks to reduce conflicts with pedestrians. It suggests that they should not be installed if there is not enough space. The guide also mentions that dimensions and placement will vary depending on context, but it suggests a 10 feet depth and 6.5 feet width. "No Turn on Red" restrictions should be enforced to prevent vehicles from entering the queuing area. This guidebook also mentions that TSTQBs can be used to facilitate complex movements and transitions between one-way and two-way bike facilities.

Overall, published guidelines generally communicate the need to implement TSTQBs as a recommended practice at signalized intersections, particularly on multilane roads with high traffic speeds and volumes, as well as on routes where a substantial number of bicyclists are making left turns from a right-side bike facility. Collective information indicates that the dimensions of the TSTQBs should be approximately 10 feet deep and a minimum of 3 feet wide. TSTQBs should be positioned between the bike lane and crosswalk to prevent disruption to through bicyclists, except when on-street parking is present, in which case they can be located between the bike lane and vehicle travel lane. To ensure proper direction, the box should be marked with a bicycle symbol and a turn arrow, and a "No Turn on Red" sign must be installed to prevent vehicles from entering the queue area in cities that permit right turns on red signal indications. Moreover, colored pavement inside the queue area and markings across intersections is recommended to enhance visibility. It is also recommended to utilize intersection markings to direct bicyclists towards the queue box and establish the positioning of bicyclists through intersections.

Table 3.2: Summary of two stage turn queue box design guidelines of state, county and city level in the US

Guidebook	Two Stage Turn Queue Box Depth [ft]	Two Stage Turn Queue Box Width [ft]	Bicycle Stencil and Turn Arrow	Green colored Pavement	White Line Boundary	Guide Signs[1]	Regulatory Signs[1]	"No Turn on Red" Sign
City of Portland Bikeway Facility Design: Survey of Best Practices (*5*)		4		Required				Required
City of Columbia Engineering Regulations Part 9: Pedestrian, Bicycle, and Complete Streets Design Guidelines (*12*)	6		Required					Required
VDOT: Bicycle and Pedestrian Treatments (*19*)			Required	Recommended				Required
Colorado Springs Bicycle Facility Toolbox (*21*)	6.5	10	Required	Required	Required			Required
Denver Bikeway Design Guidelines (*9*)	3-6	6	Required	Recommended	Required (4-inches width on only 3 sides)			Required
Berkeley Bicycle Facility Design Toolbox (*22*)	3-6	6-8	Required					Recommended
District Department of Transportation Bicycle Facility Design Guide (*18*)	4	4	Required	Required	4'' (or 6'' if adjacent to a vehicular travel path)		Required	Required (when conflicts with the TSTQB are present)

[1]: see Figure 3.2

3.2Two-stage Turn Queue Boxes Design: Research Findings

The review of TSTQB research findings can be divided into two main sections: safety assessment and analysis of bicyclist behavior.

3.2.1 Safety Assessment

A few studies, including Götschi et al., 2018 (*25*) and Casello et al., 2017 (*26*), analyzed crash data and surrogate measures to assess the safety impact of TSTQBs.

Götschi et al., (2018) (*25*) evaluated the impact of a TSTQB in Zurich using a combined objective-subjective safety assessment approach. The researchers measured objective safety by analyzing the distance between left-turning bicycles and passing motor vehicles. Subjective safety was assessed through survey responses. The study found that the left-turning bicycle box significantly increased perceived safety for bicyclists crossing the intersection. The study also found a greater discrepancy between experienced and perceived safety in women compared to men. The researchers questioned whether the cost of marking a bicycle box justified the 0.7 increase in perceived safety but noted that given the minimal cost, and the effect may be greater among those bicyclists that are most concerned about safety. Finally, they suggest that the TSTQB may have led to the elimination of very large passing distances.

Ohlms & Kweon (2018) (*27*) evaluated the impact of two bike boxes and two TSTQBs installed at an intersection in Charlottesville, Virginia. Data collection involved the utilization of video equipment and the Miovision traffic data collection system. The Miovision system employs computer recognition to classify moving objects based on length, distinguishing between pedestrians, bicycles, cars, small trucks, and heavy trucks. Additionally, researchers manually reviewed the video footage to compile movement logs, i.e., legal violations by motor vehicles and bicycles, and conflict analysis involving bicyclists. However, the study was not able to conclude with certainty whether safety improves when TSTQBs are implemented.

3.2.2 Bicyclist Behavior

The review of the literature on bicyclist behavior at intersections with TSTQBs reveals limited studies that have investigated this topic.

Casello et al. (2017) (*26*) analyzed bicyclist behavior during left turns at six intersections in Toronto, Canada using video recordings. The study found that 70% of bicyclists completed left tuns by following the traffic rules, and approximately 54% of bicyclists used the two-phase design (utilized TSTQB) for those intersections, which had TSTQB. The intersection with the second-best compliance rate had a cycle track at the approach, along with a two-phase left-turn design, resulting in legal left turns about 68% of the time, with 55% of bicyclists using the two-phase approach.

However, conflicting findings were reported by Ohlms & Kweon (2018) (*27*). In particular, the study recorded bicyclist and motorist infractions as well as proper or not bicyclist use of

TSTQBs. However, the results of both bicyclist proper use of the TSTQB and change in infractions were inconclusive.

Furth et al. (2019) (*28*) used microsimulation models to evaluate multistage pedestrian crossings and two-stage bicycle turn designs for various traffic scenarios. They found that by dividing the left turn into two stages and utilizing well-timed signals, the two-stage maneuver for bicyclist significantly reduces delay for bicyclists compared to those who performed left-turn from the left turn lane and increases their safety by reducing conflicts with motor vehicles. The reduction in delays observed in this study does not align with the findings of some studies (*4*, *5*, *8*, *12*).

Conversely, Colville-Andersen (*29*) examined how cyclists turned left compared to their intended paths using data from a busy intersection in Bremerholm, Copenhagen. The intersection featured a two-phased left-turn box (i.e., TSTQB) design. During the study 71% of all traffic in the observation period were bicycle users. The study results showed that 86.5% of the left turning bicyclists performed the Copenhagen Left (i.e., utilized the TSTQB for their left turn maneuver at the intersection). Among the remaining 13.5%, only 2.2% adopted a conventional left-turning maneuver, while 11.3% chose a "snake" crossing, imitating pedestrian movements through the intersection.

Lastly, the FHWA has evaluated data from various TSTQB studies concluding significant improvements in consistency as it pertains to the use of the TSTQB by left-turning bicyclists (*10*). They also concluded that bicyclists were less willing to use it when fully occupied by other bicyclists, while signage was not seen as a requirement for the proper use of TSTQBs.

3.2.3 Research Gap

In summary, the literature on bicyclist behavior around TSTQBs and their effectiveness in improving safety and this treatment is limited. The few studies that have already been published indicate increased perceived and actual safety, with the caveat of fewer bicyclists using TSTQBs when already fully occupied. Other studies have confirmed the gap in research pertaining to the safety performance of TSTQBs (*30*). This gap underscores the need for further research to understand bicyclist behavior at intersections and comprehensively evaluate the effectiveness of TSTQBs.

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4.0 Results

4.1TSTQB Inventory

4.1.1 Survey Results

The survey conducted among Massachusetts municipalities resulted in a total of 57 responses from all six MassDOT districts, as detailed in Table 4.1 below.

Table 4.1: Distribution of survey responses from municipalities

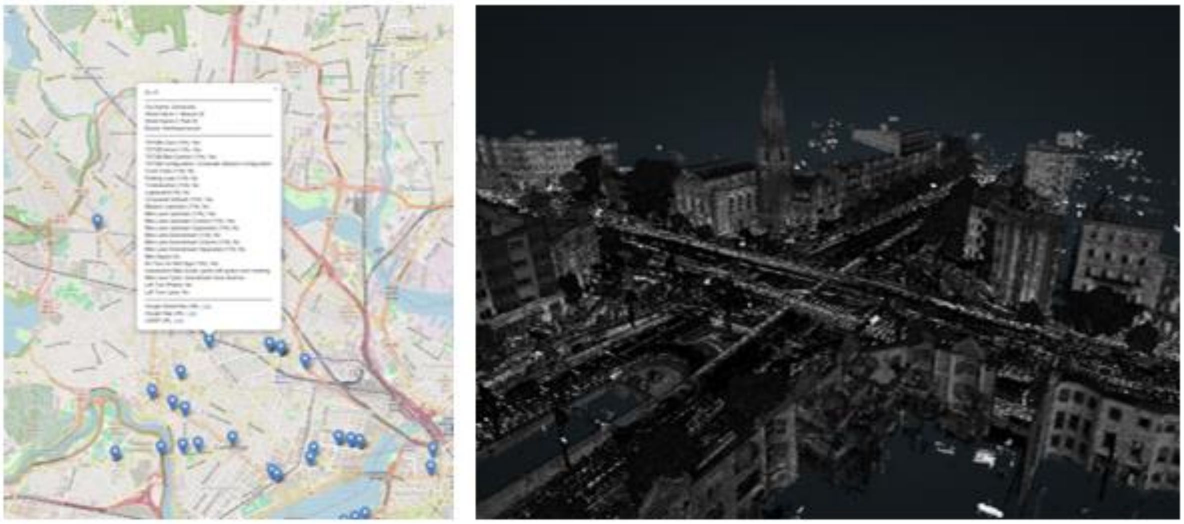
MassDOT District	Number of Responses
1	1
2	20
3	7
4	16
5	7
6	6
Total	57

The responses, combined with the existing TSTQBs on record, led to the identification of 91 TSTQBs in the Commonwealth. Among the 91, 24 were identified through survey responses. Notably, three responses from Belmont highlighted TSTQBs that were not found on Google Maps. These were excluded from the inventory analysis, leaving 88 TSTQBs for analysis.

Responses to the open-ended part of the surveys, even though limited, revealed general concerns on bicyclist safety and an interest in implementing bicycle facilities such as bike lanes but also TSTQBs at their jurisdictions. However, there were also concerns expressed by one respondent encapsulating the need for driver and bicyclist education on how to navigate TSTQBs and the added maintenance costs for municipalities.

4.1.2 Design Characteristics

As a deliverable, the research team developed a GIS web page to facilitate the subsequent analysis and improve the visualization of the bike box inventory results. This web page includes all 88 TSTQB inventoried in this study. Figure 4.1 shows an example of the GIS web page and the corresponding LiDAR point cloud viewer page.



(a) GIS TSTQB inventory (b) LiDAR point cloud data viewer

Figure 4.1: Data visualization for TSTQB locations and LiDAR data

The detailed design characteristics of the 16 TSTQB that were scanned with the LiDAR are also shown in Table 4.2. These results showcase the great variability that exists in the design of bike boxes.

Overall, the average depth and width of the TSTQBs varies between 8.8 ft. and 14.0 ft., and 7.3 ft. and 14.0 ft. The NACTO Urban Bikeway Design Guide (*4*) suggests depths of 10 ft and widths of 3-4 ft, while the FHWA’s Separated Bike Lane Planning and Design Guide (*6*) suggests a minimum of 6.5 ft depth and 10 ft width. As a result, some of the recorded dimensions of the TSTQBs in Massachusetts comply with some of the guidance and others do not. Most of the TSTQBs are painted with regular rectangular shapes, where others are tracing along the painted marking and the curb arcs, leaving them with irregular contours. In this study, the depth and width of the TSTQBs were measured based on the bounding boxes of the TSTQBs (*24*), which indicate sufficient space for possible bikes to stop at.

Most of the TSTQBs are within proximity of sidewalk facilities (i.e., curb), i.e., less than 20 ft. However, the distance to curb on the south bound of the intersection between Beacon St. and Park Dr. is 32.9 ft. due to the median configuration and right-only lane for bike of the bound.

The overall marking thickness for the TSTQBs is consistent with the typical 4–6-inch pavement marking. Some of the TSTQBs did not have the white painted marking around the area (e.g., Beacon St. and Park Dr, Mass Ave. and Columbus Ave.), or only one edge was painted (e.g., Mass Ave. and Washington St.). However, the presence of the marking does not appear to be significantly affecting the visibility of the TSTQBs, as all the TSTQBs were accompanied with extensive bike lane markings (e.g., egress lane) and crosswalks.

Table 4.2: TSTQB design dimensions

Intersection Street 1	Intersection Street 2	Bound	TSTQB Geometry (ft.) Depth	TSTQB Geometry (ft.) Width	TSTQB Geometry (ft.) Distance	TSTQB Geometry (ft.) Thickness
Beacon St	**Harvard St**	EB	9.02	8.27	12.37	0.39
Beacon St	**Harvard St**	SB	8.99	7.97	19.00	0.36
Beacon St	**Harvard St**	WB	9.02	8.07	18.11	0.36
Beacon St	**Harvard St**	NB	8.86	7.91	18.73	0.36
Beacon St	**Park Dr***	EB	13.32	13.98	6.20	0.00
Beacon St	**Park Dr***	NB	13.06	12.37	5.84	0.00
Beacon St	**Park Dr***	WB	14.04	10.04	4.66	0.00
Beacon St	**Park Dr***	SB	11.61	9.35	32.87	0.00
Mass. Ave	**Columbus Ave**	NB	14.70	6.63	17.36	0.00
Mass. Ave	**Columbus Ave**	SB	15.22	7.78	14.80	0.00
Mass. Ave	**Washington St**	NB	12.99	11.12	10.20	1.18[+]
Mass. Ave	**Washington St**	SB	12.89	11.32	15.09	1.25
Beacon St	**Park St**	NB	10.40	8.07	6.04	0.69
Somerville Ave	**Prospect St**	WB	13.16	8.10	13.48	0.43
Somerville Ave	**Prospect St**	NB	13.19	8.20	9.19	0.49
Somerville Ave	**Prospect St**	EB	13.42	7.28	11.88	0.43

[*] The depths and widths of the TSTQB were estimated based on the bounding boxes due to the irregular shape.
[+]Only one edge of the TSTQB has painted lines.

The 88 TSTQB locations were checked through Google Maps (both the bird's-eye view and street views were examined to obtain design characteristics and approximate installation time). The majority of the bike boxes in Massachusetts were implemented after August 2017. This section provides some descriptive statistics on important design features.

Despite the number of TSTQBs recorded, the majority of them are concentrated in a few cities/towns, namely Boston, followed by Cambridge and Somerville. Figure 4.2 shows their distribution across 8 cities. Figure 4.3 illustrates the TSTQB locations throughout the Commonwealth of Massachusetts.

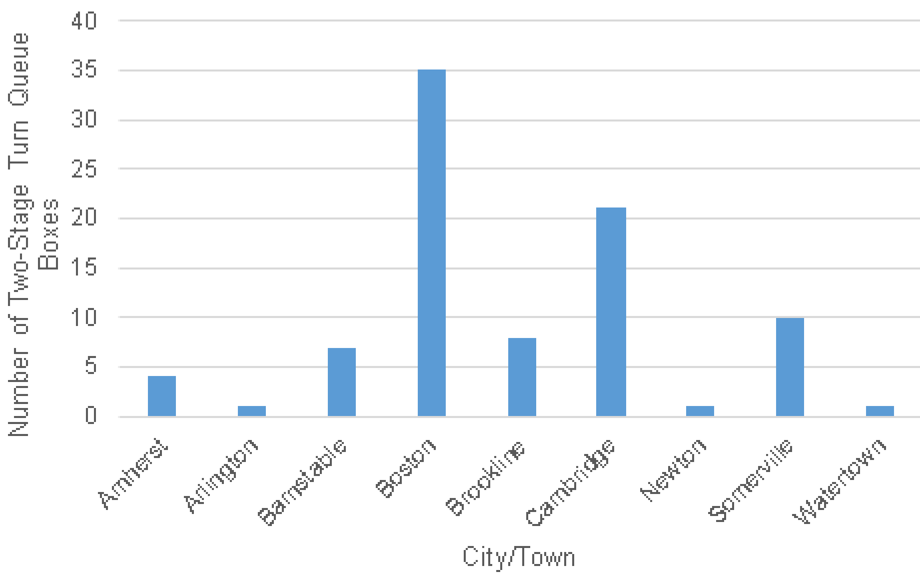
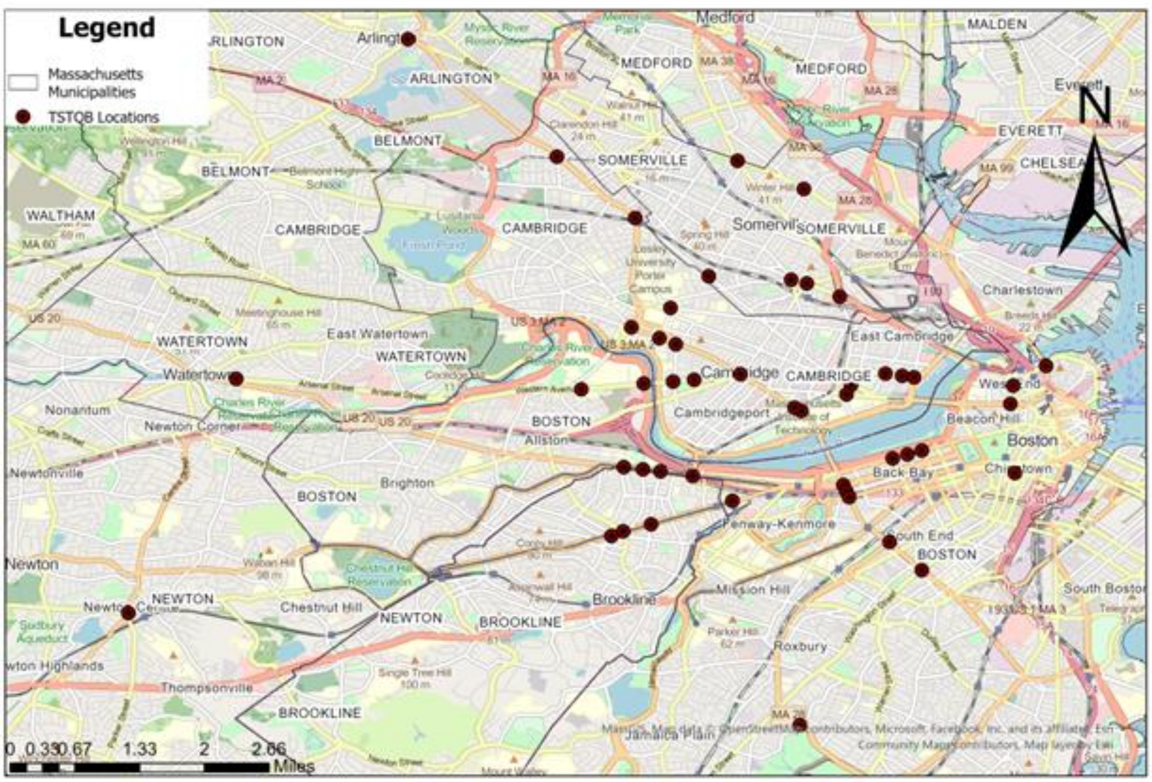


Figure 4.2: Distribution of TSTQBs by city/town

(a) State of Massachusetts



(b) Greater Boston Area

Figure 4.3: Distribution of TSTQBs

Many of the cities/towns have multiple TSTQBs per intersection, each of which is individually described. For example, as seen in Figure 4.4, the intersection of Beacon St. at Harvard St. in Brookline, MA has four separate TSTQBs.

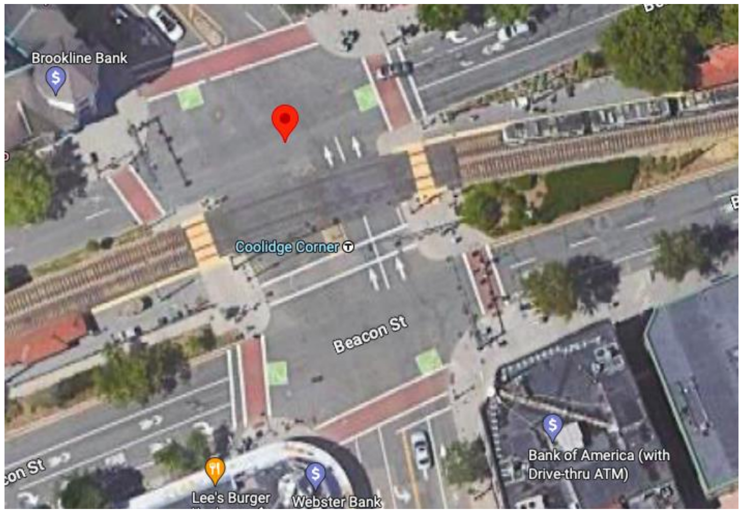


Figure 4.4: Intersection of Beacon St. at Harvard St. with multiple TSTQBs

The majority of the identified TSTQBs feature green-colored pavement, a bicyclist marking, and a turn arrow. Among the 88 boxes examined, all have colored pavement, and 87 (98.86%) boxes have a bicyclist stencil. The one missing the bicyclist stencil is located at the intersection of Park Dr. at Beacon St. in Boston. Additionally, four of the boxes lack a turn arrow. Two of these boxes are located at the same intersection in Boston (Columbus Ave. and Walnut Ave.), while the others are found in Somerville (Medford St. and Broadway) and Boston (Park Dr. at Beacon St.).

The NACTO Urban Bikeway Design Guide (*4*) identifies six configurations, five of which are observed for the 88 TSTQBs in this study; the only ones missing are the “T-Intersection Parking Lane” configuration; see Figure 4.5 for the distribution of TSTQB configurations in Massachusetts. The most prevalent configuration among TSTQBs is the crosswalk setback one (68.18%). The next two most common configurations are the cycle track buffer configuration (17.05%) and parking lane configuration (11.36%). Finally, there are only two instances of the T-intersection "jughandle" sidewalk configuration, one intersection with a bike box configuration, and no TSTQBs with the T-intersection parking lane configurations. The data also indicates that among less common configurations, Boston includes 60% of the TSTQB with the cycle track configuration, while Brookline presents the majority of the TSTQB with the parking lane configuration (i.e., 70% of all TSTQBs with that configuration). The two T-intersection configurations are located in two different cities: one in Boston and one in Cambridge. Additionally, the sole identified bike box configuration is located in Boston. Given Boston’s abundance of TSTQBs, it is reasonable that it exhibited the greatest diversity in terms of TSTQB configurations.

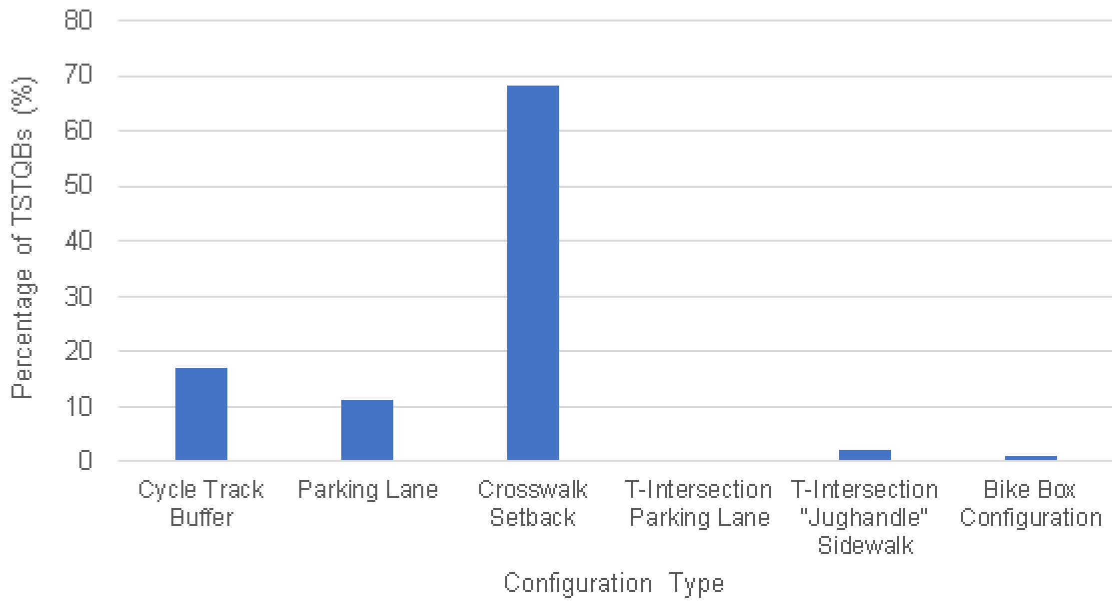


Figure 4.5: Distribution of TSTQB configurations in Massachusetts

Figure 4.6 shows the percentage of TSTQBs that are accompanied by certain types of bicycle treatments, such as conventional and protected bike lanes, both for the upstream approach where left-turning bicyclists come from and the downstream one they are supposed to end up on after completing their left turn. A high percentage (75%) of TSTQB approaches[1] feature any type of bike lane (i.e., conventional and protected) directly upstream, where only 9.09% of those bike lanes feature colored pavement. Notably, 38.64% of those approaches have protected bike lanes and 36.36% of those approaches have conventional bike lanes upstream, contrasting with previous studies on bike boxes where only 9% of the bike lanes upstream of bike boxes were separated (*13*). This could be explained by: 1) the timing of this study, which is a few years after previous studies that reported on these characteristics, and therefore, it is expected that more protected bike lanes are in place, and 2) the likelihood that protected bike lanes are more likely to be accompanied by TSTQBs at intersections to facilitate left-turning movement of bicyclists, who would otherwise have to exit the protected bike lane at the intersection approach and cross in front of potentially multiple lanes of traffic (*4*). For example, the 2020 Cycling Safety Ordinance in Cambridge, MA mandates that streets on the Cambridge Bicycle Plan build protected bike lanes when undergoing reconstruction according to the Five-Year Sidewalk and Street maintenance plan (*31*).

Fewer bike lanes are present downstream of TSTQB approaches (56.68%), yet a higher percentage of them features colored pavement (12.50%) compared to the bike lanes upstream of TSTQB approaches. Additionally, 21.59% of the bike lanes located on the downstream path of TSTQBs are protected and 34.09% of these bike lanes are conventional. In terms of sharrows, 18.18% are present downstream, compared to 15.91% upstream. These variations in bicycle infrastructure treatments are important considerations for bicyclist comfort and perceived safety, potentially impacting overall bicyclist demand levels and TSTQB utilization.

[1] A TSTQB approach is defined as the approach where the left-turning bicyclist using that TSTQB is expected to be coming from

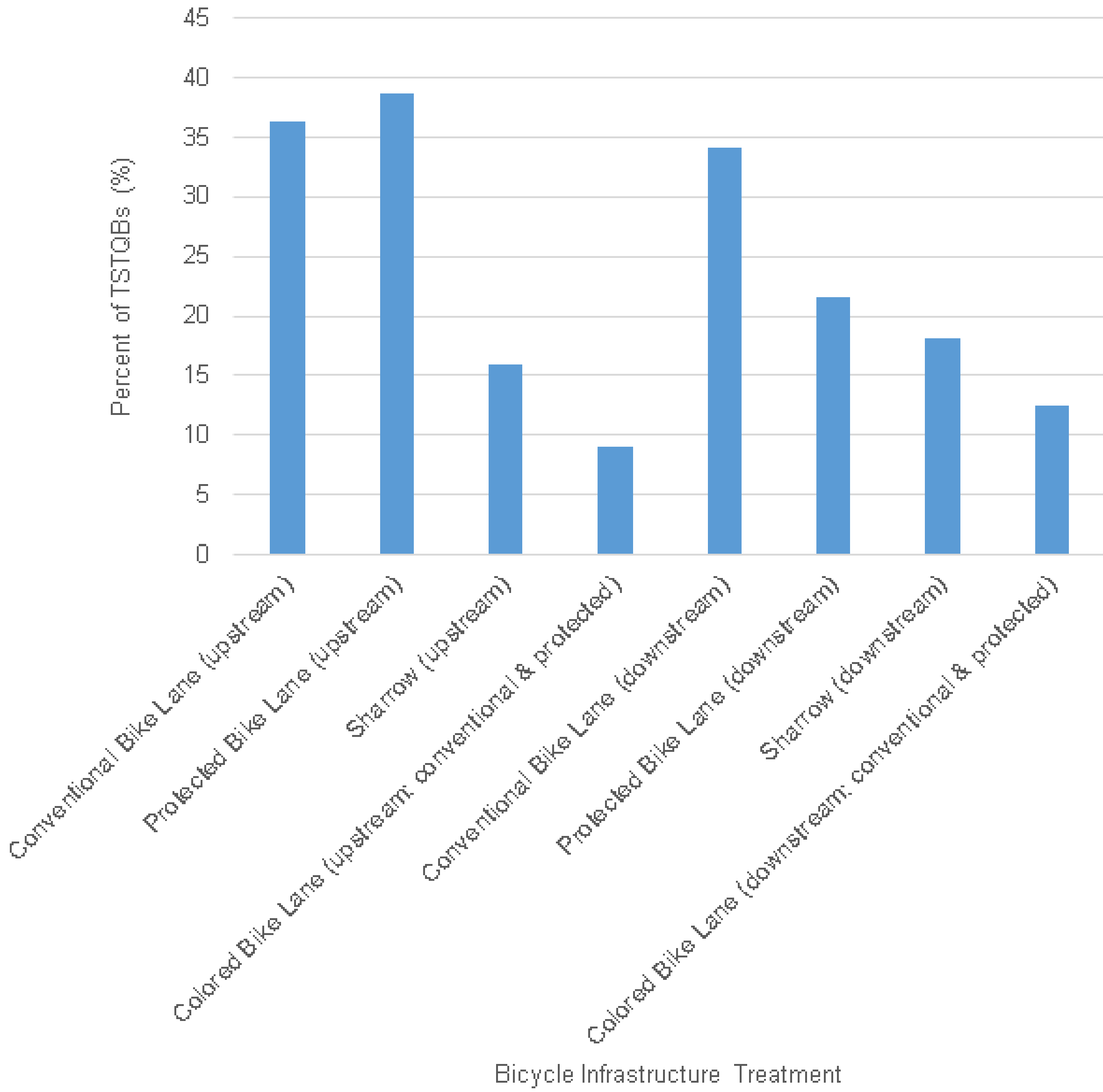


Figure 4.6: Percentage of TSTQB locations featuring various types of bicycle infrastructure treatments

Figure 4.7 provides information on the types of signage, signal control, and lane allocation to turning movements, accompanying TSTQB implementations and relevant approaches in Massachusetts. More specifically, the figure shows that 68.18% of TSTQB approaches feature a "No Turn on Red" sign, which complies with national guidebook requirements (*1*, *4*, *6*), 59.09% have dedicated left turn lanes, and 36.36% have dedicated left turn phases. In addition, only two TSTQBs with bike signals were found, both located in Cambridge. Approximately 7.95% of the TSTQB approaches feature TSTQB sign, with Somerville using their own customized sign instead of the one required by the MUTCD. One possible explanation could be the recent release of the new MUTCD (*1*), suggesting that it may take time for these signs to be implemented across the state.

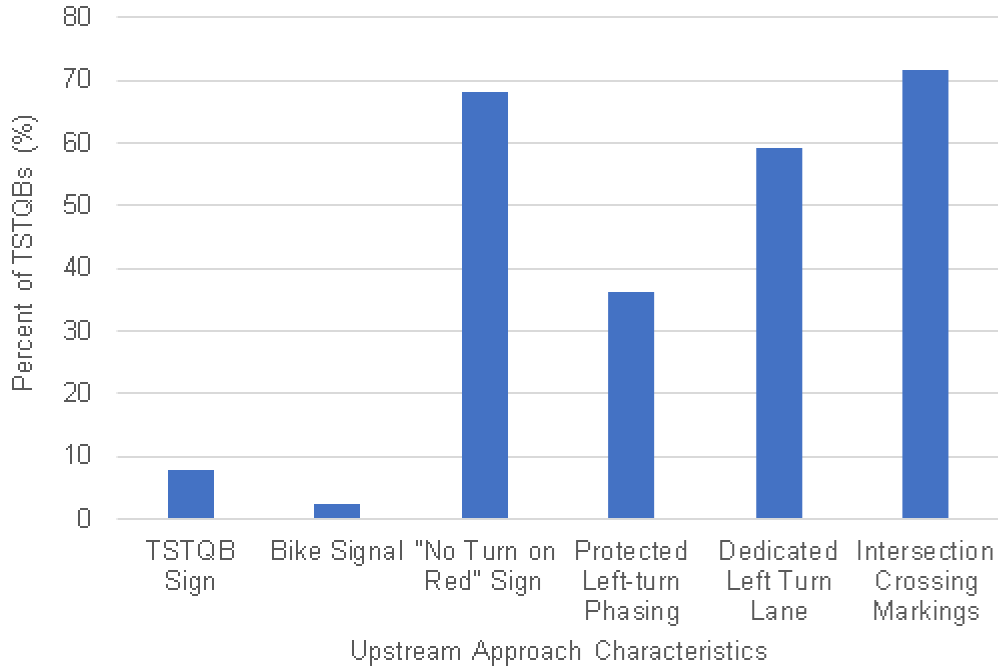


Figure 4.7: Percentage of TSTQBs featuring various types of signage, signal control, lane allocation, and pavement markings[2]

4.2 Behavior Analysis

4.2.1 Study Site Characteristics

A total of 16 TSTQBs exist within the six intersections. Out of these, data from only 14 were collected and analyzed, including at least one TSTQB at each of the six intersections. Figure 2.16 shows the selected TSTQBs for this study.

Table 4.3 summarizes the types of bicycle infrastructure treatments that are located on the upstream approaches of the TSTQB study sites. With the exception of Beacon St. at Harvard St. (EB-NB), Beacon St. at Harvard St. (NB-WB), and Park Dr. at Beacon St. (NB-WB), all other approaches feature bike lanes upstream. Among these, Park Dr. at Beacon St. (SB-EB), Park Dr. at Beacon St. (EB-NB), and Beacon St. at Park St. (SEB-NEB) have conventional colored bike lanes upstream, while Somerville Ave. & Prospect St. (SB-EB), and Somerville Ave. at Prospect St. (EB-NB) have protected bike lanes upstream. Conversely, Beacon St. at Harvard St. (EB-NB), Beacon St. at Harvard St. (NB-WB), and Park Dr. at Beacon St. (NB-WB) feature sharrows at their respective upstream approaches.

Table 4.4 presents the types of bicycle infrastructure treatments that are located on the downstream end of the path of a TSTQB user, showing that some feature downstream bike lanes and others not. Only one approach, Park Dr. at Beacon St. (NB-WB), includes a colored protected bike lane downstream. On the other hand, the Park Dr. at Beacon St. (SB-EB) TSTQB

[2] TSTQB sign includes guide signs that are both MUTCD compliant and others implemented before the new version of MUTCD was released.

features a conventional green colored bike lane downstream. Apart from this, Massachusetts Ave. at Columbus Ave. (NEB-NWB), Park Dr. at Beacon St. (NB-WB), and Somerville Ave. at Prospect St. (NB-WB) also have protected bike lanes downstream of the TSTQBs. However, the remaining approaches lack protected bike lanes. Additionally, Beacon St. at Harvard St. (NB-WB), Park Dr. at Beacon St. (WB-SB), and Beacon St. at Park St. (SEB-NEB) feature sharrows downstream of the TSTQBs.

Table 4.5 summarizes other characteristics related to the TSTQB approaches of the selected study sites. All approaches have either two or three upstream travel lanes except for the Beacon St. at Park St. (SEB-NEB) approach. Three of the approaches feature bike boxes in addition to being upstream of TSTQBs, namely the one at Beacon St. at Park St., and two at Park Dr. at Beacon St. Notably, only the Somerville Ave. at Prospect St. (SB-EB) and Somerville Ave. at Prospect St. (EB-NB) approaches present the cycle track configuration, while the other approaches feature either crosswalk setback or parking lane configurations. All TSTQB are uniformly green colored, accompanied by bicycle stencils and turn arrows, except for Park Dr. at Beacon St. (WB-SB), which lacks bicycle stencils and turn arrows. Additionally, excluding Park Dr. at Beacon St. (NB-WB) and Park Dr. at Beacon St. (SB-EB), "No Turn on Red" signs are present at all approaches. The presence of protected left-turn phasing and dedicated left turn lanes varies across approaches.

Table 4.3: Bicycle infrastructure treatments for the upstream approach of the TSTQB study sites

Approach	Conventional Bike Lane	Protected Bike Lane	Sharrow	Bike Lane Colored
Beacon St. at Harvard St. (EB-NB)	✗	✗	✓	✗
Beacon St. at Harvard St. (NB-WB)	✗	✗	✓	✗
Park Dr. at Beacon St. (WB-SB)	✗	✓	✗	✗
Park Dr. at Beacon St. (NB-WB)	✗	✗	✓	✗
Park Dr. at Beacon St. (SB-EB)	✓	✗	✗	✓
Park Dr. at Beacon St. (EB-NB)	✓	✗	✗	✓
Massachusetts Ave. at Columbus Ave. (NEB-NWB)	✓	✗	✗	✗
Massachusetts Ave. at Columbus Ave. (SWB-SEB)	✓	✗	✗	✗
Washington St. at Massachusetts Ave. (SEB-NEB)	✓	✗	✗	✗
Washington St. at Massachusetts Ave. (NWB-SWB)	✓	✗	✗	✗
Somerville Ave. at Prospect St. (NB-WB)	✓	✗	✗	✗
Somerville Ave. at Prospect St. (SB-EB)	✗	✓	✗	✗
Somerville Ave. at Prospect St. (EB-NB)	✗	✓	✗	✗
Beacon St. at Park St. (SEB-NEB)	✓	✗	✗	✓

Table 4.4: Bicycle infrastructure treatments for the downstream approach of the TSTQB study sites

Approach	Conventional Bike Lane	Separated Bike Lane	Sharrow	Bike Lane Colored
Beacon St. at Harvard St. (EB-NB)	✓	✗	✗	✗
Beacon St. at Harvard St. (NB-WB)	✗	✗	✓	✗
Park Dr. at Beacon St. (WB-SB)	✗	✗	✓	✗
Park Dr. at Beacon St. (NB-WB)	✗	✓	✗	✓
Park Dr. at Beacon St. (SB-EB)	✓	✗	✗	✓
Park Dr. at Beacon St. (EB-NB)	✓	✗	✗	✗
Massachusetts Ave. at Columbus Ave. (NEB-NWB)	✗	✓	✗	✗
Massachusetts Ave. at Columbus Ave. (SWB-SEB)	✓	✗	✗	✗
Washington St. at Massachusetts Ave. (SEB-NEB)	✓[3]	✗	✗	✓[4]
Washington St. at Massachusetts Ave. (NWB-SWB)	✗	✗	✗	✗
Somerville Ave. at Prospect St. (NB-WB)	✗	✓	✗	✗
Somerville Ave. at Prospect St. (SB-EB)	✗	✓	✗	✗
Somerville Ave. at Prospect St. (EB-NB)	✓	✗	✗	✗
Beacon St. at Park St. (SEB-NEB)	✗	✗	✓	✗

[3] Bike Bus Lane

[4] Red Color

Table 4.5: TSTQB approach characteristics

Approach	Configuration (NACTO)	Number of Travel Lanes on the TSTQB Approach	Bike Box	Bicycle Stencil and Turn Arrow	Green Colored Pavement	Protected Left-turn Phasing	Dedicated Left Turn Lane	"No Turn on Red" Sign	Intersection Crossing Markings
Beacon St. at Harvard St. (EB-NB)	Parking Lane	3	✗	✓	✓	✗	✗	✓	✗
Beacon St. at Harvard St. (NB-WB)	Parking Lane	2	✗	✓	✓	✗	✗	✓	✗
Park Dr. at Beacon St. (WB-SB)	Crosswalk Setback	3	✓	✗	✓	✓	✓	✓	✓
Park Dr. at Beacon St. (NB-WB)	Crosswalk Setback	3	✓	✓	✓	✓	✓	✗	✓
Park Dr. at Beacon St. (SB-EB)	Crosswalk Setback	2	✗	✓	✓	✗	✗	✗	✓
Park Dr. at Beacon St. (EB-NB)	Crosswalk Setback	3	✗	✓	✓	✗	✗	✓	✓
Massachusetts Ave. at Columbus Ave. (NEB-NWB)	Parking Lane	2	✗	✓	✓	✓	✓	✓	✓
Massachusetts Ave. at Columbus Ave. (SWB-SEB)	Crosswalk Setback	2	✗	✓	✓	✓	✓	✓	✓
Washington St. at Massachusetts Ave. (SEB-NEB)	Crosswalk Setback	3	✗	✓	✓	✓	✓	✓	✓
Washington St. at Massachusetts Ave. (NWB-SWB)	Crosswalk Setback	3	✗	✓	✓	✓	✓	✓	✓
Somerville Ave. at Prospect St. (NB-WB)	Crosswalk Setback	2	✗	✓	✓	✗	✓	✓	✓
Somerville Ave. at Prospect St. (SB-EB)	Cycle Track Buffer	2	✗	✓	✓	✗	✗	✓	✓
Somerville Ave. at Prospect St. (EB-NB)	Cycle Track Buffer	2	✗	✓	✓	✗	✓	✓	✓
Beacon St. at Park St. (SEB-NEB)	Crosswalk Setback	1	✓	✓	✓	✗	✗	✓	✓

4.2.2 Left-Turning Bicyclist Behavior Observations

Throughout the data collection period, a total of 8,682 bicyclists were observed from the 20 approaches (14 TSTQB approaches and 6 control approaches) completing all types of movements at the intersection. Figure 4.8presents the distribution of these bicyclists across all 20 approaches. The highest proportion of bicyclists was found at the Beacon St. at Park St. (NWB-SWB) approach, which is a control approach, accounting for 17.07% of all bicyclists. Conversely, the lowest proportion was recorded at the Washington St. at Massachusetts Ave. (SWB-SEB) approach, which is also a control approach, representing only 1.88% of the observed during this field study bicyclists. When focusing on TSTQB approaches, the highest percentage of bicyclists was found at Somerville Ave. at Prospect St. (SB-EB) (8.57%) and the lowest at Park Dr. at Beacon St. (SB-EB) (2.42%). It should be noted that various factors could influence the number of bicyclists, including weather conditions, seasonal changes, and the day of data collection.

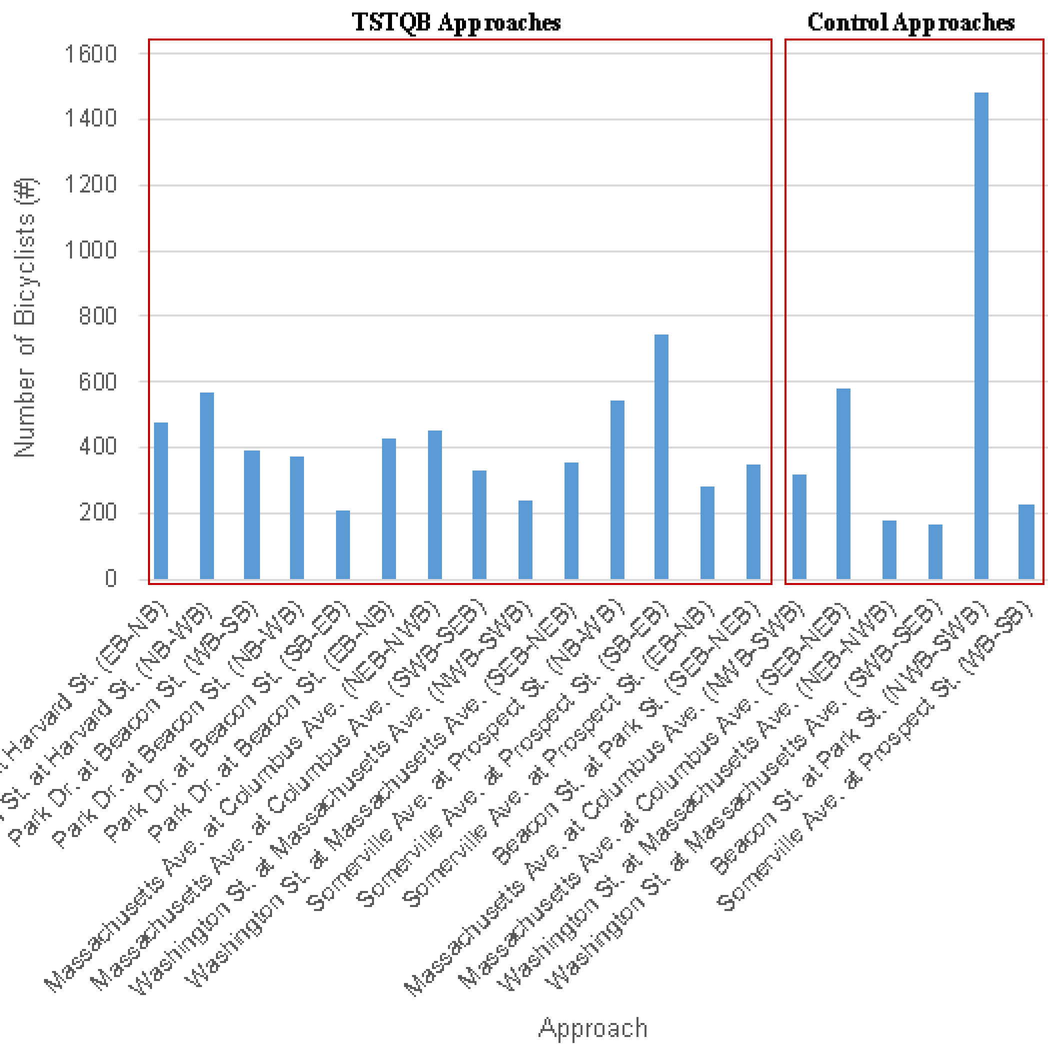


Figure 4.8: Bicyclists' distribution across study sites

Figure 4.9 shows the distribution of turning movements observed from the 20 different study approaches (14 TSTQB approaches and 6 control approaches). Except for the Somerville Ave. at Prospect St. (SB-EB) and Somerville Ave. at Prospect St. (EB-NB) approaches, the highest proportion of bicyclists at all other approaches were observed to perform through movements. Specifically, Beacon St. at Park St. (SEB-NEB) had the highest (93.71%) proportion of through bicyclists, while Somerville Ave. at Prospect St. (EB-NB) had the lowest (39.72%). Regarding right-turning movements, Somerville Ave. at Prospect St. (SB-EB) had the highest proportion (50.54%), whereas Somerville Ave. at Prospect St. (WB-SB) had the lowest (2.68%). As for left-turning movements, Somerville Ave. at Prospect St. (EB-NB) had the highest proportion (49.65%), which is the highest from that approach for any turning movement, while Somerville Ave. at Prospect St. (SB-EB) had the lowest (0.40%). Only for the Massachusetts Ave. at Columbus Ave. (NEB-NWB) approach, the proportion of through movement (50.33%) closely approximates the proportion of left-turning movement (41.24%). For the other approaches, the proportions of through and left-turning movements vary significantly. Regarding control approaches, the Washington St. at Massachusetts Ave. (NEB-NWB) approach had the highest percentage (27.27%) of left-turning bicyclists (27.27%), followed by Somerville Ave. at Prospect St. (WB-SB) with the second highest percentage (20.54%). In a comparative analysis, at the Washington St. at Massachusetts Ave. intersection, a greater percentage of bicyclists (12.88% and 27.27%) performed left turns from the control approaches compared to the TSTQB approaches (2.90% and 24.65%). At the Somerville Ave. at Prospect St. intersection, having three TSTQB approaches and only one approach without a TSTQB, 20.54% of bicyclists made left turns from the control approach versus 0.40%-49.65% from the three TSTQB approaches. The underlying factors influencing this turning behavior may include road layout, land use, and the origin-destination of the bicyclists.

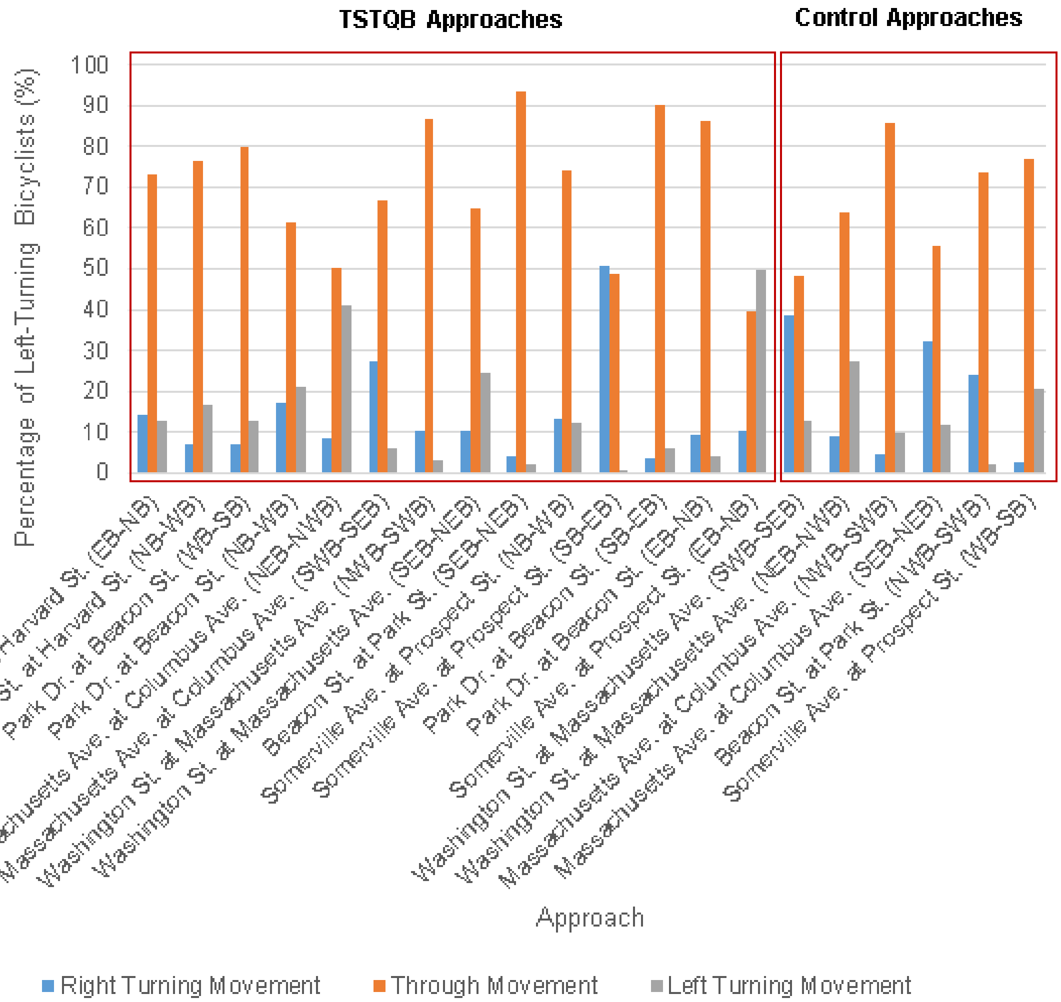


Figure 4.9: Bicyclists' turning movement distribution

Figure 4.10 presents the distribution of left-turning behavior for bicyclists coming from both control (no TSTQB) and TSTQB approaches. As shown on the Figure the majority of bicyclists are opting for the conventional left turn form both types of approaches, likely due to the presence of dedicated left turn lanes and protected left turn phases in many of the studies approaches. The higher percentage of bicyclists using the conventional left turn at TSTQB approaches compared to control approaches (56.18% vs 46.03%) could be attributed to the fact that often TSTQB are located at approaches that lack left-turn lanes or protected left-turn phasing. The second most used method is utilizing the crosswalk, which may be because bicyclists feel safer avoiding traffic conflicts by using the crosswalk. The lower percentage of sidewalk usage for the TSTQB approaches compared to control approaches (34.26% vs 28.49%) could be attributed to the provision of an alternative safe way to complete the left turn when using the TSTQB that deters them from using the sidewalk. The third most common way is the two-stage maneuver with a slightly higher usage among bicyclists from the TSTQB approaches (10.46%) compared to control approaches (9.56%). TSTQB usage ranks fourth for the corresponding approaches. In addition, more cyclists use the TSTQB (11.90%) compared to the two-stage maneuver (10.46%) at TSTQB approaches.

Finally, the least used maneuver type is the bike box (3.13%); this is likely driven by the fact that only three approaches had bike boxes present.

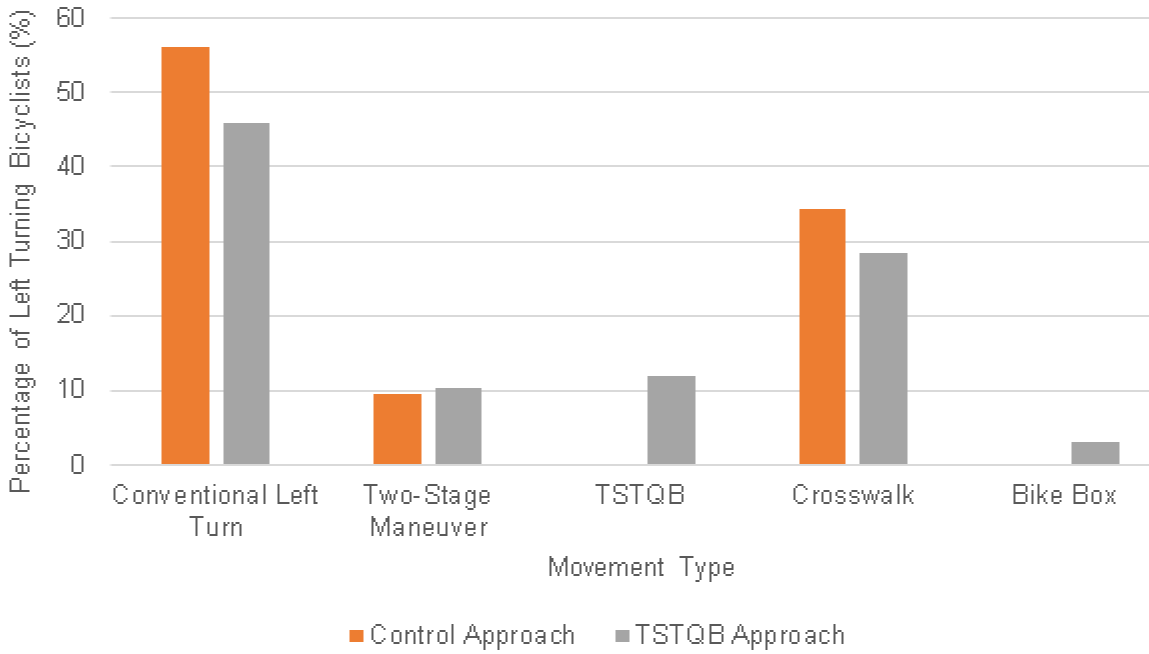


Figure 4.10: Bicyclists' left-turning behavior distribution

Figure 4.11 presents the distribution of upstream infrastructure use among left-turning bicyclists, considering both control and TSTQB approaches. The data shows that most bicyclists utilized the upstream left-turn lane before executing their turn, with higher usage among those from the control approach compared to the TSTQB approaches (41.43% vs 33.77%), likely due to the absence of TSTQBs in those approaches. Additionally, some approaches (control and TSTQB ones) feature a protected left turn phase, which could have motivated the use of the left turn lane. The figure also reveals that bicyclists from the TSTQB approaches used the right turn/through lane more compared to those from the control approaches (25.84% vs 10.76%). This is surprising because most of the TSTQB approaches are accompanied by either conventional or protected bike lanes, which provide a smooth transition for bicyclists to the TSTQBs. In terms of bike lanes, more bicyclists used the conventional bike lanes (19.71%) compared to the protected bike lanes (8.77%) from TSTQB approaches. This is reasonable as most of the TSTQBs in the studied areas had conventional bike lanes. Conversely, for control approaches, more bicyclists used protected bike lanes (22.31%) compared to the conventional bike lanes (14.34%), despite the greater presence of conventional bike lanes at those approaches. Sidewalk usage appears to be similar for control and TSTQB approaches. When a bicyclist comes from the sidewalk, it is easier for them to use the crosswalk directly from the sidewalk to perform the left turn maneuver compared to moving to any other lanes. The fact that even though the upstream sidewalk use percentages are similar for both control and TSTQBs, the TSTQB approaches saw a lower percentage of crosswalk use for completing the left turns, could be an indication that the presence of TSTQBs reduces crosswalk use.

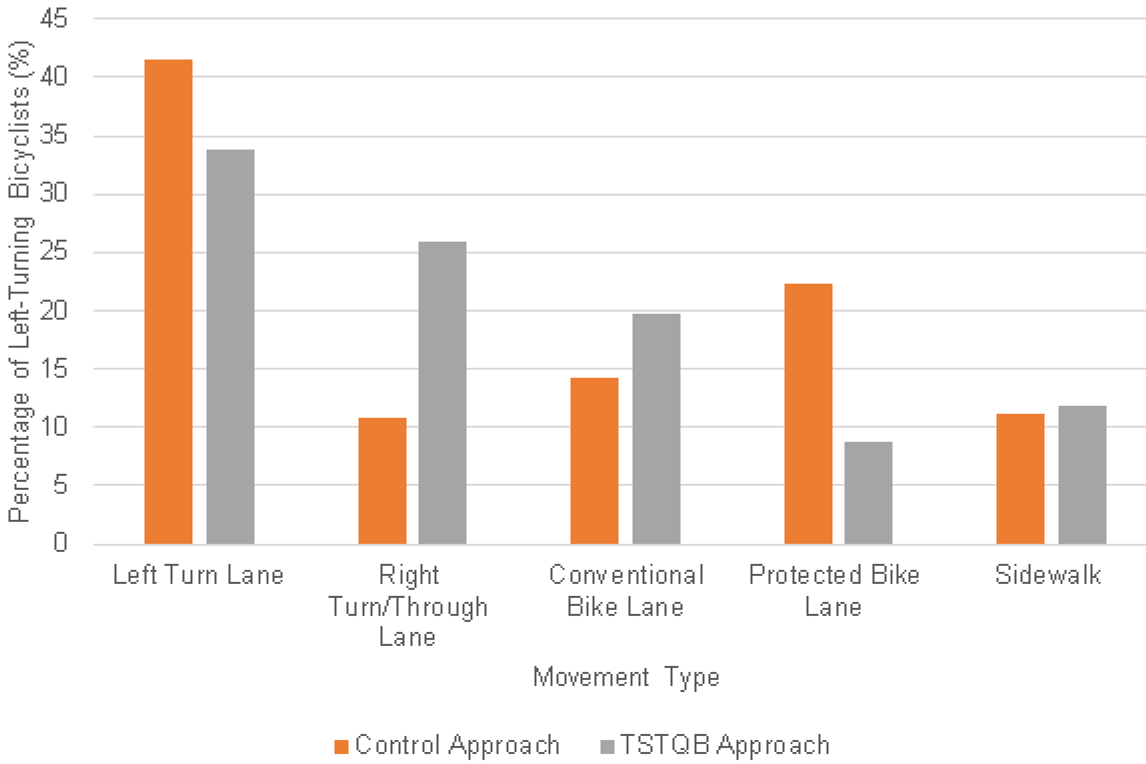


Figure 4.11: Bicyclists' upstream lanes for all approaches

Figure 4.12 illustrates the distribution of downstream infrastructure usage among left-turning bicyclists, post-maneuver, considering both control and TSTQB approaches. The majority (39.61%) of bicyclists utilized the right turn/through lane after completing their left turn regardless of whether they were coming from a TSTQB approach or a control one. The conventional bike lane was the second most used, with a higher percentage of bicyclists coming from control approaches using it compared to left-turning bicyclists coming from TSTQB approaches (37.85% vs 29.21%). Interestingly, a higher proportion of bicyclists (15.14%) used the sidewalk compared to protected bike lanes (14.04%), likely due to the limited availability of protected bike lanes downstream of the approaches.

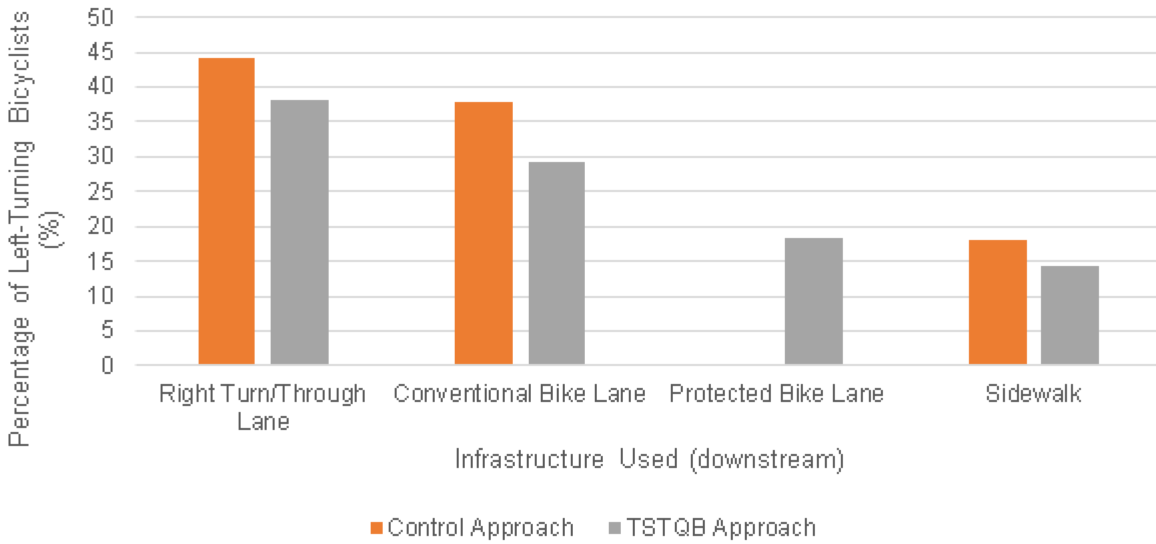


Figure 4.12: Bicyclists' downstream lanes for all approaches

Figure 4.13 shows the utilization of upstream dedicated bike infrastructure (i.e., conventional and protected bike lanes) for only those left-turning bicyclists that utilize the TSTQB. The results show that when conventional bike lanes are present, the percent of TSTQB users utilizing the bike lane varies from 50% to 100%, indicating bicyclists could be approaching the TSTQB from other lanes or even the sidewalk. In the case of protected bike lanes, when there are TSTQB users 100% of them travels on the protected bike lane upstream, indicating some correlation between the presence of a protected bike lane and the use of TSTQBs. It should be noted that the Somerville Ave. at Prospect St. (SB-EB) approach 100% of the left-turning bicyclists used the crosswalk, potentially due to the design of that protected bike lane at the intersection.

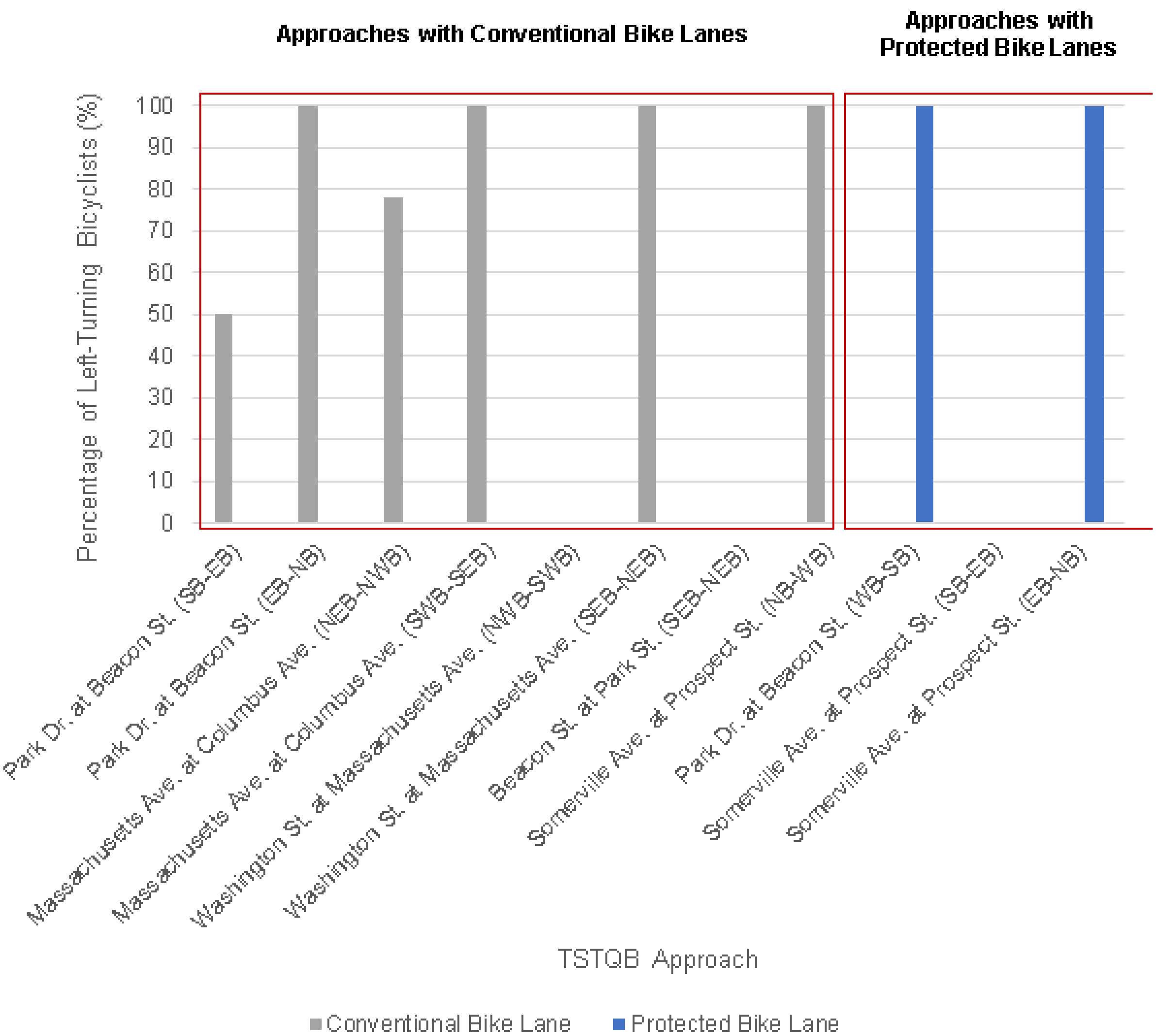


Figure 4.13: Upstream bike lane usage of left-turning bicyclists using TSTQBs

Figure 4.14 provides a detailed illustration of the way bicyclists complete their left-turning movements at the selected study sites for individual TSTQB approaches. Figure 4.15 presents a detailed illustration of how bicyclists complete their left-turning movements from the control approaches. Figure 4.16 and Figure 4.17 show the bicycle infrastructure treatment type used by left-turning bicyclists upstream and downstream of the selected TSTQBs. The rest of this section presents a detailed description of left-turning bicyclist behavior for each of the studied TSTQBs and adjacent control approaches.

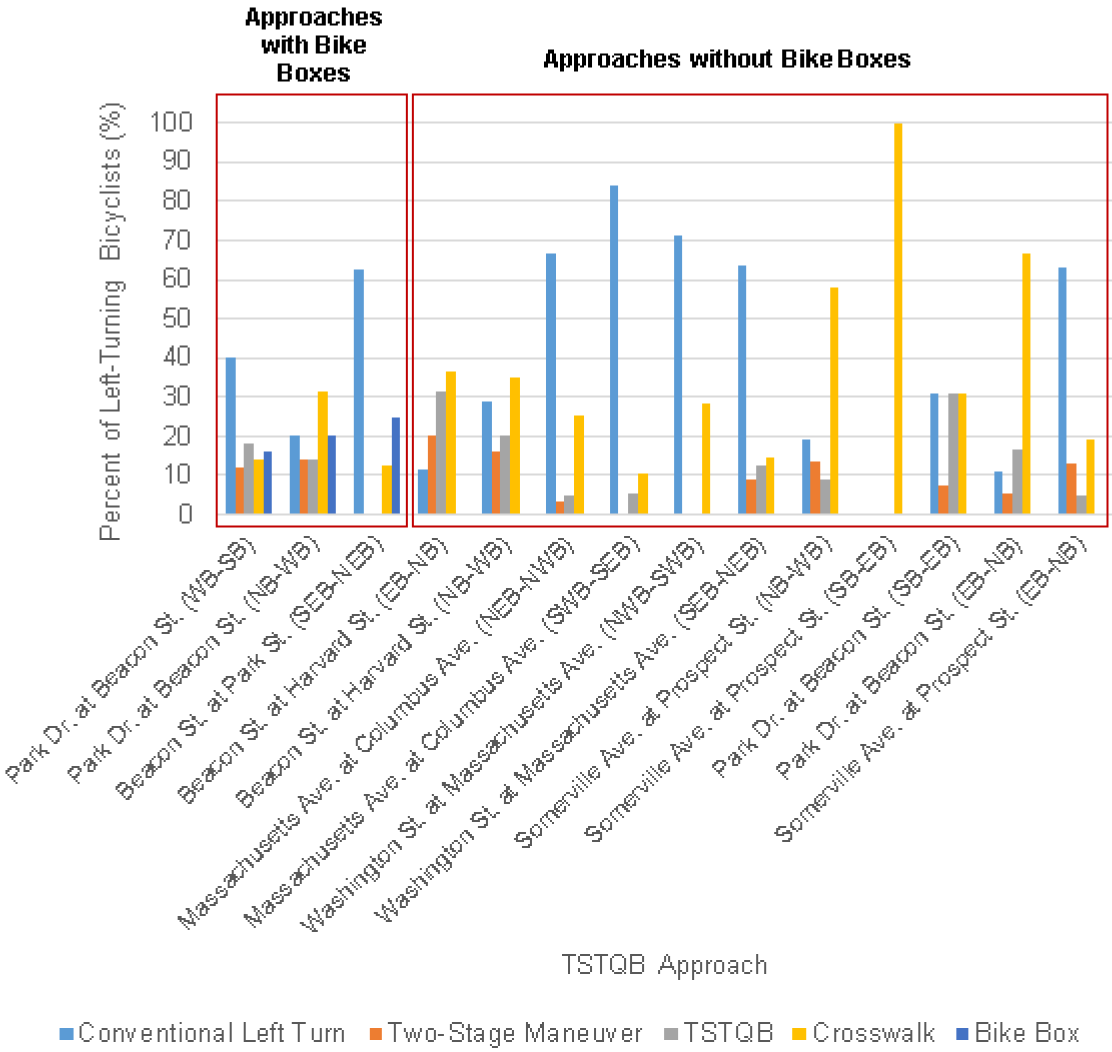


Figure 4.14: Bicyclists' left-turning movement distribution by TSTQB approach

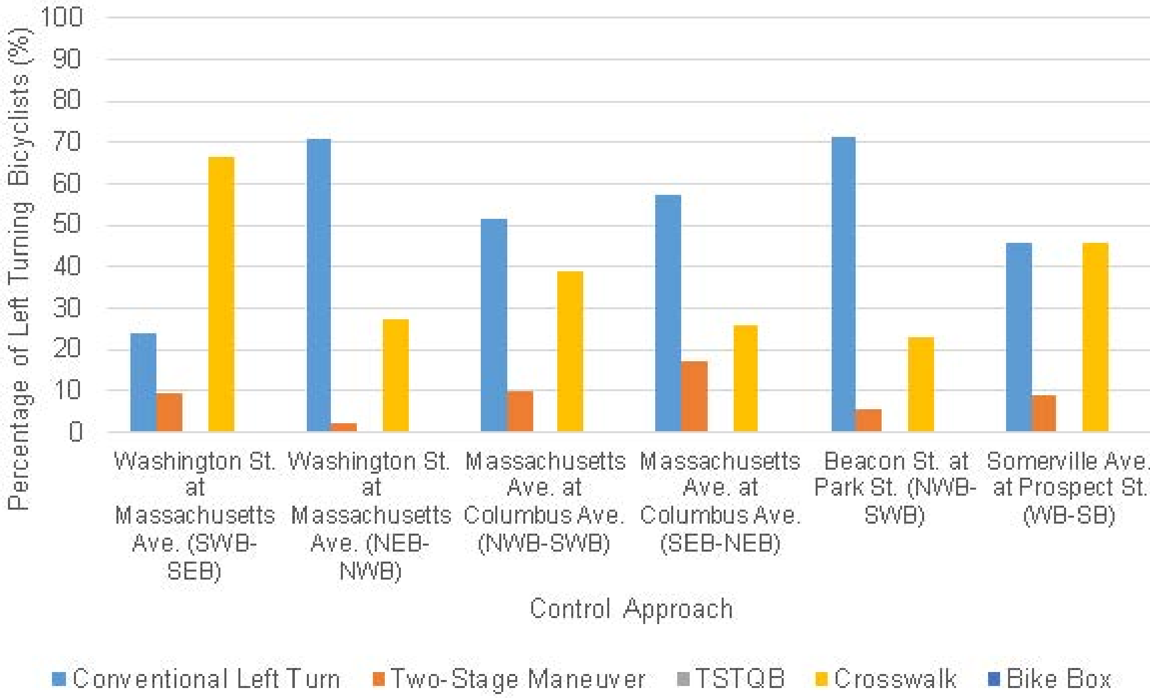


Figure 4.15: Bicyclists' left-turning movement distribution by control approach

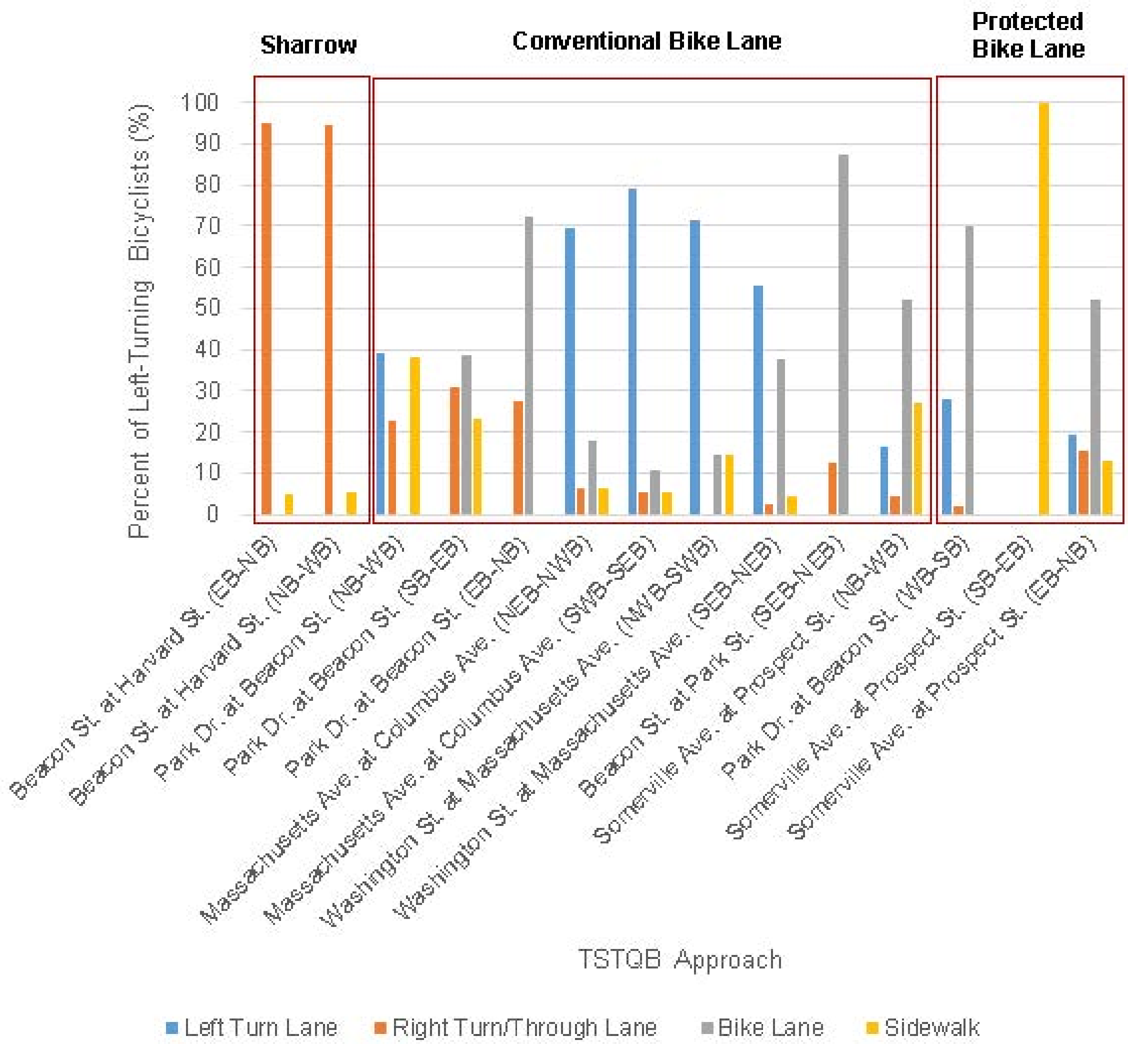


Figure 4.16: Bicycle infrastructure treatment usage upstream of TSTQBs by approach

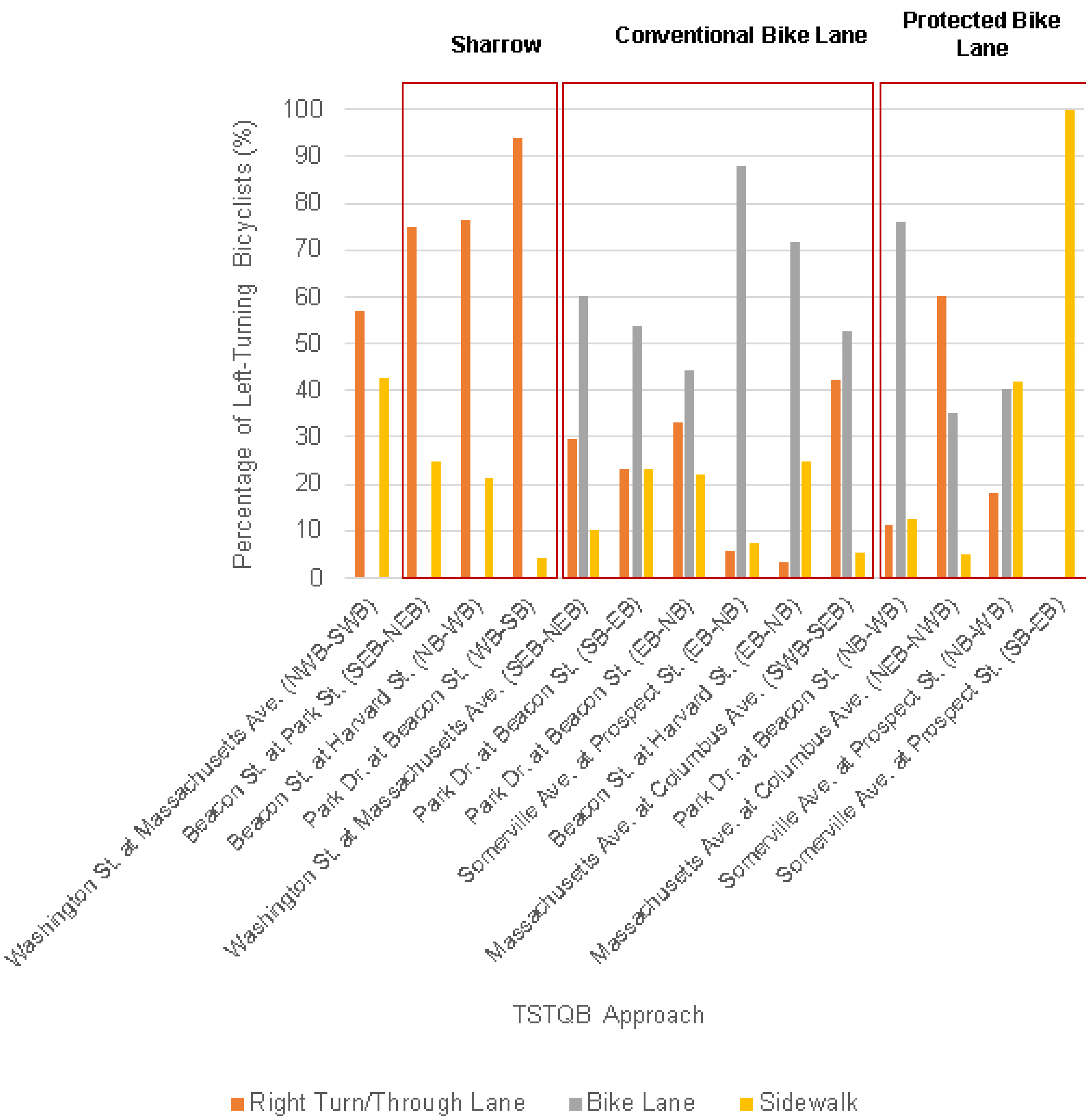


Figure 4.17: Bicycle infrastructure treatment usage downstream of TSTQBs by approach

1. Beacon Street at Harvard Street, Brookline

Despite left turns being prohibited from the EB-NB and NB-WB approaches, 11.67% of bicyclists still performed the conventional left turn movement from the EB-NB approach and 28.72% bicyclists from the NB-WB approach. Notably, 36.67% and 35.11% of bicyclists from those two approaches respectively utilized the crosswalk for their left-turning movements. This behavior may be attributed to the unique intersection layout, featuring a MBTA T line passing through in the East-West direction.

The second-highest percent of left-turning behavior involved the use of TSTQBs (31.67%) at the EB-NB approach. This percentage was the highest observed across all TSTQBs. In addition, 20.09% of bicyclists executed the two-stage maneuver without utilizing the TSTQB (see Figure 2.15(b)) at the same approach. At the same time, these percentages of TSTQB and two-stage maneuvers without use of the TSTQB was 20.21% and 15.96% respectively for the EB-NB TSTQB at the same intersection.

In terms of infrastructure utilization upstream and downstream of the TSTQB, 95% and 94.68% of left-turning bicyclists from the EB-NB and NB-WB TSTQB approaches respectively utilized the Right Turn/Through Lane upstream as they were approaching the intersection, which includes a sharrow. Conversely, downstream, 71.67% of bicyclists that had completed the left turn from Beacon St. at Harvard St. (EB-NB) approach utilized the conventional bike lane. No bike lane is present downstream of the NB-WB TSTQB; most of the left-turning bicyclists utilized the travel lane downstream (76.60%). Additionally, the sidewalk saw the second-highest usage for both upstream and downstream, with percentages of 5% and 25%, respectively for the Beacon St. at Harvard St. (EB-NB) approach, and 5.13% and 21.28% respectively for the Beacon St. at Harvard St. (NB-WB) approach.

2. Park Drive at Beacon Street, Boston

At the Park Dr. and Beacon St. intersection, most bicyclists opted for conventional left turn maneuvers when traveling the WB-SB approach (40.00%), which was the highest percentage of such a maneuver among all approaches. Conversely, the EB-NB approach had the lowest percentage of bicyclists making conventional left turns (11.11%) across all approaches. From the EB-NB approach, the highest percentage of left-turning bicyclists (66.67%) used the crosswalk. The WB-SB approach saw a 14% using the crosswalk, which is the lowest for all approaches at that intersection.

The usage of TSTQBs was high for the SB-EB approach (30.77%), whereas the lowest TSTQB usage at that intersection was observed on the NB-WB approach (13.92%). The WB-SB and NB-WB approaches also feature bike boxes, potentially motivating some left-turning bicyclists that would have utilized the TSTQB to stay on that approach and complete their left turn using the bike box. Bike box usage was 20.25% of the left-turning bicyclists for the NB-WB approach and 16.00% for the WB-SB one. Lastly, a notable portion of bicyclists performed the two-stage maneuver, with the NB-WB exhibiting the highest percentage (13.92%) and the EB-NB approach the lowest (5.56%) at that intersection. The fact that the highest percentage of left-turning bicyclists using TSTQBs is observed for the SB-EB approach, could potentially be related to the fact that the specific TSTQB is located out of the path of the right-turning movement, therefore, improving its perceived safety. The lack of bike box on that approach compared to the other two could also be a contributing factor to this high percentage.

On the WB-SB approach, most bicyclists (70%) used the protected bike lane upstream, while 28.57% used the left turn lane. Conversely, on the NB-WB approach, 39.24% of bicyclists used the left turn lane upstream, and 37.97% used the sidewalk, possible due to the presence of a sharrow versus a dedicated bike lane. The EB-NB and SB-EB approaches showed that 72.22% and 38.46% of bicyclists used the conventional bike lane upstream, with no bicyclists using the left turn lane, which is reasonable as these approaches do not have any dedicated left turn lanes.

On the WB-SB approach at Park Dr. and Beacon St., 94% of bicyclists used the right turn/through lane downstream, with only 4.08% using the sidewalk; note that there is no sidewalk downstream. For the NB-WB approach, 75.95% utilized the protected bike lane, while 12.66% used the sidewalk. The SB-EB approach saw 53.85% of bicyclists in the protected bike lane and an equal 23.08% using the right turn/through lane and sidewalk. On the EB-NB approach, 44.44% used the conventional bike lane that is available at the beginning of the downstream link, 33.33% the right turn/through lane, and 22.22% the sidewalk.

Notably, 15.38% and 14.65% of the left-turning bicyclists from the WB and EB approaches used the TSTQB in front of their approach as bike box before making any turning movement.

3. Massachusetts Avenue at Columbus Avenue, Boston

At this intersection, most left-turning bicyclists chose "Conventional Left Turn" maneuvers from both the NEB-NWB approach (66.67%) and the SWB-SEB approach (84.21%). Additionally, 69.35% of left-turning bicyclists from the NEB-NWB approach and 78.95% from the SWB-SEB approach used the left-turn lane upstream to complete their turns, which was the highest observed proportion across all approaches that featured one. This preference is likely due to the presence of dedicated left-turn lanes and protected left-turn phases at those two approaches. The second most common type of left turn was using the crosswalk, accounting for 25.27% for the NEB-NWB and 10.53% for the SWB-SEB approaches. The utilization of TSTQBs ranked third for both approaches at 4.84% for the NEB-NWB and 5.26% for the SWB-SEB approaches. These utilizations were some of the lowest ones across all study approaches most likely due to the presence of dedicated left-turn lanes and phases as mentioned above.

Two-stage maneuvers without the use of the TSTQB were infrequent for the NEW-NWB approach and non-existent in the sample for the SWB-SEB approach.

As expected, based on the results presented so far, most left-turning bicyclists utilized the left-turn lane prior to completing the left turn (69.35% for the NEB-NWB and 78.95% for the SWB-SEB approaches) with bike lanes being the second highest choice of infrastructure used upstream for both approaches but at much lower percentages 17.14% for the NEB-NWB and 10.53% for the SWB-SEB approaches).

While bike lanes are available downstream of both approaches, bicyclists from the NEB-NWB approach favored the right turn/through lane more (60.22%) than those from the SWB-SEB approach (42.11%). Conversely, bicyclists from the SWB-SEB approach utilized the bike lane the most (52.63% vs 34.95% for the NEB-NWB). This might be because the bike lane downstream of the NEB-NWB TSTQB is a buffered one for a few feet before being converted to a conventional one, potentially requiring left-turning bicyclists (especially those completing conventional left turns) to perform a wider turn to end up on the bike lane.

On the other hand, the control approach (NWB-SWB) saw 51.61% of left-turning bicyclists performing a conventional left turn, with 38.71% using the crosswalk and 9.68% opting for a two-stage maneuver. Similarly, at the control approach (SEB-NEB), 57.14% of bicyclists made a standard left turn, 25.71% used the crosswalk, and 17.14% performed a two-stage maneuver. The proportion of left-turning bicyclists using the crosswalk and two-stage maneuver is quite high indicating the likely need for TSTQBs at those approaches.

4. Washington Street at Massachusetts Avenue, Boston

Washington St. and Massachusetts Ave. intersection, presents two TSTQB approaches (NWB-SWB and SEB-NEB). Most left-turning bicyclists opted for "Conventional Left Turn" maneuvers for both the NWB-SWB approach (71.43%) and the SEB-NEB approach (63.64%). None of the bicyclists from the NWB-SWB approach utilized the TSTQB or performed a two-stage maneuver for their left-turning movement. This could be attributed to the fact that on the day of data collection this approach experienced a very low left-turning bicyclist demand in addition to the presence of a dedicated left-lane and dedicated left turn signal phasing. Additionally, 28.57% of bicyclists for the NWB-SWB approach and 14.77% for the SEB-NEB approach used the crosswalk for their left-turning movement, ranking as the second highest choice at both of those approaches. For the SEB-NEB approach, the usage of the TSTQB ranked as the third highest (12.50%) among all other ways for completing a left turn potentially to the low visibility of the TSTQB from the upstream approach and the presence of a dedicated left-turn lane.

Given the high percentage of conventional left turn maneuvers, it should be no surprise that 71.43% of bicyclists for the NWB-SWB approach and 55.68% for the SEB-NEB approach used the left-turn lane upstream. As explained earlier this may be attributed to the presence of dedicated left-turn lanes and protected left-turn phases. Using the bike lane upstream ranked as the second highest choice for the SEB-NEB (37.50%) and shared the second place along with the use of sidewalk for the NWB-SWB approach (14.29%).

Most of the left-turning bicyclists utilized the right/through lanes with 57.14% for the NWB-SWB and 29.35% for the SEB-NEB approaches. In addition, a significant 42.86% of left-turning bicyclists for the NWB-SWB approach used the sidewalk downstream after completing their left turning movement possibly to avoid bus traffic on the right most lane. Note that the downstream approach for the NWB-SWB TSTQB features a right most lane that becomes a bus/bike lane further downstream. However, due to the fact that it is not marked as such right downstream of the TSTQB approach and it does not feature colored pavement, in this study it was considered a regular travel lane for the purposes of tracking utilization by left-turning bicyclists. Notably, a high 60.23% of left-turning bicyclists from the SEB-NEB TSTQB approach is using the bus/bike lane. It is likely that left-turning bicyclists are more aware of its existence and feel more comfortable using it due to the unique aspects of accommodating both buses and bikes and its related wider lane and alternate color (i.e., red).

On the other hand, the SWB-SEB control approach had most left-turning bicyclists (66.67%) using the crosswalk, while 23.81% made conventional left turns, and 9.52% performed a two-stage maneuver. At the other control approach (NEB-NWB), 70.83% of bicyclists opted for conventional left turns, and 27.08% used the crosswalk, with only 2.08% performing a two-stage maneuver. Notably, 15.91% of left-turning bicyclists at the NEB-NWB approach used the TSTQB in front of their approach as bike box, possible due to its placement right in front of the bike lane.

5. Beacon Street at Park Street, Somerville

Both bike boxes and TSTQBs are present at this intersection for the SEB-NEB approach. The proportion of left-turning bicyclists from the SEB-NEB approach is notably low, with the majority (62.50%) opting for the conventional left-turn movement, followed by utilizing the bike box (25%) and the crosswalk (13.92%). None of the bicyclists were recorded using the TSTQB from this approach. This might be related to the fact that the TSTQB, while having a crosswalk setback configuration like other TSTQBs included in the study site, is located outside of the path of bicyclists when moving through the intersection from the SEB approach. This placement is possibly due to the widening of the road downstream. As a result, it is possible that the TSTQB is not visible to a bicyclist approaching the intersection from the SEB approach.

In terms of upstream bike infrastructure, 87.5% of all left-turning bicyclists utilized the conventional bike lane and 25% the crosswalk at the downstream end of their left turn.

The control approach (NWB-SWB) showed that the vast majority of left-turning bicyclists (71.43%) opted for conventional left turns. Additionally, 22.86% of the left-turning bicyclists used the crosswalk, while 5.71% performed a two-stage maneuver at that control approach.

6. Somerville Avenue at Prospect Street, Somerville

At this intersection, most left-turning bicyclists utilized the crosswalk for their left-turning maneuvers, accounting for 58.21% from the NB-WB approach and 100% from the SB-EB approach, while most bicyclists opted for conventional left turns for the EB-NB approach. The left-turning behavior for the SB-EB approach could be attributed to the fact that all left-turning bicyclists used the sidewalk upstream. The second most common left-turning movement type from the NB-WB approach was “Conventional Left Turn” at 19.40%, with the use of the TSTQB being the least common at 8.96% of the left-turning bicyclists possibly due to the TSTQB positioning. Despite the presence of a TSTQB for the EB-NB approach, only 5% of left-turning bicyclists used the TSTQB while a higher 12.86% of them performed the two-stage maneuver. This could be attributed to the fact the TSTQB is located outside of the straight path coming from the protected bike lane upstream.

Most left-turning bicyclists from the NB-WB approach (52.24%) utilized the conventional bike lane before making the left turn. In addition, most left-turning bicyclists entered the sidewalk downstream (41.79%). The second most utilized infrastructure type upstream for the NB-WB approach was the sidewalk (26.87%). For the SB-EB approach, all bicyclists used the sidewalk both upstream and downstream, possibly due to the bicyclist origin-destination location. For EB-NB approach, the highest proportion of left-turning bicyclists used the protected bike lane upstream (52.14%) and the conventional bike lane downstream (87.88%).

For the only control approach at this intersection, the WB-SB approach, the majority of bicyclists utilized either the "Conventional Left Turn" maneuver or the crosswalk, each accounting for 45.65%. A smaller portion of left-turning bicyclists (8.70%) performed a two-stage maneuver.

4.2.3 Hypotheses Testing

This section presents the results of the statistical testing of the hypotheses presented in the Research Methodology Chapter. Two Proportion z-tests were conducted with a confidence interval set at 95%. The two-proportion z-test was chosen because it is suitable for testing the statistical significance of the differences between two proportions, for example, for this study, percentage of left-turning bicyclists that utilized the TSTQB. The condition for using this test is that the proportions come from two independent populations and that data in each group come from a random sample of the population. The independence of the populations is guaranteed since the data used for these tests have been obtained from different approaches.

In addition, the researchers assume that samples from the same approach are random, i.e., the behavior of a left-turning bicyclist is not affected by the behavior of another one arriving at the same intersection approach at approximately the same time. While this is an assumption that could not be tested due to the lack of signal timing data that would allow consideration of only the first arriving left-turning bicyclist in each signal cycle, low left-turning bicycling demands at the study locations are a reasonable justification for this assumption; in other words, with few left-turning bicyclists overall at an intersection approach over 24 hours of data collection, it is unlikely that many arrived during the same signal cycle and affected left-turning maneuver decisions.

Hypothesis 1. *The presence of a bike box at an approach reduces TSTQB utilization for bicyclists coming from that approach.*

Comparing the percentage of left-turning bicyclists using the TSTQB when coming from approaches that also feature a bike box vs not, reveals a higher percentage of bicyclists from bike box approaches utilizing the TSTQB. However, based on the results of the two-proportion Z-test (see Table 4.6) the difference in the percent of left-turning bicyclists using the TSTQB between these two types of approaches is not statistically significant at the 95% level of significance. This means that the TSTQB utilization is not significantly affected by the presence of bike boxes. This could be because the majority of bicyclists still complete their left-turns in a conventional manner or by utilizing the crosswalk. It should also be noted that the descriptive analysis earlier revealed that even though a higher percentage of left-turning bicyclists use the TSTQB at approaches that also feature bike boxes versus not, more of those bicyclists use the bike box for their left turns, in many of these bike box approaches.

Table 4.6: Two proportion z-test for Hypothesis 1—bike box presence

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Bike Box	129	20	15.50	0.856822	0.391543
No Bike Box	95	11	11.58	0.856822	0.391543

Hypothesis 2. *The presence of a bike lane at an approach increases TSTQB utilization for bicyclists coming from that approach.*

Based on the data used to test this hypothesis, the percent of left-turning bicyclists using the TSTQB is lower when a bike lane is present upstream (conventional or protected) compared to when sharrows are present; see Table 4.7. The results of the two-proportion z-test reveal that these two percentages are not statistically different at the 95% level of significance, which in practice means that no difference should be expected in the utilization of TSTQBs based on the presence of bike lanes versus sharrows.

Table 4.7: Two proportion z-test for Hypothesis 2—bike lane presence

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Bike Lane	42	7	16.67	-1.192143	0.233205
Sharrows	154	38	24.68	-1.192143	0.233205

Hypothesis 3. ***The presence of a protected bike lane at an approach increases TSTQB utilization for bicyclists coming from that approach compared to the presence of conventional bike lanes.***

The percent of left-turning bicyclists using the TSTQB when coming from approaches with protected bike lanes is very similar compared to those coming from conventional bike lanes based on the results presented in Table 4.8. This is confirmed statistically with the performance of a z-test indicating that the two percentages are not statistically different at the 95% level of significance. This could be due to the fact that there are other factors affecting one's decision to use the TSTQB for completing a left turn and differences associated with accessing different ways to complete a left turn do not seem to affect the TSTQB utilization.

Table 4.8: Two proportion z-test for Hypothesis 3—protected bike lane presence

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Protected Bike Lane	193	16	8.29	-0.033138	0.973565
Conventional Bike Lane	406	34	8.37	-0.033138	0.973565

Hypothesis 4. ***The existence of protected left-turn phasing decreases TSTQB utilization for bicyclists coming from that approach***

A higher percentage of left-turning bicyclists is observed using the TSTQB when the upstream approach lacks protected phasing for the left-tuning movement; see Table 4.9. The two-proportion z-tests performed confirms the statistical significance of the difference in the TSTQB utilization at the 95% level of significance. This is reasonable, as left-turning bicyclists are presented with a safe alternative to the TSTQB, i.e., utilizing the dedicated left-turn lane and protected left-turning phasing to complete their turns.

Table 4.9: Two proportion z-test for Hypothesis 4—protected phasing

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Protected Left-turn Phasing	429	41	9.56	-2.144593	0.031985
Without Protected Left-turn Phasing	403	58	14.39	-2.144593	0.031985

Hypothesis 5. ***The presence of dedicated left turn lanes decreases TSTQB utilization for bicyclists coming from that approach***

Based on the results presented in Table 4.10 the utilization of TSTQBs located downstream of approaches with no dedicated left-turn lane is much higher compared to those that do present a dedicated-left-turn lane upstream. The two-proportion z-test performed confirms the statistical significance of this difference at the 95% level of significance. This is related to the previous hypothesis tested in that protected left-turn phasing is always combined with dedicated left-turn lanes. Even in the absence of left-turn phasing, when dedicated left turn lanes exist, they allow for permissive left turns. In addition, the visibility of the left-turn arrow markings could make this an appealing way for left-turn bicyclists to complete their turns.

Table 4.10: Two proportion z-test for Hypothesis 5—dedicated left-turn lanes

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Dedicated Left-Turn Lane	636	54	8.49	-4.520494	0.000006
No Dedicated Left-Turn Lane	196	45	22.96	-4.520494	0.000006

Hypothesis 6. ***The presence of TSTQBs at intersections increases the occurrence of two-stage maneuvers compared to control approaches without TSTQBs***

The percent of left-turning bicyclists completing their left turn through a two-stage maneuver, whether using the TSTQB or not is higher at TSTQB approaches versus control ones per the data presented in Table 4.11. The two-proportion z-test reveals that the difference is statistically significant at the 95% level of significance, indicating that the presence of a TSTQB is associated with a higher percentage of left-turning bicyclists completing their left turns through two-stage maneuvers. This could indicate that TSTQBs might already be installed at approaches where two-stage maneuvers are common and additional elements might need to be considered (e.g., guide signs) to increase their utilization.

Table 4.11: Two proportion z-test for Hypothesis 6—two-stage maneuvers

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB and Two-Stage Maneuver	Percent of Left-Turning Bicyclists Using the TSTQB and Two-Stage Maneuver (%)	z-test statistic	p-value
Control	251	24	9.56	-5.442512	0.000000
TSTQB	832	186	22.36	-5.442512	0.000000

Hypothesis 7. *TSTQB utilization is greater at larger compared to smaller intersections*
The results presented in Table 4.12 reveal a higher percentage of left-turning bicyclists using TSTQB at small intersections compared to large one. While this seems counterintuitive it could be related to the fact that large intersections most likely provide alternative opportunities for comfortable and safe left turns such as left-turning phasing. However, the two-proportion z-test does not confirm the statistical significance of this difference at the 95% level of significance, indicating that TSTQB utilization is not affecting by intersection size.

Table 4.12: Two proportion z-test for Hypothesis 7—intersection size

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Large Intersection	205	10	4.88	-1.855233	0.063563
Small Intersection	95	11	11.58	-1.855233	0.063563

Hypothesis 8. *Crosswalk utilization for left-turning bicyclist maneuvers is greater when there is no TSTQB to accommodate those left-turning bicyclists*
The percent of left-turning bicyclists utilizing the crosswalk for their turns is higher in the absence of TSTQBs. The two-proportion z-test confirms the statistical significance of this difference at the 95% level of significance. This indicates that the presence of TSTQBs decreases crosswalk usage by left-turning bicyclists.

Table 4.13: Two proportion z-test for Hypothesis 8—crosswalk utilization

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the Crosswalk	Percent of Left-Turning Bicyclists Using the Crosswalk (%)	z-test statistic	p-value
Control	170	57	33.53	2.820957	0.004788
TSTQB	300	64	21.33	2.820957	0.004788

Hypothesis 9. ***The presence of a TSTQB sign increases TSTQB utilization***
As mentioned in the methodology no data were collected at TSTQB approaches that features one of the TSTQB signs. As a result, it was not possible to test this hypothesis, that is being recommended for future work.

Hypothesis 10. ***The TSTQB parking lane configuration increases its utilization compared to the crosswalk TSTQB configuration***
The percent of left-turning bicyclists using the TSTQB with parking lane configuration is very similar compared to crosswalk setback configuration based on the results presented in Table 4.14. This is confirmed statistically with the performance of a z-test indicating that the two percentages are not statistically different at the 95% level of significance. This is probably because these two configurations are similar in terms of where they are located with respect to the intersection crossing markings, with their primary difference being the size of the TSTQB. This indicates that the TSTQB size might not be a factor impacting TSTQB utilization.

Table 4.14: Two proportion z-test for Hypothesis 10—parking lane configuration

Condition	Number of Left-Turning Bicyclists	Number of Left-Turning Bicyclists Using the TSTQB	Percent of Left-Turning Bicyclists Using the TSTQB (%)	z-test statistic	p-value
Parking Lane	340	47	13.82	0.358747	0.719784
Crosswalk Setback	349	45	12.89	0.358747	0.719784

Overall, the results of the statistical analysis indicate that the presence of bike boxes or bike lanes (protected or conventional) does not affect the utilization of TSTQBs. In addition, the presence of protected bike lanes does not motivate a higher TSTQB utilization compared to when conventional bike lanes are in place. These results indicate that there is no correlation between bike facility presence and design at the intersection and TSTQB utilization. Additional testing with larger sample sizes from more locations and longer durations are recommended to further tests these correlations. In addition, the size of the intersection does not significantly influence left-turning bicyclists' choice of using the TSTQB. No difference was also observed in TSTQB utilization based on its configurations when comparing the parking lane versus the crosswalk setback configuration.

Conversely, the lack of protected left-turn phasing and dedicated left turns lanes, which indicate lack of protected or permissive left turn phasing, do motivate higher TSTQB utilization. This is expected as in the absence of alternative ways to complete a left turn in a safe and comfortable way, TSTQBs can be attractive for left-turning bicyclists. Possible reasons for these preferences include increased perceived safety and clearer guidance for bicyclists when dedicated signal timing and infrastructure, such as protected left-turn phasing and dedicated lanes, is present. These features likely provide a more structured environment for bicyclists, reducing the need for TSTQBs. In addition, the percent of left-turning bicyclists performing two-stage maneuvers at intersections with TSTQBs was significantly higher, indicating the likelihood that TSTQBs are indeed installed where bicyclists prefer the two-stage maneuver for completing their left turns, and perhaps other design elements, e.g., signs need to be added to motivate higher TSTQB utilization.

When examining how the presence of TSTQBs affects left-tuning behavior, it was found that more bicyclists use the crosswalk for their left-turning maneuver if the approach lacks a TSTQB, indicating that the absence of TSTQBs increases the likelihood of bicyclists opting to use the crosswalk for their left-turning maneuvers.

5.0 Implementation & Technology Transfer

This Chapter provides recommendations on the design of TSTQBs and emphasizes the needs for bicyclist and driver education, in addition to outlining guidance for future data collection efforts to understand the effectiveness of TSTQBs. The recommendations presented in this Chapter have been obtained through both the thorough review of guidebooks and published research and primarily through the detailed exploraton of left-turning bicyclist behavior at 14 TSTQBs and an additional six control sites.

Design:

- Ensure future TSTQB implementations comply with the newly published MUTCD (*1*).
- Implement regulatory or guidance TSTQB signs (see Figure 3.2) to increase bicyclist awareness of TSTQB presence.
- Position TSTQBs near corner curbs of intersections to enhance bicyclist comfort and reduce potential conflicts with motor vehicles.
- Position TSTQBs near the through moving path of bicyclists to improve utilization.
- Consider implementation of two-stage turn queue boxes in the absence of dedicated left-turn lanes to facilicate left-turning maneuvers for bicyclists.
- Implement TSTQBs at locations with high crosswalk use for bicyclists' left-turning maneuvers.

Education:

- Educate bicyclists on the proper use of TSTQBs, emphasizing advantages of using TSTQBs and correct positioning within the box.
- Implement educational campaigns to enhance driver awareness of bicyclists and the function of TSTQBs.

Data Collection:

- Develop and administer surveys to supplement existing data, correlating bicyclists' comprehension and familiarity with TSTQBs with their behavior at these locations.
- Expand data collection to cover a more diverse range of intersection designs and layouts, as well as demands, and seasons.
- Collect and analyze bicyclist and motorist trajectories at intersections with TSTQBs for conflict analysis to further understand safety risks associated with their implementation.
- Investigate alternative bike infrastructure usage at intersections where TSTQBs are not utilized, trajectory analysis may be helpful for this study.

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6.0 Conclusions

This research project addressed three main objectives, each contributing to the overall goal of developing recommendations for the implementation of TSTQBs to enhance bicyclist safety. First, an inventory of TSTQBs across Massachusetts was created to summarize their design characteristics. Second, the study investigated how left-turning bicyclists utilize TSTQBs and correlated their behavior with intersection and bicycle infrastructure characteristics and TSTQB design features. Lastly, recommendations on TSTQB features that are more effective in improving bicyclist utilization and ultimately, safety were provided. Field data used for studying left-turning bicyclist behavior were collected from 14 TSTQB at six intersections, utilizing 24-hour video recordings at each of those locations.

6.1 Inventory

The study identified a total of 88 TSTQB in the Commonwealth. These TSTQBs were primarily concentrated in major cities like Boston, Cambridge, and Somerville. Most of these TSTQBs featured green-colored pavement, bicycle stencils, and turn arrows, complying with the national guidelines (*1*, *4*, *6*), with the exception of one box missing the bicycle stencil at Park Dr. at Beacon St. in Boston. Based on the detailed measurement from the LiDAR point cloud, the depths and widths of the TSTQBs in Massachusetts range between 8.8 ft. and 14.0 ft., and 7.3 ft. and 14.0 ft., respectively, which do not always meet requirements stated in existing guidebooks. Notably, the majority of TSTQB approaches included "No Turn on Red" signage, complying with national guidelines (*1*, *4*, *6*). Among the various configurations identified, the Crosswalk Setback Configuration was the most prevalent, comprising 68.18% of all TSTQBs. Additionally, downstream bicycle infrastructure treatments, such as bike lanes and sharrows, were less common compared to upstream infrastructure. Moreover, only two TSTQBs with bike signals were found, both located in Cambridge. The newly required by the MUTCD TSTQB signs were found at only 4 TSTQBs approaches in Amherst. Overall, the findings underscore the importance of consistent infrastructure design and signage to enhance bicyclist safety and compliance across TSTQBs in Massachusetts.

6.2 Bicyclist Behavior

This study also investigated bicyclist behavior concerning utilization of TSTQBs at signalized intersections. The study found that in Massachusetts, only 11.91% of bicyclists used the TSTQB, while another 10.47% of left-turning bicyclists performed two-stage maneuvers without using the TSTQB. This rate is notably lower compared to a similar study conducted in Toronto, Canada (*26*), where 54% of the bicyclist utilizing this treatment, and very low compared to the study conducted in Copenhagen (*29*), where 86.5% of the left-turning bicyclists utilized the TSTQB. Various factors such as differences in bicycle infrastructure, intersection characteristics, bicyclist experience, bicyclist familiarity with TSTQBs, cultural norms, and land use may account for these disparities.

The analysis of the left-turning behavior also revealed that the most prevalent way to complete a left turn at an intersection, was by either utilizing a conventional left turn (46.03%) or the crosswalk (28.49%). A noteworthy discovery was that despite left turns being prohibited at some approaches many bicyclists still executed conventional left turn maneuvers (e.g., Beacon St. at Harvard St., 11.67% for the EB-NB and 28.72% for the NB-WB TSTQBs respectively). This could be attributed to variations in intersection layout, coupled with the restriction on left turns for all users, which may have led bicyclists to perceive the maneuver as safer as they are not interacting with any other moving vehicles.

Another notable finding is that some bicyclists from other approaches also used adjacent TSTQBs as bike boxes, with usage rates rising to 15.91% for the TSTQB at the Washington St. at Massachusetts Ave. (NEB-NWB) approach and 15.38% for the TSTQB at the Park Dr. at Beacon St. (WB-SB) approach. All of these TSTQBs shared the crosswalk setback configuration. One possible explanation for this behavior could be a lack of awareness about the TSTQB, leading bicyclists to prefer staying ahead of traffic by utilizing the TSTQB as a bike box. However, the real reason for this behavior remains uncertain since this study did not include individual surveys that could have been used to obtain bicyclists comprehension and familiarity with such treatments.

The statistical analysis revealed that the presence of bike boxes, bike lanes (protected or conventional), and size of intersection do not significantly affect the utilization of TSTQBs. Additionally, the bike lane type (whether conventional or protected) and TSTQB configuration type (specifically, crosswalk setback versus parking lane configuration) did not result in a statistically significant difference in the TSTQB utilization. However, TSTQBs observe significantly higher utilization in the absence of protected left-turn phasing and dedicated left turns lanes and result in significantly lower crosswalk utilization for bicyclists' left turns. These findings can directly inform placement of TSTQBs at approaches that lack protected left-turn phasing and dedicated left-turn lanes as well as at locations with high crosswalk use for left-turn completion. Lastly, the frequency of two-stage maneuvers is statistically higher at TSTQBs approaches, indicating that TSTQBs have been placed at locations where the two-stage maneuver is preferred by left-turning bicyclists but perhaps additional signage or alternate TSTQB placement could motivate higher TSTQB utilization.

Overall, this study significantly contributes to the current literature on bicyclist safety and infrastructure design by providing comprehensive insights into TSTQB design characteristics and their use in Massachusetts. The findings offer valuable information on bicyclist behavior and infrastructure usage, highlighting areas for improvement and standardization in bicyclist infrastructure implementation. Based on these findings, practical recommendations are provided to enhance TSTQB placement decision-making and improve bicyclist safety, thereby contributing to evidence-based design guidelines and policy initiatives aimed at creating safer transportation environments for bicyclists. More specifically this study (1) offers evidence of much lower TSTQB utilization in the Greater Boston area than what has been reported in the literature, (2) reveals the most common ways for bicyclists completing left turns at signalized intersections, (3) offers evidence for TSTQB implementation at locations with high crosswalk use by left-turning bicyclists and those that lack protected left-turn phasing or dedicated left-turn lanes, (4) suggest the need for additional elements accompanying TSTQBs, such as guide and regulatory signage to increase TSTQB utilization, and (5) reiterates the need for education of bicyclists and motorists to improve comprehension and awareness of such infrastructure treatments with the goal of improving safety for all.

6.3 Future Work

The inventory was compiled using information from Massachusetts municipalities, but it is possible that some implemented TSTQBs were missed, and others in planning stages were not included. Additionally, obstacles or construction sometimes hindered capturing design characteristics accurately on Google Maps. It is important for future efforts to continually update the inventory of TSTQB locations and their characteristics to maintain a current inventory for Massachusetts.

The field data in this research focused on just 14 TSTQB locations in Massachusetts. Future studies should expand to more locations with higher bicyclist and motorist activity to further understand bicyclist left-turning behavior. The hypotheses presented in this report were tested with the minimal number of TSTQB and control approaches for which data had been collected. Additional approaches would allow for a more comprehensive testing of these hypotheses especially those that appeared to be significant but at lower than 95% levels of significance. In addition, they would allow for more hypotheses to be tested, including the impact of TSTQB regulatory and guidance signs, the age of the TSTQB, and intersection crossing markings that were not possible due to inadequate data. Detailed geometric design characteristics of the intersection and TSTQBs obtained through LiDAR scans should also be incorporated to enhance the understanding of the geometric features’ impact on bicyclist left-turning behavior.

This study did not delve into assessing how bicycle infrastructure and design features might influence motorist behavior around TSTQBs. Future studying motorist activity can provide insights into drivers' behavior around TSTQBs and their behavior when encountering a bicyclist waiting in the TSTQB, which can inform TSTQB placement and design decisions. Furthermore, it did not explore the potential variations in motorist and bicyclist behavior in response to the presence and number of bicyclists near or within TSTQBs, which should be explored in the future with data from high-demand intersections.

A crash/conflict analysis at TSTQB locations would be useful for assessing safety improvements before and after implementation. Finally, conducting surveys could offer valuable insights by establishing correlations between bicyclists’ and motorists’ perceptions, comprehension, and familiarity with TSTQBs and their behaviors at these specific locations to further enhance design recommendations. These findings could be further supported by simulation-based studies.

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