Effectiveness of Bike Boxes in Massachusetts

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16. Abstract Bike boxes provide a designated space for bicyclists to gather at the front of a traffic queue, to improve bicyclist visibility and predictability. This project studied the effectiveness of bike boxes in Massachusetts by investigating motorist and bicyclist behaviors and the effects of bike box design. The study included a comprehensive inventory, descriptive analysis of historic crashes, and field study that provided trajectories of motorized vehicles and bicyclists from 11 bike boxes in Boston and Somerville, MA. A total of 91 bike boxes were identified in Massachusetts that included a variety of designs in terms of dimensions, signage, pavement markings, and bicycle infrastructure. Bike box depths were found to be on the lower end of guidebook requirements. The crash analysis using five years of data, though limited, revealed that the majority of crashes are attributed to motorists or bicyclists not complying with control devices. The study also indicated lower motorist compliance rates compared to previous studies and similar results to other studies regarding bicyclist positioning within the bike box; however, the results of impact of design features on user behavior were inconclusive. Further research is needed to understand user behavior at bike boxes and to relate behavior to safety outcomes, and for outreach and education efforts to support bike box effectiveness.				
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Effectiveness of Bike Boxes in Massachusetts

Final Report

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Executive Summary

Introduction

Bicycle or bike boxes or advanced stop lines are an area dedicated to bicyclists to facilitate bicyclists getting ahead of a car queue and waiting during a red signal phase. Boke boxes are defined by pavement markings denoting the outline of the box and are usually supplemented by colored pavement (most frequently green color).

Bike boxes present multiple advantages, such as:
- Reduction in right-hook conflicts.
- Improved bicyclist visibility.
- Provision of priority to bicyclists by placing them in advance of idling motorized vehicles, often coupled with leading bicycle intervals at traffic signals.
- Reduced crosswalk encroachment by both motorists and bicyclists and, therefore, improved pedestrian safety.
- Facilitating left turns for bicyclists.
- Improved intersection efficiency by grouping bicyclists.
- Reduction of bicyclist exposure to harmful emissions by placing them in advance of idling motorized vehicles.

Potential disadvantages associated with bike boxes include:
- Intersection efficiency loss due to the elimination of "Right Turn on Red."
- Higher-risk right-angle collisions from through-going vehicles running a red light due to the advanced placement of the bike box at intersection.
- Higher maintenance costs compared to alternatives.
- High motorist encroachment due to unfamiliarity, which could compromise bicyclist comfort and safety.

Despite the plethora of bike box implementations over the past 10 years, the impact of bike box design on motorist and bicyclist behavior is not well understood. The main goal of this project is to study the effectiveness of bike boxes in Massachusetts by investigating motorist and bicyclist behavior and how it is affected by bike box design. More specifically, the research objectives of this project are:
1. Create an inventory of bike boxes in Massachusetts that includes their design.
2. Describe safety outcomes of bike box implementations in Massachusetts based on historical crash data and a conflict analysis of field data.
3. Characterize bicyclist and motorist behavior at intersections with bike boxes, to assess whether bike boxes are utilized as intended by both bicyclists and motorists.
4. Recommend general guidelines on bike box features that are more effective in improving bicyclist and motorist safety.

Methodology

The research methodology consists of four components:
1. A comprehensive review of published literature and public agency documentation on bike boxes, their design guidelines, and their documented safety outcomes.
2. Creation of an 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 crash analysis using information from crash reports at bike box locations across Massachusetts.
4. A field study on bicyclist and motorist behavior at 11 bike box locations in Massachusetts, analyzing motorist compliance and bicycle positioning within the bike box in an effort to assess the effectiveness of bike boxes.

Results

Inventory
- At least 91 bike boxes are currently installed in Massachusetts.
- The majority of bike boxes are colored green (86%) and connected with bike lanes upstream (67%).
- Even when bike lanes are absent, the majority of the bike boxes feature a colored ingress lane green (76%).
- Very few implement an additional stop line (3.4%).
- 72% of the bike box approaches present a "No Right Turn on Red" sign.
- Only 45% present a "Stop Here on Red" sign.

Safety Analysis
- Safety analysis was limited by the availability of data.
- Limited data imply that bike boxes may reduce right-hook crashes.
- The majority of the obtained crashes were attributed primarily to the bicyclist running a red light (~40%) and secondarily due to motorist failure to yield, most frequently during a left-turning movement (22%). These results reveal the need for motorist and bicyclist education not only with regards to their interactions with bike boxes but in general on how to safely utilize shared roadway space to mitigate conflicts.
- Some of the motorist-bicyclist crashes occurred on crosswalks while bicyclists were riding their bikes to cross the roadway. This calls for improved bicycle infrastructure to legitimize bicyclists and encourage them to behave in accordance with control devices.

Motorist and Bicyclist Behavior
- Motorist compliance to bike box markings is lower in Boston and Somerville, Massachusetts, compared to findings from earlier studies reporting compliance rates.
- This study confirmed findings of previous studies reporting that vehicles performing turning movements are less compliant than through-moving vehicles.

- The majority of bicyclists tend to utilize the bike box region right in front of the bicycle lane, with the only exception being left-turning vehicles that were more likely to utilize the main bike box region (i.e., to the left of the bike lane).
- Left-turning bicycles were more likely to utilize region at multilane bike box approaches where a designated left-turn lane exists.

Recommendations

The majority of the recommendations provided in this section are based on motorist and bicyclist behaviors, given that a comprehensive safety analysis was limited by the availability of data (both near-miss and crash data).

Design:
- Additional stop lines and "Do Not Stop" blocks improve motorist compliance and should be considered at all bike box implementations.
- "No Right-Turn on Red" signs can improve bike box compliance for right-turning motorists.
- Two-stage turn queue boxes should be considered to accommodate left-turning bicycles in the absence of a bike signal with an advanced green signal: a) for multilane approaches, since the risk of traversing the bike box width when the green signal is on is higher with more lanes; and b) for single-lane approaches that present lower rates of proper bike box use by left-turning bicyclists.
- Ensure compliance of future bike box implementations with required bike box features as presented in national guidelines, e.g., the NACTO *Urban Bikeway Design Guide* (2014).

Education:
- Bicyclists should be educated on the proper use of bike boxes, especially in terms of positioning themselves ahead of motorized vehicles rather than waiting within the bike lane upstream of the bike box when a bike lane is present.
- Motorists should be educated to improve comprehension of bike boxes, their compliance, and consequent safety outcomes stemming from reduced bike box encroachment and increased yielding to bicyclists' rates.
- Education campaigns should also focus on improving the visibility and awareness of "No Right Turn on Red" signs (e.g., through installation of blank-out signs).

Data Collection:
- Field data collection occurred during the COVID-19 pandemic, and bicyclist and motorized vehicle demands might not be representative. It would be beneficial to replicate this study after the pandemic in "new normal" conditions.
- An effort should be made for additional data collection efforts to take place during the warmer months and at other high-trafficked corridors with dense bicycle-friendly infrastructure elements (e.g., in Cambridge) so that larger samples of bicycle trajectories can be obtained for behavioral and near-miss analysis.

- Surveys should be developed and administered to supplement collected data and allow for correlating bicyclist and motorist levels of comprehension and familiarity with bike boxes and their behavior at such locations.

Conclusions

Overall, this study contributes by:
1. offering evidence that motorist compliance rate can be lower at some intersections compared to findings from previous research.
2. confirming research findings from previous studies that reported that motorist compliance is dependent on the turning movement performed.
3. confirming high bicyclist compliance as reported in previous studies.
4. offering additional evidence for the implementation of two-stage turn queue boxes to facilitate left-turning movements.
5. reiterating the need for education of and outreach to motorists and bicyclists to properly utilize bike boxes, with the goal of improving safety for all.

Future work should focus on:
- expanding and updating the bike box inventory to maintain a current list of bike boxes and their design characteristics in Massachusetts.
- continuing the LiDAR scanning of all bike boxes to obtain a comprehensive inventory of their design specifications in Massachusetts.
- obtaining multiyear longitudinal data and utilizing crowdsourced data and video analytics that will allow for larger sample sizes of near-misses.
- repeating the safety analysis using alternative surrogate safety measures such as the Time to Collision (TTC); investigating whether differences in the numbers and severity of near-misses exist between TTC and Post-Encroachment Time (PET).
- performing a comparative safety analysis between intersections with bike boxes and those without (i.e., control site) in terms of near misses (from additional trajectory data) and motorized vehicle-bicycle crashes.
- further exploring the correlation between bike box and intersection design characteristics and motorist and bicyclist demand with motorist and bicyclist behavior, using a larger dataset of bike box locations at a future time with higher bicyclist and motorist demands.
- performing before-and-after bike box implementation behavioral observations of motorists and bicyclists.
- assessing the impact of educational campaigns on motorist and bicyclist behavior
- performing surveys to supplement collected data and allow for correlating bicyclist and motorist level of comprehension and familiarity with bike boxes with their behavior at such locations.

Table of Contents

List of Tables

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List of Figures

List of Acronyms

Acronym	Expansion
AASHTO	Association of American State Highway Transportation Officials
BORIS	Behavioral Observation Research Interactive Software
FHWA	Federal Highway Administration
LiDAR	Light detection and ranging
MSHA	Maryland State Highway Administration
MUTCD	Manual of Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
PBOT	Portland Bureau of Transportation
PET	Post Encroachment Time
TMC	Turning Movement Counts
TTC	Time to Collision

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1 Introduction

Bicycle or bike boxes are a dedicated area for bicyclists located ahead of traffic lanes, just upstream of signalized intersections, where bicyclists can get ahead of a car queue and wait during a red signal phase *(1,2,3)*. Figure 1.1a presents an example of a bike box in Cambridge, Massachusetts. Bike boxes are often also referred to as advanced stop boxes, advanced stop lines, advanced stop bars, head start areas, or bicycle storage boxes. They are placed in front of the stop line and usually upstream of pedestrian crosswalks *(2)*. They are defined by pavement markings denoting the outline of the box and are usually supplemented by colored pavement (most frequently green) *(4)*. Bike boxes are not to be confused with turn queue boxes that are implemented specifically for facilitating safe left-turn movements for bicyclists; see Figure 1.1b for an example of a turn queue box in Seattle, Washington.

(a) Bike box in Cambridge, MA   (b) Two-stage turn queue box in Seattle, WA
Figure 1.1: Examples of bike box and two-stage turn queue box

Bike boxes fall under the category of traffic control devices, according to the Federal Highway Administration (FHWA) *(3)*. While bike boxes are not included in the current version of the *Manual for Uniform Traffic Control Devices* (MUTCD) *(5),* processes exist at the federal level to allow for interim approvals until the official inclusion of bike boxes in the manual. In addition, several states have statewide approval for the use of bike boxes, i.e., they do not need to seek FHWA approval before implementing bike boxes. Bike box implementation is optional and allowed only at signalized intersections. The ultimate goal of implementing bike boxes is to improve safety for all users without compromising the operational efficiency of signalized intersections *(6)*.

Bike boxes improve bicyclist visibility *(1,6,7,8,9)* as well as behavior predictability *(1),* which in turn can have a positive impact on driver awareness *(1,10)* and more practically result in a reduction of crashes, in particular, right-hook crashes *(3,7)*. The presence of bike boxes has been found to encourage legal bicyclist left turns and, in general, preferred paths compared to when such infrastructure is absent *(9)*. In addition, bike boxes provide some level of priority to bicyclists at the traffic signal by placing them in advance of motorized

vehicles *(2,7.9,11)*. In some cases, bike boxes are supplemented with bike signals and advanced signal phases to further provision of priority *(7,12)*. Bike boxes also allow for bicyclists to appropriately place themselves for left turns or a through-movement in the case that a bike lane is relocated from the right side of the roadway to the left *(2,13)*. Increased perception of safety has been reported as an additional benefit of bike boxes *(6,11)*. This increased safety perception can result in higher bike mode share *(6,14)*.

In addition to safety benefits for both motorists and bicyclists, bike boxes have been associated with reduced crosswalk encroachment from both motorists and bicyclists *(4,12)*, which can result in improved safety for pedestrians as well. Grouping bicyclists to move through a signalized intersection also improves the efficiency of the intersection *(3)*. Finally, relocating bicyclists in front of idling vehicles reduces bicyclist exposure to harmful vehicle emissions *(11,13)*.

However, motorist unfamiliarity can lead to bike box encroachment by vehicles, which can in turn compromise bicyclist comfort and safety. In addition, "Right Turn on Red" is commonly eliminated when a bike box is implemented, which can have implications for the efficiency of a signalized intersection. Another potential disadvantage of bike boxes from a safety perspective is a higher risk of right-angle collisions from through-going vehicles running a red light due to the advanced placement of the bike box at intersections (*12*). Finally, maintenance costs need to be considered when implementing bike boxes, especially for areas with snow and the use of snowplows *(15)*, because they may be higher than alternatives.

In the United States (U.S.), bike boxes are currently being implemented in at least 20 cities across 17 states, based on data reported by the National Association of City Transportation Officials (NACTO). In Europe, bike boxes have been commonly implemented in cities for over 20 years *(12,15)*. The motivation behind these implementations has varied from addressing right-hook crashes, i.e., when a bicyclist is moving through while a motorist is turning right, to facilitating bicyclist left turns or offering continuity in bicycle infrastructure when a bicycle lane is located on a different side of the street downstream from an intersection as compared to upstream *(7)*.

Despite the fact that multiple bike box studies have been performed over the past 10 years in the United States, a comprehensive understanding of how bike box design affects the safety performance of bike boxes is missing. Several bike boxes have been installed in the Commonwealth of Massachusetts in recent years. However, the only bike box-related study performed in Massachusetts, Fournier et al., has been based on driving simulation *(16)*. The outcomes of that study concluded a high driver compliance rate and understanding of the markings, even when drivers are not familiar with bike boxes. However, Fournier et al. *(16)* focused on the driver aspect, studying only how drivers behave in the presence of bike boxes but not assessing the impact of bike box design on driver behavior. There is a need to also study bicyclist behavior at bike boxes in order to assess their effectiveness in improving safety, and to correlate both driver and bicyclist behavior with bike box and general roadway environment design characteristics. In particular, it is important to understand how bicyclists use bike boxes, such as the purpose (e.g., to make right or left turns) and their positioning

within the bike box depending on their turning movement. This would allow for a more comprehensive assessment of bike boxes' potential in improving safety.

Driver compliance at bike boxes, e.g., motorists stopping behind the bike box stop line, is also key in ensuring improved safety outcomes for bicyclists. It is, therefore, necessary to study driver compliance, relate it to the design of bike boxes and the bicycle infrastructure surrounding them, and compare with the results of previous studies. This would allow for the development of bike box design guidelines that ensure improved safety outcomes at signalized intersections.

The objectives of this research project are to:

1. Create an inventory of bike boxes in Massachusetts that can later be used to relate design characteristics with driver and bicyclist behaviors as well as safety outcomes.
2. Describe safety outcomes of bike box implementations in Massachusetts based on historical crash data and a conflict analysis of field data.
3. Characterize bicyclist and motorist behavior at intersections with bike boxes to assess whether bike boxes are utilized as intended by both bicyclists and motorists.
4. Recommend general guidelines on bike box features that are more effective in improving bicyclist and motorist safety.

The results of this study can inform development of bike box design guidelines. In particular, the outcomes of this project will help determine when and where it is beneficial to install bike boxes across the Commonwealth of Massachusetts from a safety standpoint and advise on signage and pavement markings. As a result, it will help provide guidance and allow The Massachusetts Dept. of Transportation (MassDOT) to make appropriate investments on projects under review.

The rest of the report is organized as follows. First, the methodology followed to address the objectives listed previously is presented in Chapter 2. Chapter 3 focuses on summarizing current research on driver and bicyclist behavior at bike boxes as well as the safety outcomes associated with the implementation of such control devices. In addition, it summarizes design guidelines currently in existence in the United States. Chapter 4 discusses the results of this research effort, focusing on the development of a bike box inventory in Massachusetts, crash and conflict analyses performed for a subset of those, as well as the analysis of driver and bicyclist behavior at bike boxes in Massachusetts using field data. Based on the findings, Chapter 4 also provides some general recommendations on bike box implementations. Finally, Chapter 5 summarizes the findings of this study and provides recommendations for future work.

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2 Research Methodology

The research methodology consists of four components. The first is a comprehensive review of published literature and public agency documentation on bike boxes, their design guidelines, and their documented safety outcomes. The second component of this methodology is the creation of an 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. The third is a crash analysis using information from crash reports at bike box locations across Massachusetts. Finally, field data collection on bicyclist positioning with the bike box and motorist compliance are collected and analyzed in an effort to determine the effectiveness of bike boxes.

2.1 Literature Review

The review of existing publications focused on: 1) design guidebooks from the United States to allow for determining the state of practice of bike box implementations, and 2) peer-reviewed journal and conference papers that assess motorist and bicyclist behavior and summarize safety outcomes, with an emphasis on studies that were performed in the United States. Guidelines from various entities were reviewed, including the National Association of City Transportation Officials (NACTO) *Bikeway Design Guide (15),* Federal Highway Administration's (FHWA) *Separated Bike Lane Planning and Design Guide (2),* and the *Manual of Uniform Traffic Control Devices* (MUTCD) *(5),* as well as bike box guidelines documented by states and cities, e.g., the Maryland State Highway Administration *(17),* the city of Portland Bureau of Transportation in Oregon *(13),* the city of Boston *(18),* and the city of Los Angeles *(19).*

2.2 Bike Box Inventory

2.2.1 Survey
In an effort to determine bike box locations in the Commonwealth, a survey was developed using Google Forms and sent out to all 351 cities and towns in the state. The University of Massachusetts Transportation Center maintains a list of contacts for those cities and towns that was utilized for the purposes of this study. Six different surveys were initially developed for each of the six MassDOT districts, in an effort to limit the town and city options provided to each respondent. These city and town options are included in the survey, as explained later, to filter and present only the bike box locations that are relevant to that specific city or town.

The survey included a brief description of the study scope, an explanation of the expected time to complete the survey, which was less than 5 minutes, illustrations of bike box examples, and contact information for this study. All of these were provided on the first page

of the survey, as shown in Figure 2.1. On the same page, the respondent was asked to provide their name, affiliation, title, and email address.

The second page included a drop-down menu where the respondent could select the city/town they would be reporting for. Once the city/town was selected, a list of bike box locations that have been implemented at that jurisdiction appeared, asking the respondent to confirm those locations and indicate whether any additional bike boxes existed. A thank-you message was presented at the end of the survey, along with a comment box to allow the respondents to provide additional information

A second survey following this one was developed and shared with the six MassDOT districts, to further confirm bike box locations per district and ensure that bike boxes falling under the jurisdiction of MassDOT were also captured.
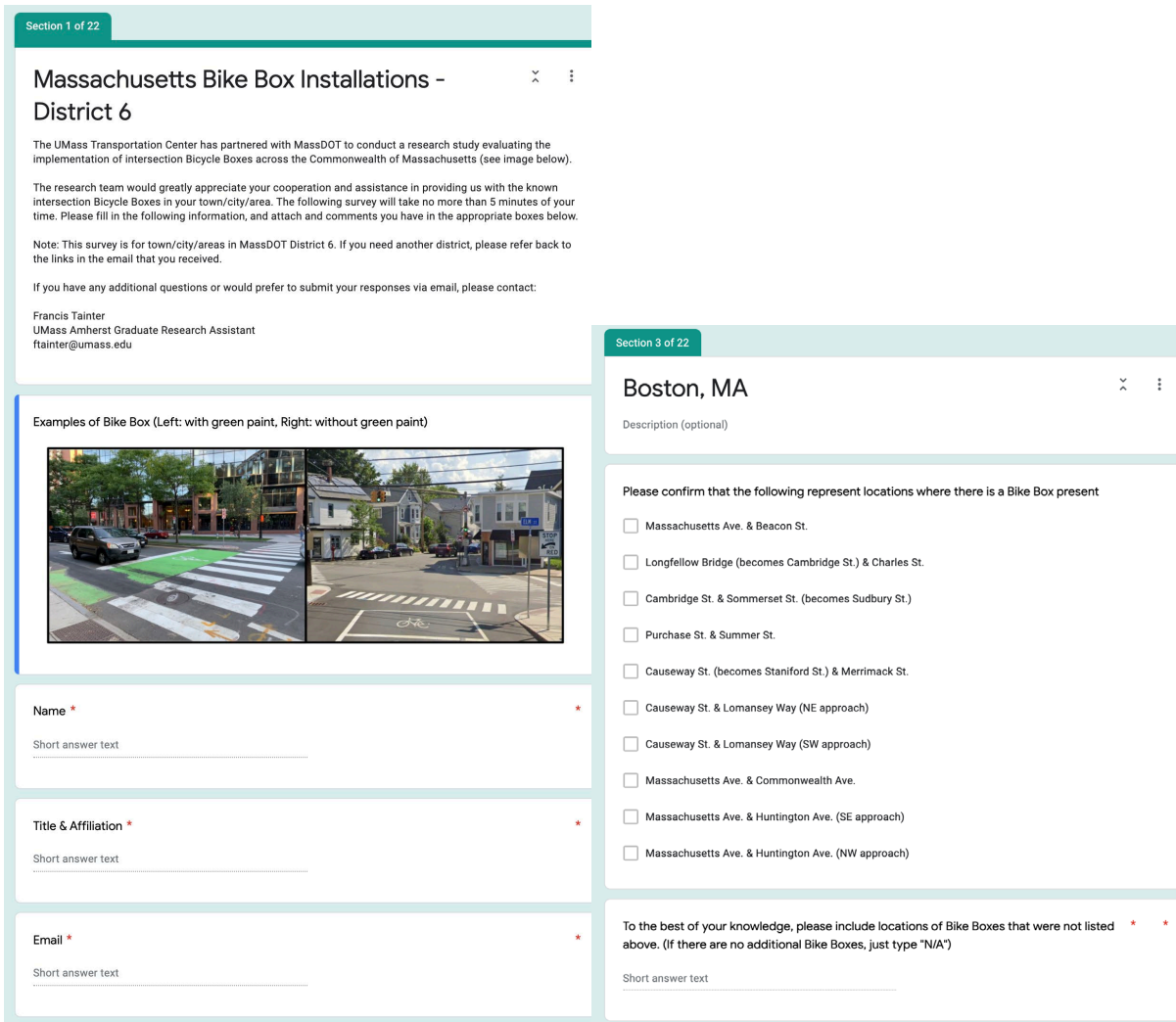
    (a) General information   (a) Bike box locations

Figure 2.1: Survey screenshots

2.2.2   LiDAR Data Collection

The objective of the bike box inventory was to comprehensively acquire the detailed information for the bike boxes of interest in this study, including location, presence, geometry, other bike facilities, traffic control devices for motorized and nonmotorized vehicles, etc. The selection of the targeted bike boxes of interest was determined based on the diversity, geographical location, and design of the bike boxes, and was guided by the bike box inventory survey described in Section 2.2.1.

The field bike box inventory data consists of mobile LiDAR data and street video logging imagery collected using an integrated sensing vehicle developed at the University of Massachusetts. Figure 2.2 shows the outlook of the sensing vehicle and examples of the captured LiDAR point cloud data and video logging imagery.

Figure 2.2: LiDAR sensing vehicle (bottom L), video log imagery (top), and point cloud data (bottom R)

In this study, the integrated sensing vehicle was instrumented with RIEGL VMZ-2000 mobile LiDAR and a FLIR Ladybug 5+ 360 panoramic video camera, accompanied by an Applanix precise positioning system. The mobile LiDAR system was used to acquire the point cloud data of the bike boxes and the surrounding intersection for bike box positioning and geometry measurement, while the video camera was used to obtain the detailed color and texture information of the bike boxes and the surrounding intersection for visual reference. Both systems were synchronized and integrated with the precise positioning system for accurate geolocation referencing.

Thanks to the accurate positioning capability (<10 cm position accuracy) and dense point cloud (>400,000 points/sec), the research team was able to take advantage of the collected mobile LiDAR data and extract the accurate bike box locations and the corresponding

geometry measurements. Compared with the traditional field survey method, the research team captured all the critical location and geometry information with much better measurement accuracy and without interrupting any traffic in the corresponding areas.

Due to the time and resource constraints, the research team could only collect field data for 21 bike boxes out of 91. 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 2.3 shows an illustration of the geometry measurements for two bike boxes captured from the point cloud data, and Table 2.1 explains in detail how geometries were defined and measured.
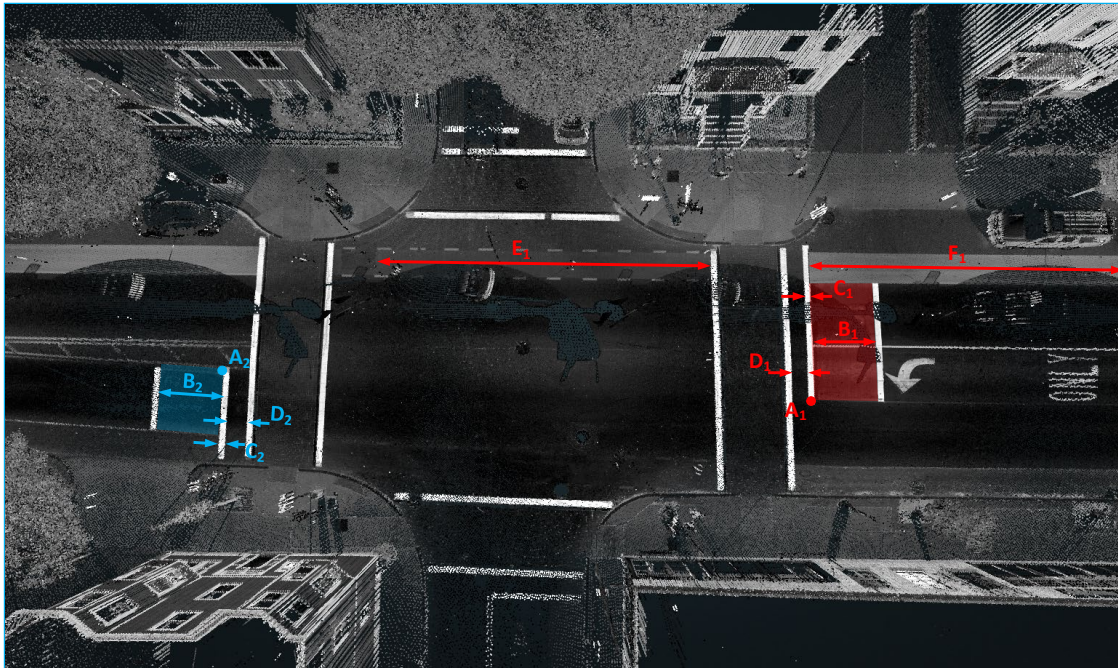
Figure 2.3: Illustration of bike box dimensions using LiDAR point cloud

Table 2.1: Definition and extraction method of geometries for bike boxes

Geometry	Definition	Method
Location	Coordinates of the bike box	The latitude and longitude coordinates measured at the left-downstream corner of the bike box along the longitudinal direction of the roadway (Ex: A1 and A2)
Depth (ft.)	Bike box depth	The length between the two edges of the bike box along the longitudinal direction of the roadway. If the bike box has a trapezoid shape, the average of its longest and shortest depth is used. (Ex. B1 and B2)
Stop Line Thickness (ft.)	Width of the stop line pavement marking	The width of the pavement marking along the longitudinal direction of the roadway. (Ex. C1 and C2)
Setback (ft.)	Distance between the crosswalk and the bike box	The distance between the upstream edge of the crosswalk and the downstream edge of the bike box along the longitudinal direction of the roadway (Ex. D1 and D2). If the bike box is downstream of the crosswalk, a negative value is used.
Egress Length (ft.)	Length of the colored bike lane exiting the bike box within the intersection	The length of the colored bike lane within the intersection. If not colored, the length is zero. (Ex. E1)
Ingress Length (ft.)	Length of the colored bike lane entering the bike box	The length of the color bike lane entering the bike box. (Ex. F1)

2.2.3 Google Maps Data Collection

In addition to scanning a subset of the identified bike boxes with the use of LiDAR technology to obtain detailed dimensions, manual observations were performed using Google Maps to allow for capturing a multitude of other characteristics. These characteristics included the existence of other bicycle treatments and relevant signage. In addition, the most recent Street View date as well as the latest Street View data showing the absence of the bike box were recorded in an effort to approximate the time of implementation of each bike box. This was deemed essential for the crash analysis, as it allowed the team to determine the crashes that can be associated with bike boxes. This is because some of the vehicle-bicycle crashes that were obtained occurred at approaches where bike boxes are currently implemented but were not necessarily present at those approaches a few years back when some of the crashes occurred. In a nutshell, the Google Maps data collection effort resulted in collecting information to respond to the following questions. Examples of some of these characteristics accompany the results of this data collection presented in Section 4.3.2.

1. *Street View date*: The most recent Street View date available showing the presence of a bike box.
2. *Most recent date without bike box*: The most recent Street View date that does not present the existence of the bike box of interest.
3. *Is the bike box colored*?: Yes if the bike box pavement is green-colored, No otherwise.
4. *Is there an additional stop line in advance of the bike box?*: Yes if there is a stop line in advance of the bike box in addition to the white line that acts as the boundary of the bike box.
5. *How many lanes does it cover?* Report the number of traffic lanes constituting the width of the bike box.

9

6. *What directions are those lanes for?* Record lane configuration, e.g., for a bike box covering two lanes, one potential configuration could be: Left, Through-Right, when the leftmost is serving only left-turning vehicles and the right most through and right-turning vehicles.
7. *Is there a bike lane upstream?* Yes if a bike lane exists upstream of the bike box, regardless of the type of bike lane (e.g., conventional, buffered, protected), No if otherwise (e.g., no bicycle treatment or sharrows).
8. *If a bike lane exists upstream, is it colored*? Yes if the bike lane is green-colored, No otherwise, and N/A if not applicable (if no bike lane exists upstream).
9. *If a bike lane exists upstream, is it separated*? Yes if the bike lane is protected, No otherwise, and N/A if not applicable (if no bike lane exists upstream).
10. *Is there a bike lane downstream?* Yes if a bike lane exists downstream of the bike box, regardless of the type of the bike lane (e.g., conventional, buffered, protected), No if otherwise (e.g., no bicycle treatment or sharrows).
11. *If a bike lane exists* downstream*, is it colored*? Yes if the bike lane is green-colored, No if it is not, and N/A if not applicable (if no bike lane exists upstream).
12. *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 not applicable (if no bike lane exists downstream).
13. *Does a through bike lane exist on the approach*? Yes if a through bike lane exists (i.e., right-turning lane is moved to the right of the bike lane at the intersection), No if otherwise.
14. *Does the intersection right downstream of the bike box approach feature intersection crossing markings*? Yes if intersection crossing markings are implemented to facilitate the through-moving bicyclists, No if otherwise.
15. *If intersection crossing markings exist, are they colored*? Yes if they are green-colored, No if otherwise, N/A if not applicable.
16. *Does the bike lane change position from one side of the roadway (upstream) to the other (downstream)*? Yes if it does, No if it doesn't, N/A if not applicable (e.g., there is no bike lane upstream and/or downstream).
17. *Does the bike box approach feature a bike signal for any of the bicycle movements?* Yes if it does, No if it doesn't.
18. *Is the bike box located upstream or downstream of the crosswalk?* Upstream or downstream.
19. *Is the bike box separated*? Yes, if the bike box presents multiple stencils to designate different lanes/movements with or without solid white lines separating the sections, No if otherwise.
20. *Does a "Stop Here on Red" sign* exist? Yes, if a "Stop Here on Red" sign exists on the bike box approach, No if it does not exist.
21. *Does a "No Turn on Red" sign* exist? Yes, if a "No Turn on Red" sign exists on the bike box approach either on the near side of the approach or the far side (i.e., downstream), No if it does not exist.
22. *Does a "Yield to Bikes" sign* exist? Yes, if a "Yield to Bikes" sign exists on the bike box approach either on the near side of the approach or the far side (i.e., downstream) indicating that motorists should be yielding to bicyclists as they are completing their turns (right or left), No if it does not exist.

23. *Is there a bicycle stencil on the bike box*? Yes if there is at least one bicycle stencil within the bike box, No if there is not.
24. *Is there a "Wait Here" pavement marking*? Yes is there is a "Wait Here" pavement marking in advance of the bike box (just upstream of the bike box stop line), No if there is not.
25. *Are there other signs in close proximity to the bike box*? Yes if there are (list signs that are located at the bike box approach and could be relevant to the bicycle and motorist operations and interactions, e.g., additional sign for bicyclists to indicate stopping location "Bikes Stop Here"; "Stop Here on Red" sign has a supplemental sign of "Except Bicycles," etc.).
26. *Any additional comments*? Issues related to obstructed or unclear views due to construction, recording of bike box shape when it is not rectangular, e.g., when it has a trapezoid shape, etc. are reported here.

It should be noted that in some cases, it was not possible to obtain certain features due to the unavailability of street views or the fact that some sites were undergoing construction when those street views were captured. In those cases, the total number of bike boxes used to obtain the percentages was adjusted to exclude those locations. The same process was followed when a certain design feature was not applicable for a specific bike box location; for example, the existence of a bike lane downstream when the bike box was located at a T-intersection.

2.3 Analysis of Bicycle-Vehicle Crash Data

The objective of this analysis was to investigate the impact of bike boxes on bicycle-vehicle crashes. In order to perform a before-and after analysis for locations with bike boxes accounting for exposure, the following data were obtained: 1) crashes for the period of 2014–2020; and 2) vehicle and bicycle demand data for the period of 2018–2020. As will be explained in Section 4.2 of this report, due to the limited crash data that were available for intersection approaches with bike boxes, a before-after crash analysis was not possible. However, the collected information has been summarized in a spreadsheet with the hope that it will be useful for other types of analysis. This project was limited to offering a descriptive analysis of the collected data.

2.3.1 Crash Data

A total of 70 crashes was obtained using MassDOT's IMPACT database *(20)* for all the intersections in Massachusetts that currently feature bike boxes as identified in the inventory. The crashes were queried for the time period of 2014–2020, and information on their longitude and latitude was obtained for 65 of them. The type of junction and the type and severity of any injuries were also obtained and recorded for the same crashes. Crash reports were obtained for the same 65 crashes. These data included the crash narrative (with non-identifiable information), the date and time of the crash, the driver contributing factor, the roadway intersection type, and the injury status when available. Two of them were excluded because 1) the crash report was filed after the crash occurred when the bicyclist visited the

police station; or 2) the crash was between a pedestrian walking their bicycle and a vehicle, resulting in a total of 63 crashes that were further analyzed. Finally, a conflict diagram was provided for 61 crashes of those 63 crashes that assisted in determining the type of bicycle-vehicle collision that occurred in each case.

2.3.2 Demand Data

Average daily bicycle traffic and average daily vehicle traffic were obtained from Streetlight Data *(21)* through MassDOT by month for the period of January 2018 to November 2020. Streetlight Data obtains location data from smart phone and navigation devices and uses them to estimate trips passing through specific locations. The benefit of such data is that they include nonmotorized users, whose demand data is otherwise challenging to obtain. The Streetlight data were queried for the intersections where crashes had been reported. Demand data for a total of 30 intersections were obtained. Zones were created in the Streetlight interface to allow for obtaining the car and bicycle demands by direction. It should be noted that it was not always possible to obtain demand data for all intersection approaches and all intersections. In addition, in many cases, the demand for a certain direction is measured at the downstream end, as shown in Figure 2.4 for the intersection of Somerville Ave. and Prospect St., Somerville.
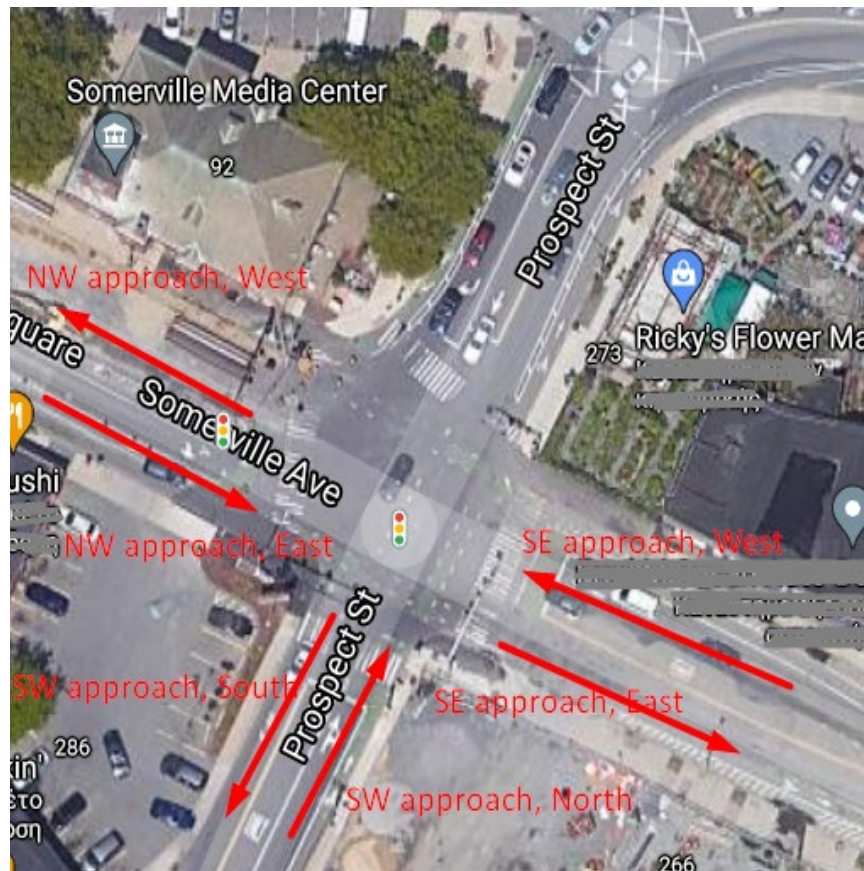
Figure 2.4: Example of approach naming convention

12

2.4   Field Data Collection

2.4.1   Installation

A total of 11 intersections were selected for field data collection in this study, with the main criteria of each study intersection having at least one approach with a bicycle box. The intersections were located in the cities of Boston and Somerville, with seven locations and four locations in each, respectively. Complete descriptions of each of these intersections, including a map layout of their proximity, is presented in Section 2.4.2. The field data collection procedures were adapted through the methods from the company Street Simplified. Following the approval of each of the 11 study intersections, the tech support from Street Simplified identified optimal camera locations in an effort to maximize the intersection capture. Once these camera layouts were finalized, a set of graduate students were tasked with going into the field to collect the data.

2.4.2   Study Sites

Boston

Figure 2.5 is a map showing locations of the seven study sites in Boston, Massachusetts.
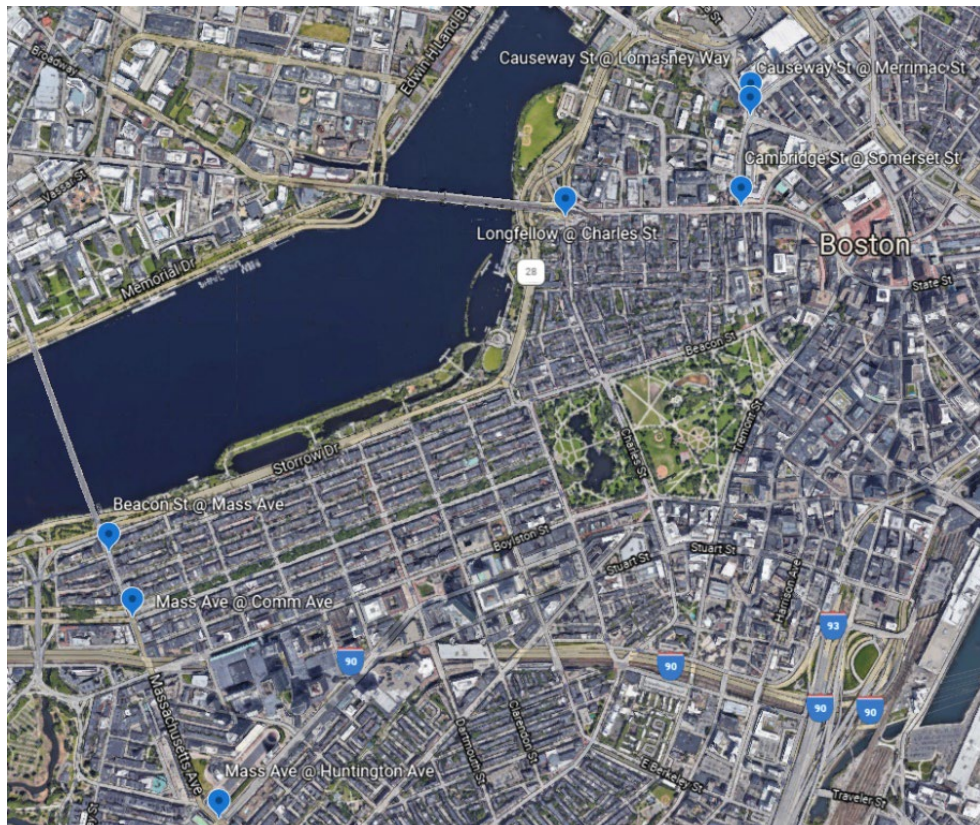
Figure 2.5: Study sites in Boston, MA

1. Beacon St. at Massachusetts Ave. (Installed Monday, 11/2/20)

Beacon Street at Massachusetts Avenue is a four-way signalized intersection, with Beacon Street approaching from the east as a one-way road, and Massachusetts Avenue approaching from the north and south. The westbound approach consists of a shared through and left-turn lane, a shared through and right-turn lane, and a separated bicycle lane. The southbound approach consists of a through lane, a shared through and right-turn lane, and a buffered bicycle lane. The northbound approach contains a through lane, a shared through and left-turn lane, and a conventional bicycle lane. The only bicycle box at this intersection is located on the southbound approach. Figure 2.6 shows photos of this study site.

Data for this approach were collected from Monday, November 2, 2020, at 12:30 p.m. to Tuesday, November 3, 2020, at 1:15 p.m.
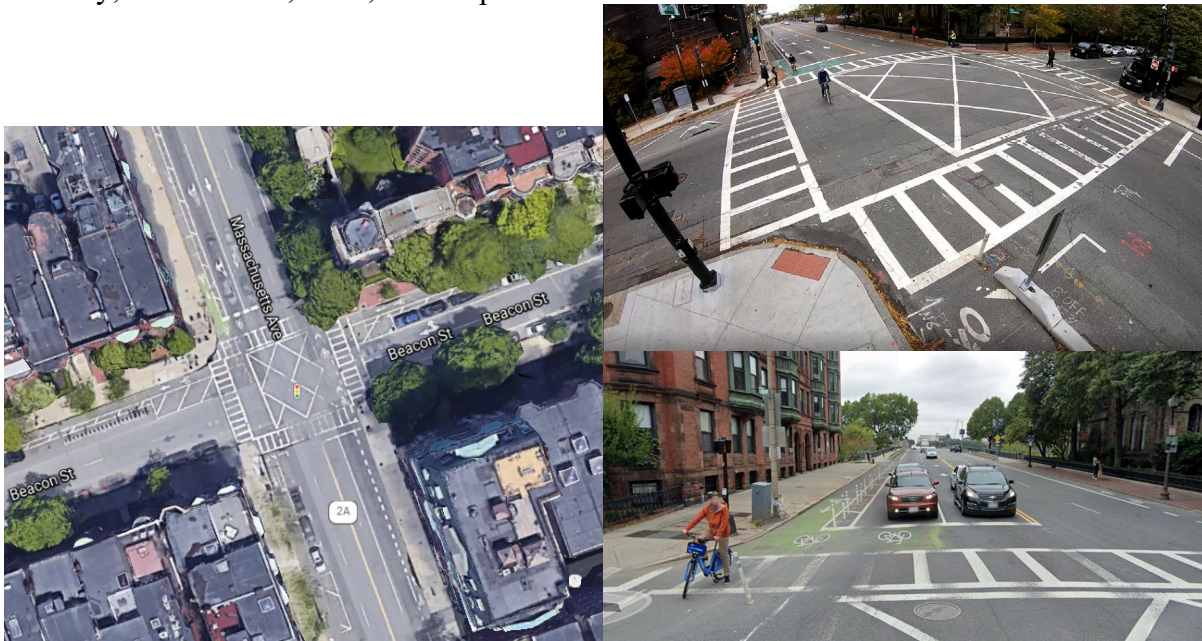
Figure 2.6: Intersection layout and camera views for Beacon St. at Massachusetts Ave.

2. Causeway St. at Lomasney Way (Installed Thursday, 11/5/20)

Causeway Street at Lomasney Way is a three-way signalized intersection with Causeway Street approaching from the northeast, Lomasney Street approaching from the northwest, and Staniford Street approaching from the south. The approach from Lomasney Street consists of a left-turn-only lane, two through lanes, and a conventional painted bicycle lane. The approach from Causeway Street consists of a right-turn-only lane, two left-turn-only lanes, and a two-way protected bicycle track. The northbound approach consists of a through lane, a shared through and right-turn lane, and a two-way protected bicycle track with a dedicated bicycle signal. There are bicycle boxes located at the Lomasney Street and Causeway Street approaches. Figure 2.7 shows photos of this study site.

Figure 2.7: Intersection layout and camera view for Causeway St. at Lomasney Way

3. *Causeway St. at Merrimac St. (Installed Thursday, 11/5/20)*

Causeway Street at Merrimac Street is a three-way signalized intersection, with Merrimac Street approaching from the east, Staniford Street approaching from the south, and Causeway Street approaching from the north. The approach from Causeway Street consists of one through lane and a shared through and left-turn lane. The northbound approach consists of two through lanes, a right-turn-only lane, and a two-way protected bicycle track with a dedicated bicycle signal. The westbound approach consists of a right-turn-only lane and a left-turn-only lane. The only bicycle box at this intersection is located on the westbound approach; however, there is a left-turn bicycle queue box located in the southbound approach. Figure 2.8 shows photos of this study site.
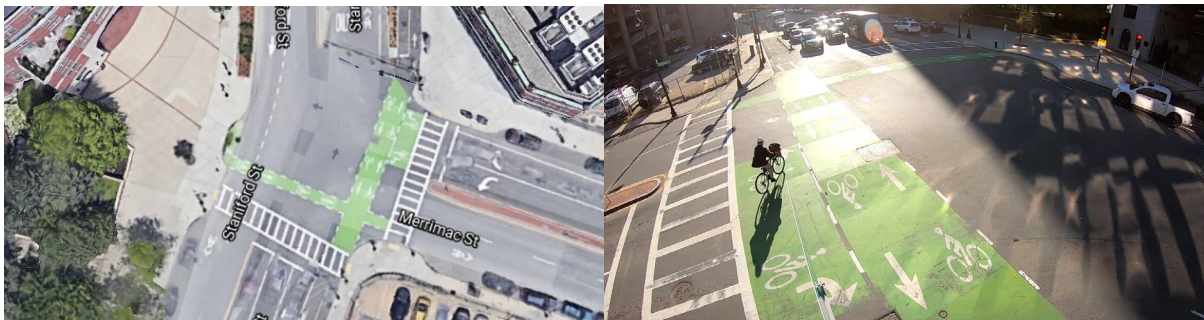
Figure 2.8: Intersection layout and camera view for Causeway St. at Merrimac St.

4. *Cambridge St. at Somerset St. (Installed Monday, 11/9/20)*

Cambridge Street at Somerset Street is a four-way signalized intersection, with Cambridge Street approaching from the east and west, Somerset Street approaching from the south, and Sudbury Street acting as a one-way street away in the north direction. The eastbound approach contains two left-turn-only lanes, a through lane, and a shared through and right-turn lane. The westbound approach contains a left-turn-only lane, a through lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The northbound approach has a shared through, left- and right-turn lane. The only bicycle box at this intersection is located on the westbound approach. Figure 2.9 shows photos of this study site.

Figure 2.9: Intersection layout and camera view for Cambridge St. at Somerset St.

5. *Massachusetts Ave. at Huntington Ave. (Installed Monday, 11/9/20)*

Massachusetts Avenue at Huntington Avenue is a four-way signalized intersection, with Huntington Avenue approaching from north and south, and Massachusetts Avenue approaching from the east and west. The eastbound approach consists of a through lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The westbound approach consists of a left-turn lane, a through lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The northbound and southbound approaches act as on/off ramps for Huntington Avenue. The southbound approach consists of a shared through and left-turn lane, and a right-turn lane. The northbound approach consists of a shared left-turn and through lane, and a shared right-turn and through lane. There are two bicycle boxes at this intersection, located on the westbound and eastbound approaches of Massachusetts Avenue. Figure 2.10 shows photos of this study site.
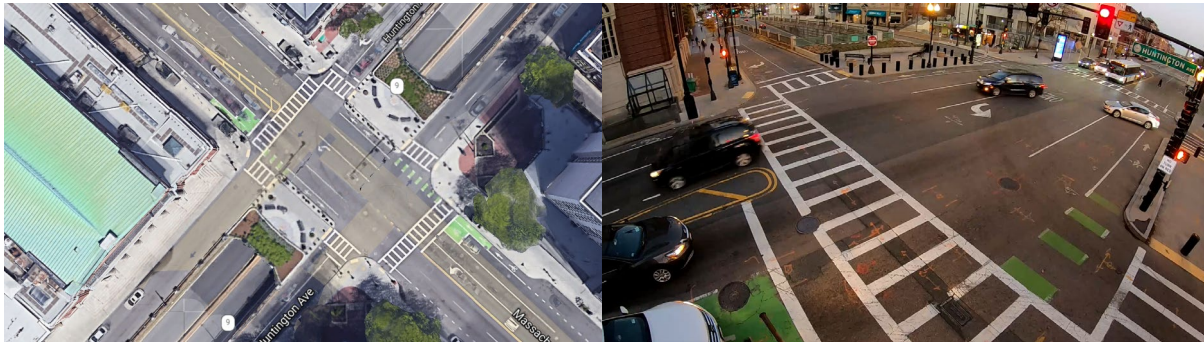
Figure 2.10: Intersection layout and camera view for Massachusetts Ave. at Huntington Ave.

6. *Longfellow Bridge at Charles St. (Installed Tuesday, 11/10/20)*

Longfellow Bridge at Charles Street is a complex five-way signalized intersection, with Longfellow Bridge approaching from the west, Cambridge Street approaching from the west, Charles Street approaching from the north and south, as well as a secondary eastbound approach considered as an off-ramp of Storrow Drive. The Longfellow Bridge approach consists of a left-turn lane, a through lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The southbound approach consists of two dedicated left-turn lanes and a through lane. The Storrow Drive off-ramp approach consists of a shared through and left-turn lane, and a shared through and right-turn lane. The only bicycle box at this intersection is located on the eastbound approach from the Longfellow Bridge. Figure 2.11 shows photos of this study site.

Figure 2.11: Intersection layout and camera view for Longfellow Bridge at Charles St.

7. Massachusetts Ave. at Commonwealth Ave. (Installed Tuesday, 11/10/20)

Massachusetts Avenue at Commonwealth Avenue is a four-way signalized intersection, with Massachusetts Avenue approaching from the north and south, and Commonwealth Avenue acting as a one-way street traveling in the eastbound direction. The southbound approach consists of a through lane, a shared through and left-turn lane, and a buffered bicycle lane that extends into a separated painted bicycle lane in the southbound direction. The northbound approach consists of a through lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The eastbound approach consists of a shared left-turn and through lane, a right-turn lane, and a conventional bicycle lane extending through Commonwealth Avenue traveling eastbound. The only bicycle box at this intersection is located on the northbound approach. Figure 2.12 shows photos of this study site.

Figure 2.12: Intersection layout and camera view for Massachusetts Ave. at Commonwealth Ave.

17

Somerville

Figure 2.13 is a map showing locations of the four study sites in Somerville, Massachusetts.
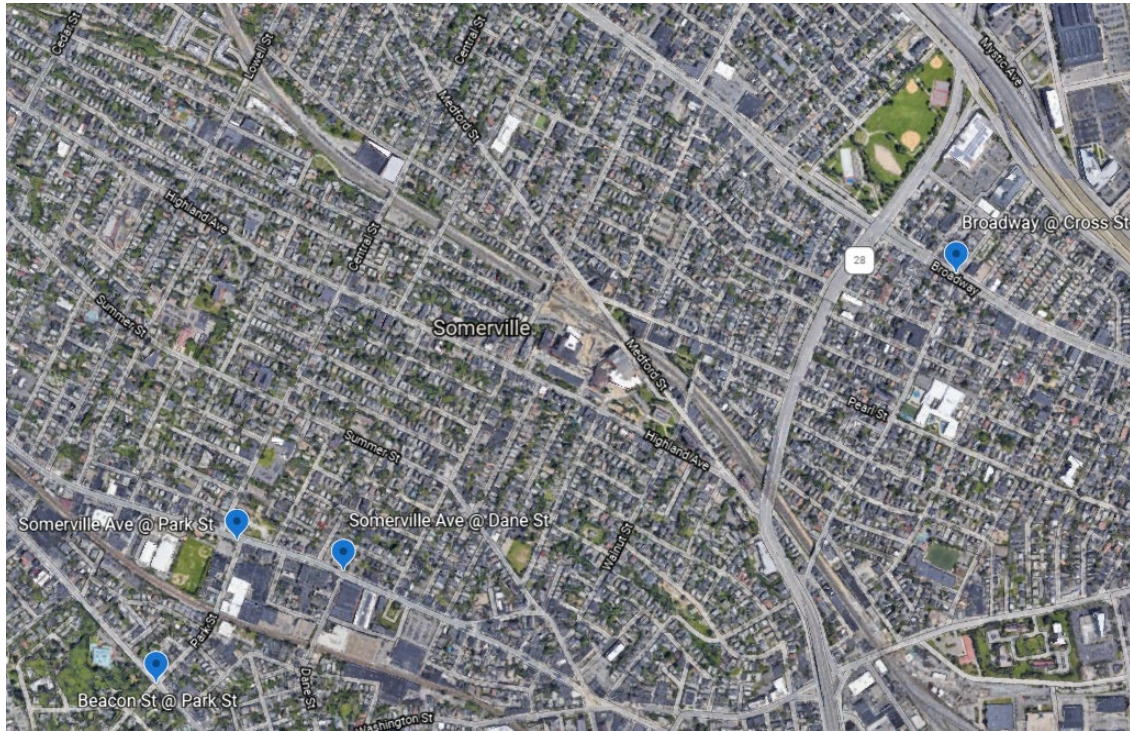
Figure 2.13: Study sites in Somerville, MA

8. Beacon St at Park St (Installed: Monday 11/16/20)

Beacon Street at Park Street is a four-way signalized intersection, with Beacon Street approaching from the east and west, Park Street approaching from the north, and Scott Street approaching as a one-way from the south. The eastbound approach consists of a shared through and left-turn lane, and a conventional painted bicycle lane that continues eastbound as a raised/separated bicycle lane. The westbound approach consists of a shared through and right-turn lane, and a raised/painted bicycle lane. The southbound approach consists of a shared left- and right-turn lane, and a conventional bicycle lane. The northbound approach consists of a shared through, left- and right-turn lane. This intersection contains three bicycle boxes, located on the southbound, eastbound, and westbound approaches. A notable characteristic of this intersection is that for the westbound approach on Park Street, there is a blocked area downstream of the bike box and before the intersection, prohibiting vehicles from entering the intersection (Figure 2.14). This could potentially lead to higher vehicle compliance rates and fewer right-hook near misses.
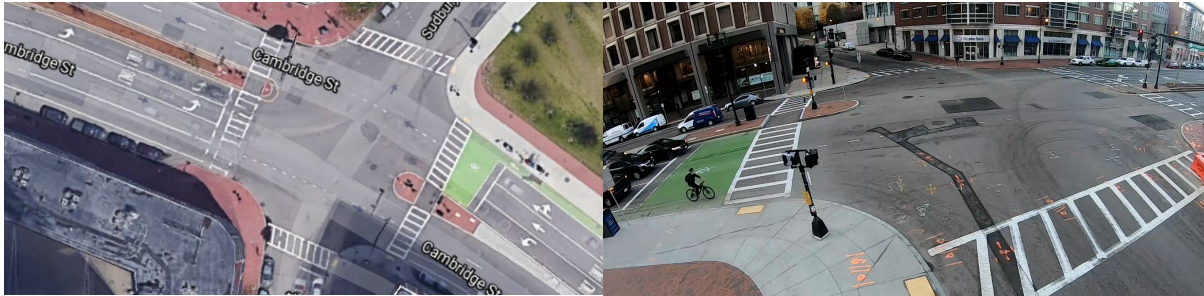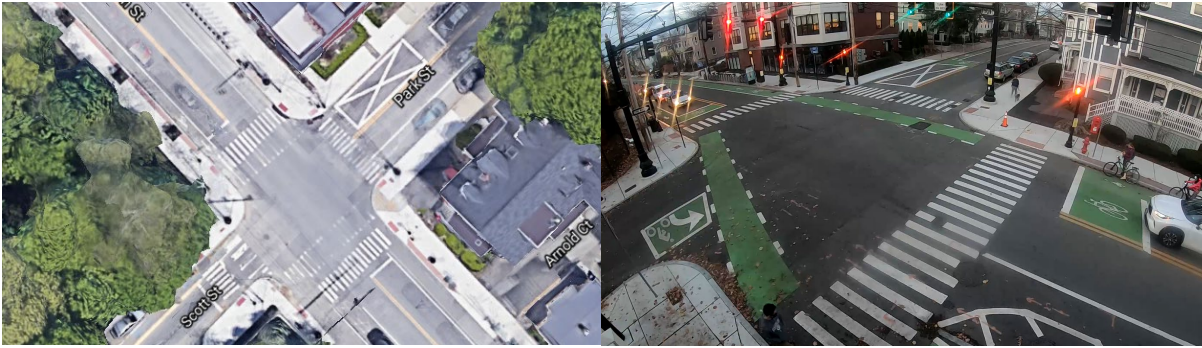
Figure 2.14: Intersection layout and camera view for Beacon St. at Park St.

9. *Broadway at Cross St. (Installed Monday, 11/16/20)*

Broadway at Cross Street is a four-way signalized intersection, with Broadway approaching from the east and west, and Cross Street approaching from the north and south. The eastbound approach consists of a left-turn lane, a through lane, and a shared through and right-turn lane. The westbound approach consists of a left-turn lane, a through lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The northbound and southbound approaches consist of a shared through, left- and right-turn lane. The only bicycle box at this intersection is located on the westbound approach of Broadway (Figure 2.15).
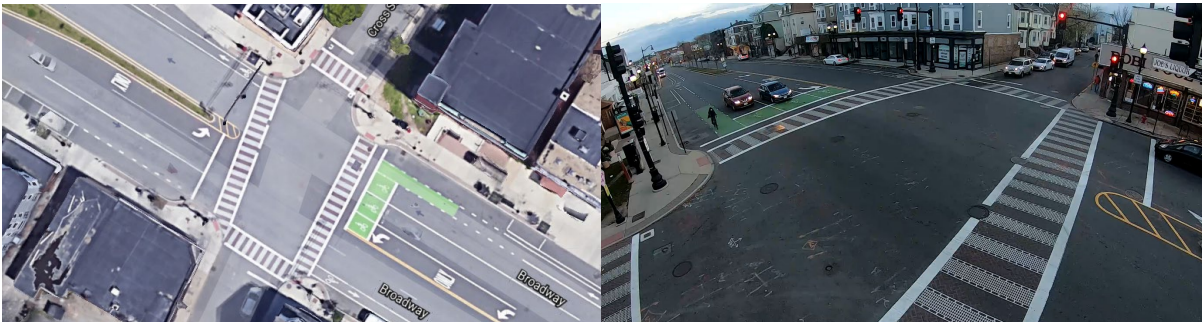
Figure 2.15: Intersection layout and camera view for Broadway at Cross St.

10. *Somerville Ave. at Dane St. (Installed Thursday, 11/19/20)*

Somerville Avenue at Dane Street is a four-way signalized intersection, with Somerville Avenue approaching from the east and west, Dane Street approaching from the south, and Granite Street from the north. The westbound approach consists of a left-turn lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The eastbound approach consists of a shared through, left- and right-turn lane, and a conventional painted bicycle lane. The southbound approach consists of a shared through, left- and right-turn lane. The northbound approach consists of a shared through, left- and right-turn lane, and a conventional painted bicycle lane. This intersection contains three bicycle boxes, located on the northbound, eastbound, and westbound approaches (Figure 2.16).

Figure 2.16: Intersection layout and camera view for Somerville Ave. at Dane St.

11. Somerville Ave. at Park St. (Installed Thursday, 11/19/20)

Somerville Avenue at Park Street is a four-way signalized intersection, with Somerville Avenue approaching from the east and west, Park Street approaching from the south, and a very low volume driveway approaching from the north. The eastbound approach consists of a right-turn lane, a shared through and left-turn lane, and a conventional bicycle lane splitting the two vehicle travel lanes. The westbound approach consists of a left-turn lane, a shared through and right-turn lane, and a conventional painted bicycle lane. The northbound approach consists of a shared through, left- and right-turn lane, and a conventional painted bicycle lane. This intersection contains two bicycle boxes located on the westbound and northbound approaches (Figure 2.17).
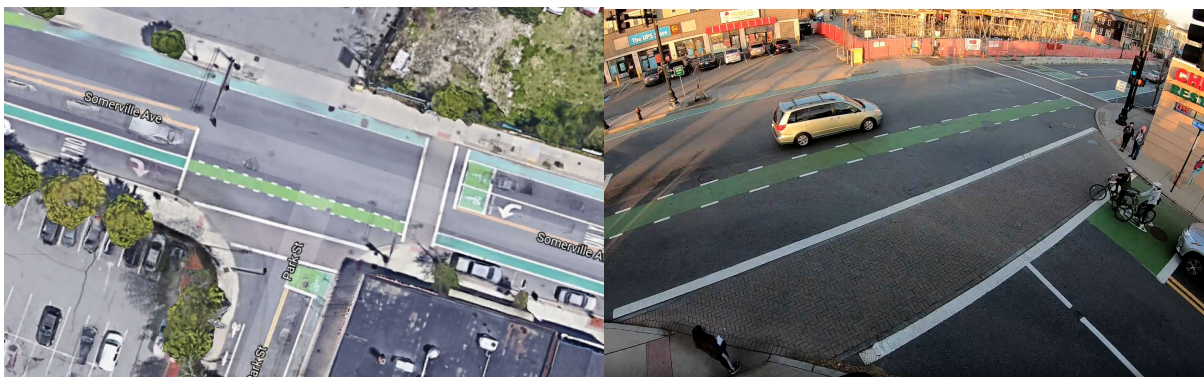
Figure 2.17: Intersection layout and camera view for Somerville Ave. at Park St.

2.4.3   Street Simplified Safety Analytics

Safety analytics and demand information were provided by Street Simplified after processing the video data recordings from the intersections described previously. It should be mentioned that Street Simplified safety analytics were provided for six of the aforementioned intersections, namely:

- Massachusetts Avenue at Beacon Street, Boston
- Cambridge Street at Somerset Street, Boston
- Beacon Street at Park Street, Somerville
- Broadway at Cross Street East, Somerville
- Somerville Avenue at Dane Street, Somerville
- Somerville Avenue at Park Street, Somerville

After processing the video recordings, Street Simplified provided various types of information through a web-based platform for each of the intersections, including street analytics such as vehicle and bicycle counts and vehicle speeds, as well as safety analytics such as near misses, pedestrians crossing on red, red-light running, speeding, and intersection blocking. For the purpose of this study, the focus was on the following events.

1. Turning movement counts (TMC) for vehicles and bicycles for the period of data collection, as well as for the identified morning and afternoon peaks for each intersection. These TMCs are illustrated by being superimposed on the intersection map, as shown for bicycles in Figure 2.18a.
2. Near misses as identified with the use of a surrogate safety metric, in particular, the post encroachment time (PET). PET is a commonly used surrogate safety measure that measures the time that elapses from the moment the first user passes from the conflict point until the second user passes from the same point. The platform provides flexibility in that the user can determine the desired PET threshold that determines whether an interaction is characterized as a near miss. PETs between 0 and 4.9 can be selected for the analysis. In addition, the severity of each of those near misses is reported and defined as follows:
   a. Severe: PET = 0s ~ 1s
   b. Moderate: PET = 1s ~ 3s
   c. Mild: PET = 3s ~ infinity

   Importantly, near misses can be queried by user sequence. For the focus of this study, this meant that near misses could be queried based on whether the bicyclist or the motorist arrived first at the conflict point. This is important, especially for vehicle-bicycle crashes, as it could be used to infer the level of severity of that crash, e.g., a crash where the car was first and the bicycle second is expected to be associated with low risk for the bicyclist. However, this is not always true, as there are cases where the car is the first user by cutting off the bicyclist, which could result in a severe crash. Near misses can also be queried by approach, movement, time period, speed for either of the two users involved in the near miss, severity, PET, and speed. Furthermore, near misses are also illustrated via images illustrating the trajectories that are involved in the near miss as well as the potential conflict point; see Figure 2.18b.

In addition to the data presented on the web-based platform, the trajectories of vehicles and bicycles were provided to the research team. This allowed for studying bicyclist behavior, i.e., bicyclist positioning within the bike box and its correlation to their turning movement, as explained in Section 2.4.5.

(a) Bicycle turning movement counts

(b) Near miss between a car (green) and a bicycle (light blue)

Figure 2.18: Street Simplified web-based platform showing bicycle turning movement counts and near misses

2.4.4   Motorist Behavior at Bike Boxes

The analysis of motorist behavior focused on driver compliance. Data on driver compliance were collected manually with the use of the Behavioral Observation Research Interactive Software (BORIS) tool *(22)*. This tool provides an interface that allows the user to record events of interest while watching a video recording. Figure 2.19 shows the interface; the left side of this interface shows the video and controls for the video recording, while the window to the right includes the recorded observations. Additional information about the predefined behavior (e.g., vehicle encroachment) and the video are shown at the bottom of the interface.
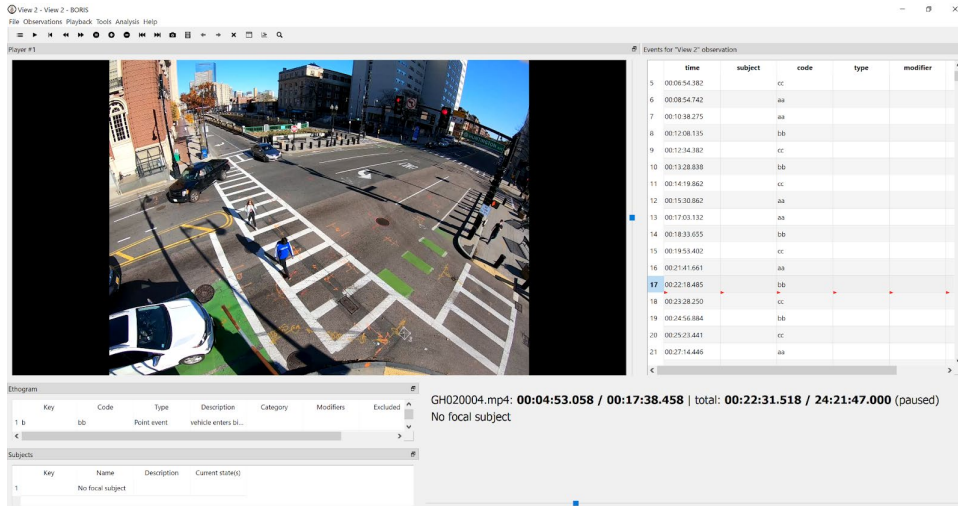
Figure 2.19: BORIS interface

Given the objective of this study to determine how motorists are using bike boxes, the manual field data processing focused only on data during the red signal indication for each approach and movement. More specifically, the focus was on recording whether each of the motorized vehicles that stopped during the red signal indication stopped properly (i.e., in advance of the bike box). A vehicle was considered not complying, i.e., encroaching upon the bike box if any part of the vehicle protruded past the white bike box perimeter line, as shown in Figure 2.20. These events were obtained for each bike box that was visible in each video and each traffic lane upstream of the bike box, for a total of 11 bike boxes at the six intersections mentioned previously.
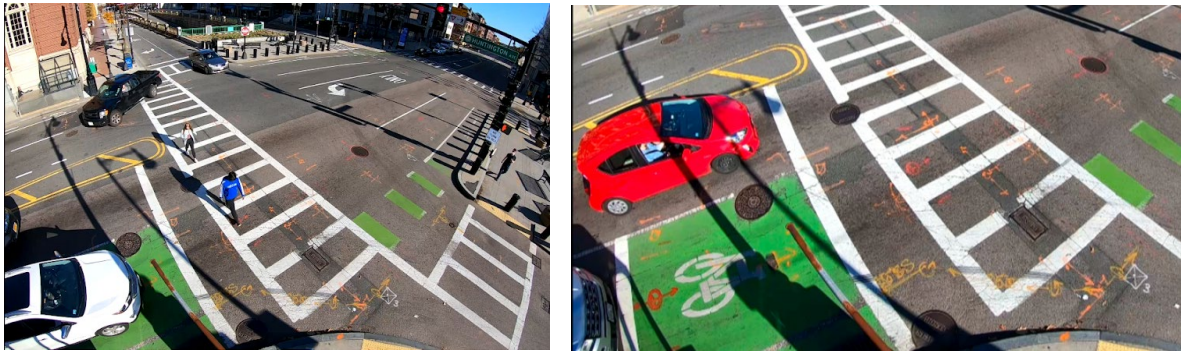
(a) Vehicle encroaching upon the bike box   (b) Vehicle properly stopped

Figure 2.20: Examples of vehicles stopped at bike box approaches

In the case that a vehicle turned right on red when not allowed or more generally ran a red light, that event was also marked as not properly stopped. In addition, the vehicle to follow this red-light runner was also observed in terms of bike box and signal control compliance, as long as it was supposed to stop upstream of the bike box given a red signal indication. For example, if the first vehicle in line were to pass through the red light and the next in line drives up and stops properly while that light is still red, record the first vehicle as interfering with the bike box and mark the second as properly stopped. When such events were present, additional comments were added next to the recorded observations to facilitate post-processing. Additional comments were also added in cases where views were blocked, for example, by the presence of a large truck or to record and exclude periods during which the signals were operating as flashing (yellow or red). Periods of blocked views or flashing signals were excluded from the compliance analysis.

It should be noted that the compliance rates presented in Section 4.3.2 include the vehicles that turned right on red (when allowed) or went through the intersection (performing any type of movement) during a red light indication (i.e., red-light runners). This was done in order to assess overall compliance at intersection approaches with bike boxes.

2.4.5   Bicyclist Behavior at Bike Boxes

Bicyclist behavior at bike boxes focused on the location bicyclists stop as well as the type of movements they perform when properly locating themselves within the bike box after arriving during a red signal (Figure 2.21). In particular, this study focused on three critical regions at the intersection, including the bike box region (A), the bike lane region upstream

of the bike box (C), and the area linking the colored bike box and the ingress bike lane (B), as pictured in Figure 2.21a. When a multilane configuration with a dedicated left-turn lane is present, the bike box region (A) is further separated into two sub-regions labelled as AL and AR, respectively, as shown in Figure 2.21b.

The bicyclist behavior analysis was conducted by analyzing bicycle trajectories at the 11 bike boxes of the six intersections mentioned above. Observations were collected for the duration of the red signal throughout the data collection period at each bike box approach. By analyzing the concentration of bicycle trajectories in the identified regions, the team could infer how bicyclists understand and utilize bike boxes.
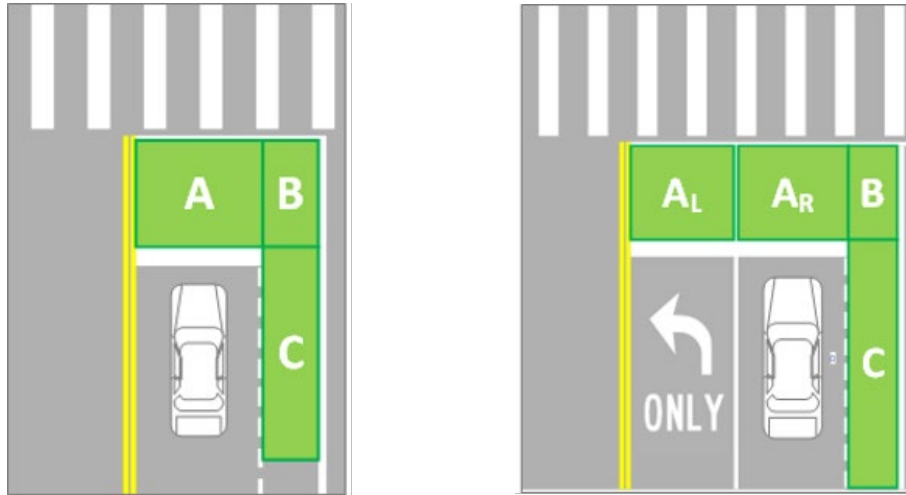
(a) Bike box at a one-lane approach

(b) Bike box at an intersection approach with a left-only lane

Figure 2.21: Bike box stopping locations

3 Literature Review

3.1 Bike Box Design Guidelines across the United States

Bike box design guidelines have been fairly limited in the U.S., with only a few recent guidebooks focusing on bicycle facilities providing some general information that is not always consistent among these publications. Commonly used design guidebooks tend to provide general guidelines on types of material to be used for the pavement markings or do not provide any guidelines at all. For example, neither the main roadway design guidebook, the American Association of Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets (23),* nor AASHTO's publication focusing on bicycle facilities, *Guide for the Development of Bicycle Facilities (24),* includes any mention of bike boxes.

While bike box design specifics are not included in the latest version (2009) of the *Manual on Uniform Traffic Control Devices* (MUTCD) *(5),* a 2016 MUTCD interim approval for optional use of an intersection bicycle box *(3)* has provided some specific guidelines on their design. These guidelines were developed following a set of experiments that concluded the success of bike boxes in reducing the number of conflicts, avoidance maneuvers, and encroachment of crosswalks, as well as a general understanding of both bicyclists and drivers on the purpose and proper use of such infrastructure.

The FHWA *Separated Bike Lane Planning and Design Guide (2)* provides some additional guidance in terms of the bike box geometric design, recommending a depth between 10 and 16 feet, and a bike box width that should be at least equal to the width of the bike lane, buffer space, and at least one (adjacent) traffic lane. It also mentions the possibility of pairing bike boxes with passive detection for advanced green and the extension of the bike box across all traffic lanes to accommodate left-turning bicyclists. Finally, it describes the same guidelines as those presented in the MUTCD regarding pavement markings and signage.

FHWA's *Bicycle Safety Guide and Countermeasure Selection System (25)* includes some guidance on the implementation of bike boxes under the "Intersection Markings" section. It recommends the implementation of bike boxes at approaches with high volumes of commuter bicyclists and high volumes of right-turning vehicles next to right-side bike lanes. The guidance includes the installation of "No Right Turn on Red" signage. This guide also provides information on the cost of implementing bike boxes.

The NACTO *Urban Bikeway Design Guide (15)* is the only document to date providing a comprehensive set of guidelines that includes detailed guidance on required, recommended, and optional bike box design characteristics. In addition, NACTO lists signalized intersection characteristics that would benefit from the implementation of a bike box, where 1) there is a high volume of bicyclists and/or motorists and a high ratio of left-turning bicyclists or right-turning motorists; 2) there are many conflicts between turning motorists and bicyclists; 3) a

left turn is required for bicyclists to follow a designated bicycle route or when the bicycle lane moves from the right to the left side of the street.

NACTO *(15)* requires the bike box depth to be between 10 and 16 feet, the installation of a "No Turn on Red" sign, and the presence of a bicycle stencil within the bike box. It recommends additional signage such as "Stop Here on Red," the use of colored pavement, an ingress lane with a length of 15 to 50 feet, and a "Yield to Bikes" sign. Optional guidelines provided by NACTO *(15)* include the presence of a "Wait Here" marking at the stop line, the placement of an additional stop line 7 feet upstream of the bike box, locating them with some distance from the crosswalk, extension of bike boxes to multiple lanes to facilitate left-turning bicyclists, combining them with bike signals to provide additional priority to bicyclists, and implementing active signs to better inform motorists about potential conflicts.

In addition to the aforementioned guidelines, states and cities have developed their own bicycle facility guidelines. The Massachusetts Department of Transportation was the first state to publish guidelines for separated bikeway design *(26)*. The District Department of Transportation *(27)* and the city of Memphis, Tennessee *(28),* have also published their own bicycle facility design manuals or guidelines specific for complete streets that also reference bicycle facilities. However, none of these documents includes any guidelines on the design of bike boxes. A few exceptions are bikeway guidelines by the Maryland State Highway Administration *(17),* the city of Portland Bureau of Transportation in Oregon *(13),* the city of Boston *(18),* and the city of Los Angeles *(19)*.

The Portland Bureau of Transportation (PBOT) recommends the use of bike boxes when there are high volumes of right-turning motorists and bicyclists (when right-turning motor traffic exceeds 25% or right-turning bicyclists exceed 15%), high rates of turning conflicts, generally high motorist and bicycle volumes, and a high number of queueing bicycles *(13)*. The design guidelines that PBOT suggests differ compared to the ones published by NACTO *(15)* and FHWA *(2)* primarily in the box depth recommendation, which is higher (13 to 16.4 feet instead of 10 to 16 feet). In addition, it recommends the use of a lead-in bike lane (similar to the ingress lane recommended by NACTO) to allow for bicyclists to bypass motorist queues in order to enter the bike box and recommends a width of at least 5 feet and a length at least equal to the queue that forms from motorists at that intersection.

The Boston *Complete Street Guidelines (18)* recommends the use of bike boxes when turning volumes are high but also mentions that bike boxes should be considered for every project targeted at improving bicycle facilities. This document lists guidelines related to the prohibition of right-turn-on-red as well as the need for a minimum depth of 13 feet. In addition, it recommends placing the bike lane to the left of the right-turning lane (when such a lane exists) and allowing right-turn-on-red when desired by ending the bike box at the edge of the bike lane. Finally, it recommends the use of MUTCD *(5)* to guide the installation of proper signage.

Maryland Highway's *Bicycle Policy and Design Guidelines (17)* include the same guidelines as those published in the NACTO *Urban Bikeway Design Guide (15),* with the exception of the bike box depth, for which a minimum of 8 feet is recommended (NACTO and FHWA

both suggest a minimum depth of 10 feet). On the other hand, the Los Angeles City Planning Department suggests a depth of 14 feet *(19)*.

A summary of the U.S. guidelines provided by different publications at the national level is presented in Table 3.1. It should be noted that many of these guidebooks are more than five years old and are in the process of being updated (e.g., AASHTO Bike Guide *[24]* and MUTCD *[5])*, which might explain why bike boxes are not in the current editions.

Table 3.1: Summary of bike box design guidelines

	Bike Box Depth [ft]	Bike Box Width [ft]	Bicycle Stencil	Green-colored Pavement	"Stop Here on Red" Sign	"Wait Here" Pavement Marking	"No Turn on Red" Sign	"Yield to Bikes" Sign	Countdown Pedestrian Signal	Ingress Bicycle Lane [ft]	Egress Bicycle Lane [ft]
MUTCD *(5)*	>10		required	optional	recommended		required		required	recommended > 50	
NACTO Urban Bikeway Design Guide *(15)*	10–16		required	recommended	recommended	optional	required	recommended		recommended 25–50 (if colored)	recommended
Separated Bike Lane Planning and Design Guide *(2)*	10–16	Bike lane, buffer space & adjacent travel lane (min. required)		optional	required		required	optional		25	

3.2 Bike Box Design: Research Findings

A review of relevant real-world implementations reveals that bike box design features affect road user behavior. In particular, the size of the bike box and visibility of the signage have been reported as having an impact on bicyclist and motorist behavior at bike boxes. Coloring of the bike box and driver education have also been cited as influential factors on user behavior *(7)*. In addition, studies have mentioned that the commonly used 8-foot bike boxes are often not sufficient for accommodating bicyclist maneuvers. While bigger bike boxes are needed to safely accommodate high bicyclist demands, bike boxes that are longer in depth can potentially lead to higher rates of motorist encroachment *(1)*.

General recommendations regarding the application of bike boxes have also been reported. In particular, research studies based on real-world implementations recommend the use of bike boxes at intersections with high bicycle volumes and high demand for vehicular through movements *(1,6,9)*. However, decisions should be made with caution for areas with low bicycling volumes, as this might be an indication of low safety perceptions rather than a reflection of limited bicycling demand *(9)*. Newman *(6)* reports that bike boxes have been implemented successfully when through traffic does not exceed 1,000 vehicles per hour and suggests a threshold of three bicyclists per red phase during peak hours as the deciding factor for implementing a bike box at an intersection. Areas with a history of high numbers of crashes, especially right-hook crashes, as well as intersections that lack downstream bicycle infrastructure (e.g., bike lanes) should consider implementation of bike boxes. On the other hand, when a continuous colored bike lane exists through the intersection, the need for a bike box diminishes *(1)*. Finally, the condition of the pavement needs to be considered before implementing a bike box.

3.3 Performance at Bike Boxes

3.3.1 Safety Performance

Driver Compliance
While early studies on bike boxes reported issues with driver compliance and bike box encroachment *(6,7,29),* several recent studies have concluded that bike boxes instill a high rate of driver compliance, measured based on whether drivers encroached on the bike box or not *(12,16)*. The types of turning movement and driver familiarity with bike boxes were found to be significant contributors to drivers' encroachment behavior, with less familiar drivers and drivers turning right or left being more likely to encroach upon the bike box *(16)*. The same study also found that familiar drivers were stopping farther upstream of the bike box as compared to unfamiliar drivers. Studies also report the influence of vehicle demand on driver compliance (e.g., encroaching the bike box), mentioning that this is especially apparent at the end of signal cycles when demand is high *(7)*. So far, no concrete conclusions have been drawn concerning the impact of the bike box color on driver encroachment of the bike box, as some studies have reported conflicting results from different sites *(1)*; yet even

in those cases, there was agreement that the presence of colored bike boxes resulted in higher bicyclist presence awareness.

Bicyclist Compliance

Bicyclist compliance has generally been higher than that of drivers from the onset of bike box installations across the globe *(6,11)*. Dill et al. *(12)* found that more than 70% of the bicyclists used bike boxes appropriately, but the bicyclist position was affected by the bicyclist demand. While some studies that followed reported lower rates of proper bike box use by bicyclists, they reported high rates of bicyclists stopping in front of vehicles (i.e., whether in the bike box or not), showing that just the presence of the bike box can motivate behavior that improves bicyclist visibility, even when not used as intended. Newman *(6)* reports that both cyclists' and drivers' comfort reduces at bike boxes due to bicyclists stacking ahead of cars and cars queuing behind bicyclists.

Bicyclist compliance, as well as bicyclist positioning and comfort, were heavily influenced by driver behavior and specifically driver compliance *(6,11)*, with studies reporting low compliance rates when motorist encroachment rate is high *(7,29)*. Another factor affecting bicycle behavior and proper use of a bike box is the presence of color with colored bike boxes motivating higher utilization of this area by bicyclists as well as higher rates of motorists stopping behind the stop line *(1)*. In addition, surveys reveal that colored bike boxes are preferred by both bicyclists and motorists *(30)*. Finally, bicyclist behavior has been associated with the presence of other bicycle infrastructure upstream and downstream of the intersection where the bike box is implemented *(1)*. For example, the presence of a continuous bike lane through the intersection might motivate bicyclists to stay within the bike lane rather than change lanes to position themselves within the bike box in anticipation of the green light.

Factors Affecting Compliance

Overall, factors thought to be contributing to noncompliant driver behavior are lack of comprehension of how bike boxes are supposed to be used, lack of acceptance of bicyclists or bicycle-specific infrastructure as legitimate, and altered behavior (e.g., higher likelihood to encroach upon the bike box) when no bicyclists are present *(6,11)*. Noncompliant bicyclist behavior has been attributed to habit, lack of awareness of bike box operations, perception of safety, and avoidance of overpassing drivers and stopping in front of them *(11)*. Overall, the behavior and use of bike boxes by both drivers and bicyclists might be affected by the presence and demand of other road users, as well as other infrastructure changes and factors affecting user behavior that are not easily identifiable *(6,11,31)*.

Education and Design Changes to Improve Compliance

Bicyclist and driver education, as well as enforcement, have been reported as ways to improve compliance *(1,6,7,11,12,29,31,32)*. While driver compliance at bike boxes is generally high, even for motorists who are not familiar with this type of bicycling infrastructure, public outreach and education are still essential to ensure proper use by both drivers and bicyclists and to improve safety *(11,12)*. In the study by Hunter, public outreach

was achieved via press releases in local newspapers and sign boards explaining how to use the bike box in close proximity to its location in Eugene, Oregon *(7)*.

In terms of design, studies suggest that colored bike box surface contributes to increased driver compliance *(7)*, although more recent studies have not been able to confirm the positive correlation between colored surface and compliance *(12)*. Markings and pavement signs such as "Wait Here" have been reported as beneficial for driver compliance. The need for proper maintenance that ensures visibility of these markings has also been emphasized *(4)*. Overall, further research is needed to determine the impact of geometric and in general design characteristics of bike boxes on driver and bicyclist compliance, as well as the appropriate types of educational campaigns and outreach activities that can promote safe behavior of both bicyclists and motorists.

Conflicts/Crashes

A major reason for implementing bike boxes is the need to mitigate right-hook crashes at intersections. Increased yielding rates to bicyclists from motorists turning right and reduced conflicts (and avoidance maneuvers by bicyclists) have been reported in the presence of bike boxes in the United States *(1,12)* and the United Kingdom *(29,31)*. In one study, the impact of pavement color appeared to have a negative impact on the avoidance maneuvers compared to the white-outlined bike box *(1)*.

When investigating actual crash data at bike box locations in New Zealand, Newman *(6)* found that driver-bicyclist crashes were reduced after the implementation of bike boxes. However, there are also studies that have seen increases or no changes in conflicts or crashes when bike boxes were implemented. For example, bicycle-motorized vehicle crashes in Portland, Oregon, doubled at some of the bike box intersections *(33)*. Another study by Hunter *(7)* found that there were no differences in the number of conflicts between motorists and bicyclists at a bike box implemented to ensure continuity of a bicycle lane (from left to right) in Eugene, Oregon. However, the same study found that when the bike box was used by bicyclists as intended, there were no conflicts. Overall, the number of conflicts and impact of bike boxes on safety are highly dependent on the bicycle demand and intersection configuration (bike box dimensions and color) as well as on driver compliance.

A challenge in directly assessing safety at bike boxes is that conflicts can be rare and hard to capture in a few hours of video recordings, especially when bicycle or vehicle demands are low *(6)*. An additional issue with assessing bicyclist safety is the low reporting rate of motorist-bicyclist crashes *(34)*. Finally, due to lack of data, assessing the severity shifts of crashes becomes a challenge.

Bicyclist Traffic Signal Violations

Studies in the United Kingdom have found that signal violations by bicyclists in the presence of bike boxes can be as low as 20% *(32,35)*. Loskorn et al. *(1)* also reported an increase in the number of bicyclists who moved through the intersection during a red light. However, a study in Eugene, Oregon, could not determine any difference in signal violations by bicyclists in the before-and-after periods of bike box implementations *(7)*. When comparing

safety implications of bike boxes in the presence or absence of a bike signal, Casello et al. *(9)* reported that the combination of a bike box with an advanced bike signal instilled the safest bicyclist behavior, while Wheeler and Wheeler et al. *(32,35*) found that a bike signal can be eliminated when a bike lane exists and the bike box is colored.

Safety Perception

Safety perception and, therefore, the potential for a bicyclist to utilize a bike box are highly correlated with driver compliance and, in particular, the frequency and extent of cars encroaching on the bike box *(7,29,31).* Safety perception has also been associated with the depth of bike boxes, with studies reporting that a depth lower than 3 meters resulted in bicyclists feeling unsafe. In addition, surveys reveal that colored bike boxes were preferred by bicyclists and motorists *(6).*

Overall, there is consensus that bike boxes result in an increased perception of safety by both motorists and bicyclists *(6,11,12,31,36).* Yet, in one study, motorists mentioned that they did not always like bicyclists aggregating in front of them *(6).* In particular, Dill et al*. (12)* reported that more than 75% of bicyclists perceived the presence of a bike box as a factor contributing to increased safety. Wang and Akar *(36)* found that this increased safety perception existed regardless of bicycling experience.

3.3.2 Operational Performance

While the operational impacts of bike boxes have not been extensively studied, Wall et al. *(31)* reported that bike boxes did not result in additional motorist delays at the intersection or changes in demand patterns and turning rates. The only potential impact was the loss of efficiency due to the prohibition of right-turn-on-red.

3.4 Summary of Literature Review

The most commonly listed guideline for bike box implementation is the prohibition of right-turn-on-red and the need for a "No Turn on Red" sign. Guidelines on the depth of the bike box vary, suggesting a minimum depth that ranges from 8 to 14 feet. In terms of the length of the bike box, it can vary from covering one to multiple lanes across the stop line. Many guidebooks recommend the use of colored surfacing, although research is not conclusive about its impact on compliance and in general on motorist and bicyclist behavior. Notably, bike boxes are still experimental and, based on MUTCD implementation of such, bicycle infrastructure should be first approved by FHWA.

The function of bike boxes is generally understood by both bicyclists and drivers. This high level of comprehension has motivated compliant behavior and safety improvements at signalized intersections. Both bicyclist and motorist demand and their respective behaviors were found to be affecting the other user type's compliance and comfort at bike box locations. While there is a general expectation on colored surfacing having a positive impact on compliance and therefore, safety, studies have been inconclusive, with some reporting positive trends and others no change in behavior. Safety perception is also improved at bike

boxes and is correlated with both drive compliance and the geometric design of the bike box (e.g., depth). No significant operational performance changes have been reported, with the exception of the potential for a small loss of efficiency due to the prohibition of right-turn-on-red.

Despite the fact that numerous bike box studies have been performed over the past 10 years in the United States, a comprehensive understanding of how bike box design and user comprehension affect the safety performance of bike boxes is missing.

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4 Results

4.1 Bike Box Inventory

4.1.1 Survey Results

The survey that was administered to Massachusetts municipalities resulted in a total of 69 responses from all six MassDOT districts, which were distributed as shown in Table 4.1. Three out of the six districts also responded confirming bike box locations and suggesting an additional one that falls under the jurisdiction of their district.

Table 4.1: Distribution of survey responses from municipalities

MassDOT District	Number of Municipalities
1	8
2	15
3	13
4	13
5	12
6	8
Total	69

These responses allowed the team to identify 91 bike box locations in the Commonwealth, which can be found on a map at the following link, along with their design characteristics that were obtained: http://massdot.ecs.umass.edu/Bikebox/.

The open-ended part of the surveys also allowed for some interesting observations:

- Cities and towns expressed interest and, in some cases, their intention to implement bike boxes.
- In some cases, funding for the implementation of bike boxes was provided by MassDOT's Complete Street projects or the Shared Streets and Spaces Program.
- Issues related to green paint were raised, e.g., slip hazards, but also confirmation from a city that has used green-colored pavement reporting that it has held up fairly well on a highly trafficked area.
- High driver compliance was observed, even in areas with low bicycle demand.
- Objection to the use of bike boxes as a means to facilitate bicyclists' intersection crossings.
- Ignorance as to what a bike box is.

While some of these observations are encouraging in implementing more bike boxes, others illustrate the need for educating the local engineering workforce on bicycle treatments that could improve safety for all users and promote bicycling.

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. All the inventory data can be accessed through http://massdot.ecs.umass.edu/Bikebox/. This web page includes all 91 bike boxes inventoried in this study. Figure 4.1 shows an example of the GIS web page and the corresponding LiDAR point cloud data viewer page.
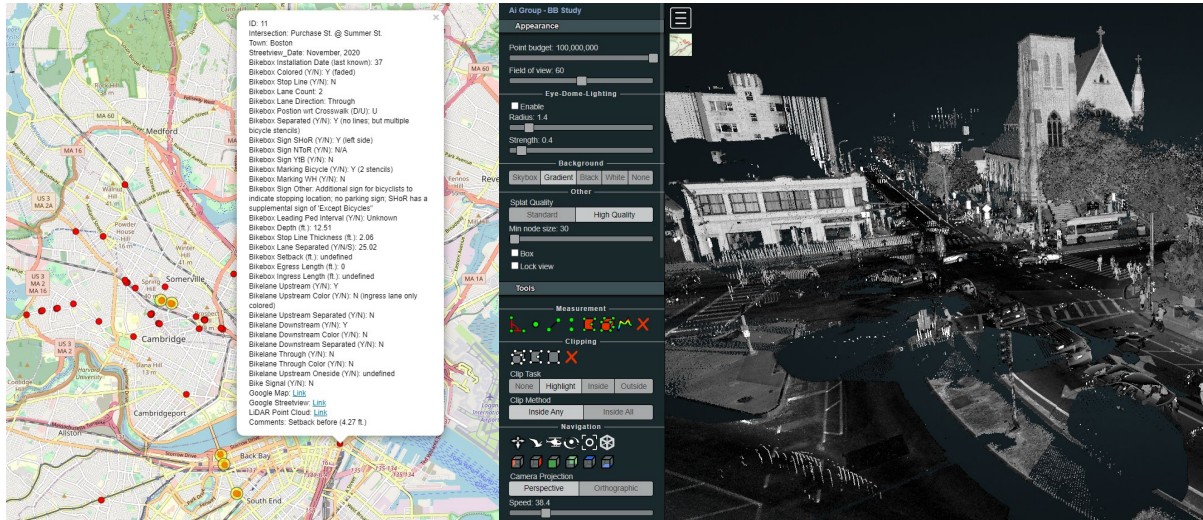
(a) GIS bike box inventory   (b) LiDAR point cloud data viewer

Figure 4.1: Data visualization for bike box locations and LiDAR data

The detailed design characteristics of the 21 bike boxes 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. All of them, with the exception of one, have the bike box located upstream of the crosswalk; the bike box that is located downstream of the crosswalk presents a negative setback, which has been excluded from the calculations of the statistical measures.

Overall, the average bike box depth indicates that bike boxes in Massachusetts are generally designed with depths that are on the lower end of the requirements as expressed in the various guidebooks. In particular, the scanned bike boxes have an average depth of 11.4 feet, while the requirement is between 10 and 16 feet.

Table 4.2: Bike box design dimensions

Intersection	Bike Box Depth (ft)	Bike Box Stop Line Thickness (ft)	Bike Box Setback (ft)	Egress Lane Length (ft)	Ingress Lane Length (ft)
Main St. with New South St. @ State St., Northampton	12.2	0.5	40.7	0.0	97.9
Route 9 (Russell St.) Westbound @ Middle St., Hadley	9.0	0.9	0.0	0.0	0.0
Route 9 (Russell St.) Eastbound @ Middle St., Hadley	9.0	0.9	0.0	0.0	0.0
Somerville Ave. Westbound @ Prospect St., Somerville	11.3	0.9	10.6	Unknown	Unknown
Somerville Ave. Eastbound @ Prospect St., Somerville	10.3	0.9	14.4	Unknown	125.4
Prospect St. @ Somerville Ave., Somerville	9.4	0.8	0.0	Unknown	42.6
Massachusetts Ave. @ Beacon St., Boston	10.6	1.8	0.0	0.0	27.5
Main St. (becomes Columbia St.) @ Sidney St., Cambridge	11.0	2.1	3.5	16.2	0.0
Longfellow Bridge (becomes Cambridge St.) @ Charles St., Boston	17.0	1.1	3.2	0.0	217.5
Cambridge St. @ Somerset St. (becomes Sudbury St.), Boston	15.8	0.4	-4.3[+]	0.0	105.6
Purchase St. @ Summer St., Boston	12.5	2.1	25.0	0.0	37.0
Merrimack St. @ Staniford St., Boston	9.4	0.9	0.0	0.0	0.0
Causeway St. Westbound @ Lomasney Way, Boston	13.2	1.1	0.0	0.0	0.0
Lomasney Way Southbound @ Causeway St., Boston	14.5	1.1	0.0	68.2	0.0
Massachusetts Ave. @ Commonwealth Ave., Boston	12.2	0.9	5.0	43.5	21.2
Massachusetts Ave. Westbound @ Huntington Ave., Boston	12.6	1.0	3.9	37.8	15.7
Massachusetts Ave. Eastbound @ Huntington Ave., Boston	12.5	1.1	3.9	15.9	18.9
Webster Ave. @ Prospect St., Somerville	9.4	1.0	0.0	0.0	0.0
Elm St. @ Somerville Ave., Somerville	10.2	1.0	2.5	0.0	0.0
Somerville Ave. Westbound @ Beacon St., Somerville	10.9	1.2	2.0	44.5	417.8

Intersection	Bike Box Depth (ft)	Bike Box Stop Line Thickness (ft)	Bike Box Setback (ft)	Egress Lane Length (ft)	Ingress Lane Length (ft)
Beacon St. Northbound @ Somerville Ave., Somerville	10.3	1.6	2.6	0.0	0.0
Mossland St. @ Somerville Ave., Somerville	11.1	1.0	2.5	0.0	0.0
Somerville Ave. Westbound @ Park St., Somerville	11.0	1.0	3.9	227.3	162.3
Park St. @ Somerville Ave., Somerville	9.4	1.1	0.0	0.0	73.6
Dane St. @ Somerville Ave., Somerville	12.7	0.9	3.2	0.0	47.1
Somerville Ave. Westbound @ Dane St. (Granite St.), Somerville	10.9	1.0	2.7	56.7	224.5
Somerville Ave. Eastbound @ Dane St. (Granite St.), Somerville	10.7	1.1	3.5	0.0	106.7
Somerville Ave. @ Washington St., Somerville	9.7	1.0	10.3	0.0	133.2
Broadway @ Cross St. E., Somerville	10.7	1.0	4.0	0.0	30.5
Broadway @ Lombardi St. (becomes Mt. Vernon St.), Somerville	13.9	1.0	5.1	0.0	22.2
Maffa Way @ Cambridge St., Somerville	10.1	1.9	4.4	0.0	67.0
Staniford St. @ Cambridge St., Boston	9.3	1.3	0.0	0.0	0.0
Average	11.2	1.1	5.1	17.6	64.3
Standard Deviation	2.0	0.4	8.4	44.9	92.1
Minimum	8.0	0.4	0.0	0.0	0.0
Maximum	17.0	2.1	40.7	227.3	417.8

[+]Bike box is located downstream of the crosswalk.

The bike box setback also seemed to vary a lot, with a standard deviation of 8.4 feet. The large variability observed for the ingress length is attributed to the fact that if the bike lane upstream is colored, then the total length of the bike lane (i.e., the total length of the upstream link) is reported at the ingress length. Egress lane length measures the extent of the colored space within the intersection that highlights the potential conflicting region between bikes and motorized vehicles. Most of the lengths are within the bound of the intersections' dimension, while one special case (Somerville Ave. Westbound @ Park St., Somerville) has an egress lane length of 227.3 feet, as the egress lane extends through the entire offset intersection. Finally, unknown entries are associated with construction preventing an accurate scanning of those features.

The 91 bike box 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.

Of the bike boxes identified, 86% feature green-colored pavement. Bike boxes that are not colored are mainly concentrated in the town of Melrose. Northampton, Chicopee, and Newton also each present one without green-colored pavement. Approximately half of the bike boxes (52%) are installed at single-lane intersection approaches, while 79% of them are installed at intersection approaches that allow for a left-turning movement regardless of the number of lanes. There are four bike boxes that span four traffic lanes, one on Main St. with New South St. at State St. in Northampton and the other on Boland Way Southbound at West Columbus Avenue in Springfield. It should be noted that in some cases, the width of the bike box does not expand across all available traffic lanes, most likely in an effort to facilitate certain movements; see Figure 4.2 for an example of an approach with two traffic lanes, but a bike box covering only one of them.

Figure 4.2: Bike box spanning one of two traffic lanes (Massachusetts Ave. at Beacon St., Boston)

Only 4% have the bike boxes located downstream of the crosswalk; see Figure 4.3 for examples. In one of those four cases, the bike box serves as both a bike box and a two-stage turn queue box for vehicles coming from the cross street and wanting to turn left (see Figure 4.3a).
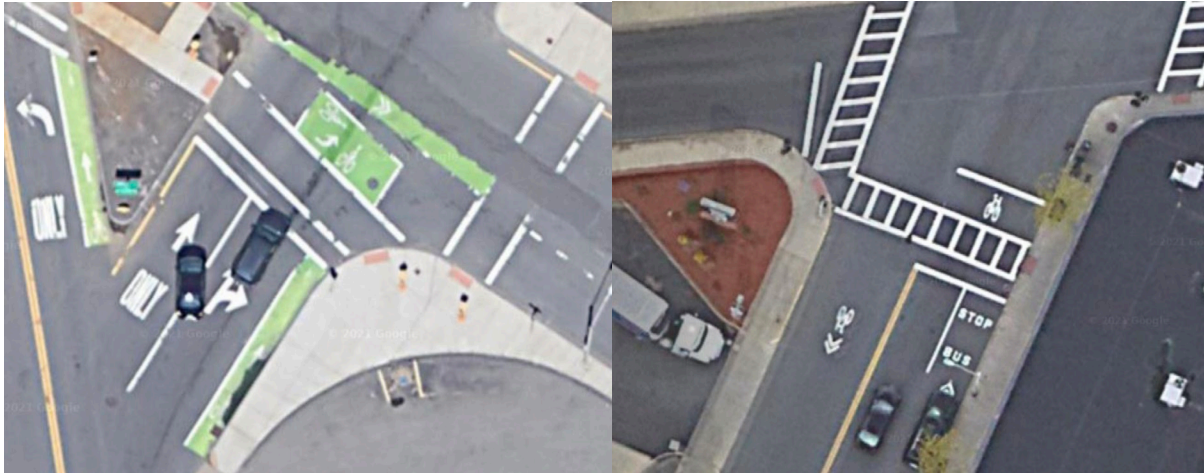
(a) Somerville Ave. at Medford St., Somerville   (b) Main St. at Grove St., Melrose

Figure 4.3: Bike boxes located downstream of a crosswalk

Out of the multilane bike boxes, about 41% are separated in the sense that multiple bicyclist stencils are on the bike box to indicate the different lanes. In 33% of those cases, lines also exist to separate the lanes within the bike box; see Figure 4.4 for examples. None of the bike boxes have been installed at intersections where the bike lane transitions from one side to the other, which is a common reason for implementing them.

(a) Lomasney Way at Causeway St., Boston   (b) Broadway at Cross St. East, Somerville

Figure 4.4: Bike boxes with separated sections with (a) no lines and (b) lines

While an additional stop line (in advance of the bike box white line) can improve motorist compliance, only 3 out of the 82 bike box approaches that locate the bike box upstream of the crosswalk (or in the absence of a crosswalk) feature this additional stop line; see Figure 4.5 for an example.
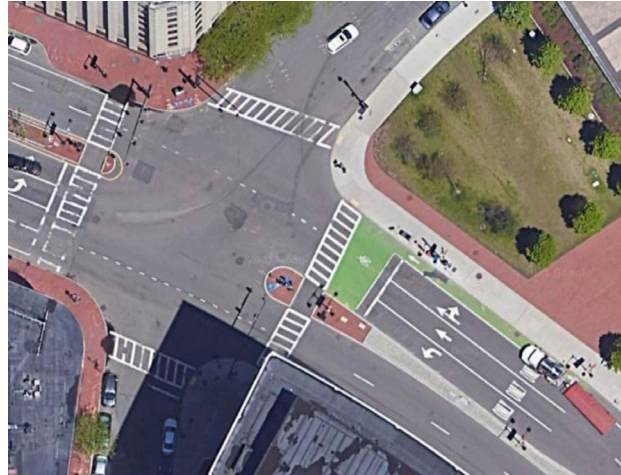
Figure 4.5: Bike box with additional stop line (Cambridge St. and Somerset St., Boston)

Bike boxes were not always accompanied by upstream or downstream bicycle infrastructure such as bike lanes. Figure 4.6 shows the percentage of bike boxes that were accompanied by certain types of bicycle treatments, such as bike lanes and sharrows (V-shaped road markings), both upstream and downstream of the bike box location. As shown in the figure, 58% of all locations present a conventional bike lane upstream, 9% a separated bike lane, and 26% sharrows. The rest, 7%, do not present any type of bicycle treatment upstream, and about 17% do not present any type of bicycle treatment downstream. The fact that it is more likely to present bicycle infrastructure upstream of the bike box compared to downstream can be attributed to the fact that implementation of bike boxes is encouraged when downstream bicycle infrastructure (e.g., bike lanes) is absent and at intersections with high numbers of right-hook crashes. The majority of bike box locations are characterized by sharrows downstream (39%), followed by conventional bike lanes (34%) and a few separated bike lanes (9%). Only eight bike boxes were installed at locations where protected bike lanes exist upstream and eight at locations where protected bike lanes exist downstream (not all overlapping), which could, however, be related to the fact that protected bike lanes are not as common as conventional bike lanes.
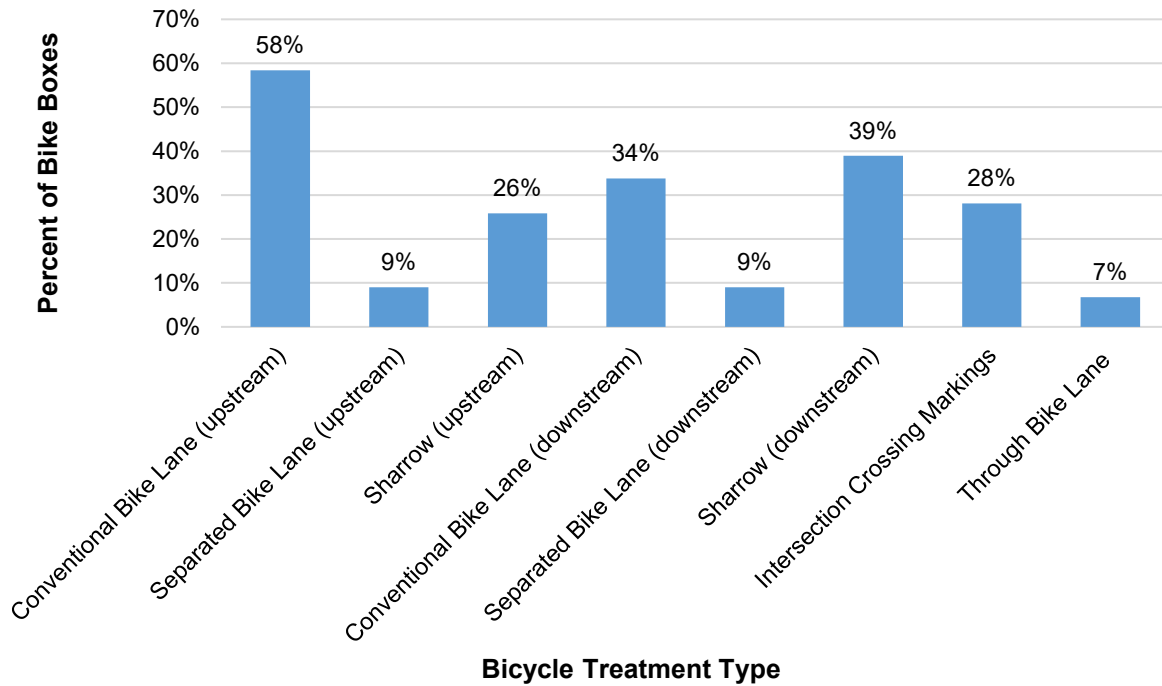
Figure 4.6: Percentage of bike box locations featuring various types of bicycle treatments

For those bike box locations that featured a conventional bike lane upstream of the bike box, a green-colored ingress lane was present in almost 76% of the cases. Ingress lanes are recommended by both MUTCD *(5)* and the NACTO *Urban Bikeway Design Guide (15)*. Intersection crossing markings are present in only 28% of the cases and are green colored (i.e., egress lanes) in 80% of the cases. Literature reveals that the need for a bike box diminishes when colored intersection crossing markings exist *(1)*. Finally, only 7% of the intersection approaches present bike through lanes (i.e., the bike lane is located to the left of the right-turning lane); see Figure 4.7. This is to be expected, as bike boxes are often installed to mitigate right-hook crashes, which would not be an issue in the presence of through bike lanes.
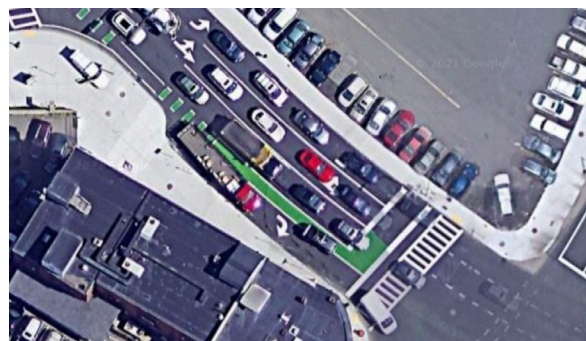
Figure 4.7 Through bike lane (Maffa Way at Cambridge St., Somerville)

Figure 4.8 shows the percentage of bike boxes accompanied by different types of signage and pavement markings. As shown in the figure, the majority of the bike box approaches (72%) feature a "No Turn on Red" sign, which is listed as required in design documents such as the

42

Urban Bikeway Design Guide (15), the *Separated Bike Lane Planning and Design Guide (2),* and the latest version of the MUTCD *(3).* 45% of them are also supplemented with a "Stop Here on Red" sign, while only 8% feature a "Yield to Bicyclists" (or "Yield to Bicyclists and Pedestrians") sign for right- and left-turning movements.
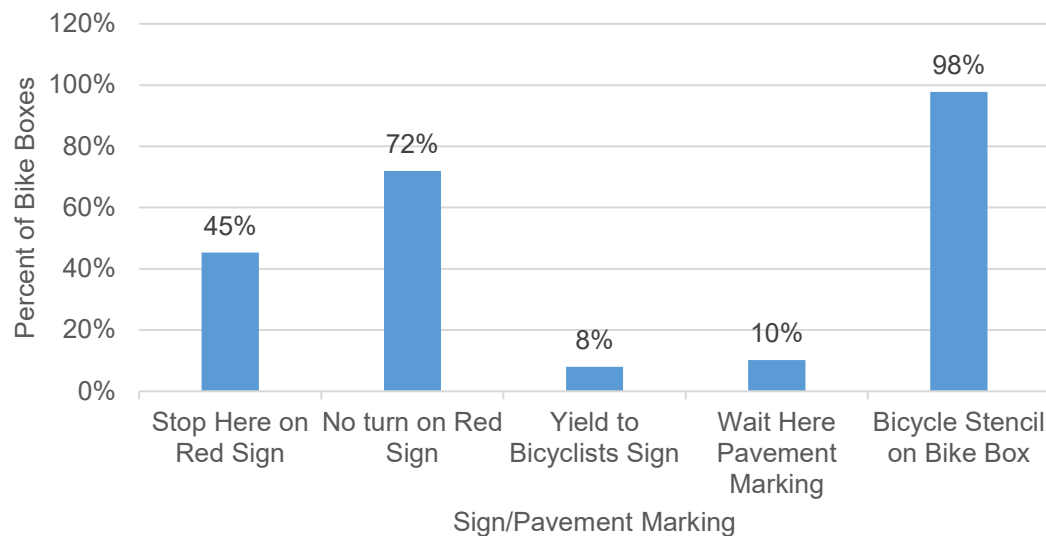
Figure 4.8: Percentage of bike boxes featuring various types of signage and pavement markings

The majority of bike boxes, yet not all of them, present one or more bicycle stencils within the bike box. However, very few present a "Wait Here" pavement marking in advance of the bike box, and only in one case this marking is supplemented with a "Stop Here on Red" sign, which is reasonable given the complementary nature of those two signs.

Information related to the signal systems (e.g., whether a leading pedestrian interval exists) was not possible to be obtained. However, one intersection approach was identified, in particular, Causeway St. Westbound at Lomasney Way, Boston, where a bike signal exists for left-turning vehicles.

4.2   Analysis of Crash Data

As mentioned in the methodology section, crash reports for 63 bicycle-vehicle crashes were identified for the time period of 2014–2020 at intersections in Massachusetts that currently feature at least one bike box. These were reduced to 35 when accounting for only those that occurred after the installation of the bike box at the corresponding intersection. When focusing on only crashes associated with a bike box approach, i.e., those that involved either the bicyclist or the motorist (or both) coming from an intersection approach and direction that featured a bike box on the date of the crash, then the total number of crashes of interest was reduced to 18. Figure 4.9 shows the 35 motorized vehicle-bicycle crashes for the Commonwealth, differentiating the 18 (in green) that occurred on a bike box approach.

Figure 4.10 shows the crashes that occurred at bike box approaches by type of crash for the whole state and the Boston metropolitan region.
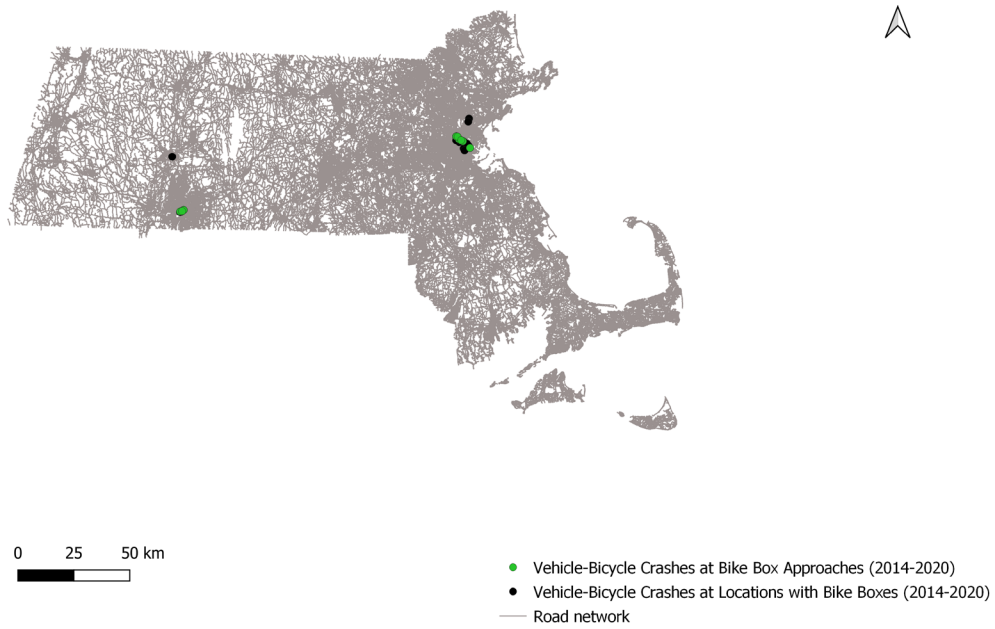
Figure 4.9: Motorized vehicle-bicycle crashes at bike box locations in Massachusetts (2014–2020)
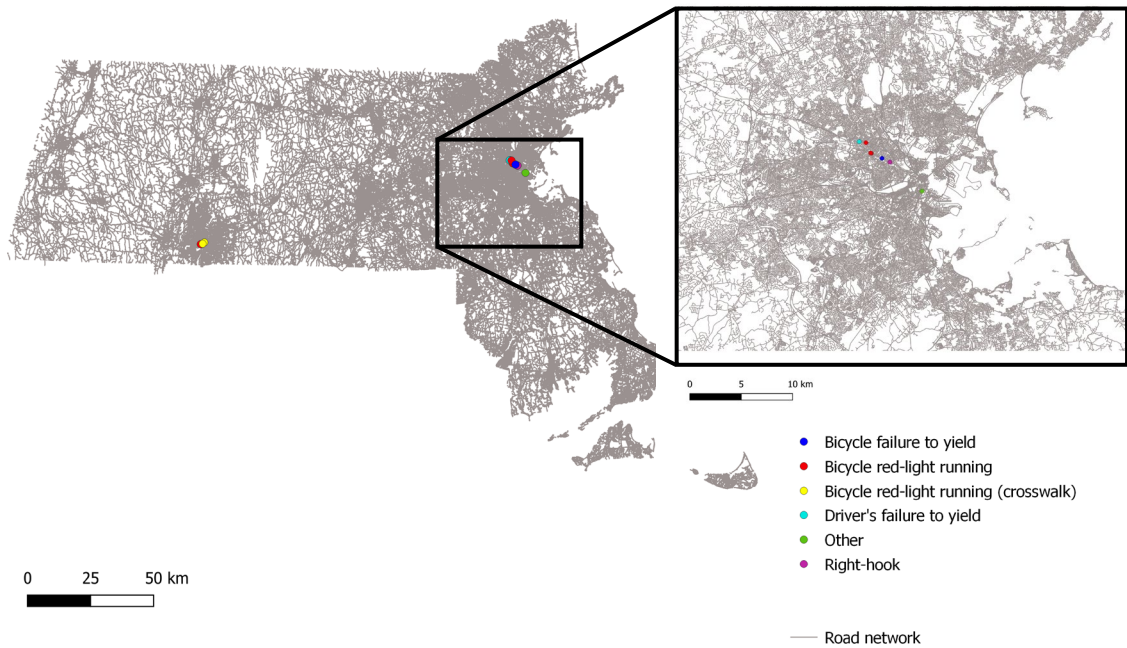
Figure 4.10: Motorized vehicle-bicycle crashes at bike box locations in Massachusetts by type (2014–2020)

44

Out of the 18 crashes, there was only 1 right-hook crash reported on an approach with a bike box over the six-year period of interest. This crash resulted in no injuries, and no apparent property damage was reported due to the low speed. As a comparison, out of the rest of the 45 bicycle-vehicle crashes that were collected on intersections that currently have at least one bike box but are not associated with a bike box, 4 right-hook crashes were observed. Given that these 45 crashes are only a subset of all vehicle-bicycle crashes in the Commonwealth for that period, it is expected that the total number of right-hook crashes is higher. The team can, therefore, hypothesize that the presence of a bike box does indeed reduce the occurrence of right-hook crashes, although the small sample sizes do not allow for a robust statistical analysis to be performed.

The rest of the crashes that involved either a bicycle or a vehicle entering the intersection from an approach with a bike box (but not from the same one) were primarily crashes due to the motorist's failure to yield during a left turn (4/18) or the bicyclist's running a red light (7/18). Motorists' failure to yield (12/45) occurred most frequently during a left turn at the intersection (8/12) or into a parking lot (2/12), and bicyclists' running a red light (8/45) were the most frequent contributors to vehicle-bicycle crashes in the non-bike box related dataset. It should be noted that there were 3 crashes that occurred on a sidewalk while a bicyclist was utilizing that crosswalk to cross the street during a red pedestrian interval. The overall number of those types of crashes occurring on the crosswalk when considering all 63 crashes was 5. The near-miss analysis explained in the next section reveals that near misses are common when bicyclists are utilizing the crosswalks.

This exercise has shown the sparsity of bicycle-vehicle crash data, especially in the presence of bicycle infrastructure treatments, which limits the analysis that can be performed.

4.3   Characterizing Bicyclist and Motorist Behavior at Bike Boxes

4.3.1   Near-Miss Analysis

Safety analytics were provided by Street Simplified for only six of the intersections where data collection took place, featuring a total of 11 bike boxes. The following subsections describe the operating conditions in terms of vehicle and bicycle demand, as well as the results of the near-miss analysis. A summary of those results is also presented in Table 4.3.

Table 4.3: Intersection volumes and bicycle-vehicle near misses

Intersection	Avg Daily Traffic (veh)	Avg Daily Bicycles (bicycles)	# of Near Misses at Intersection	Vehicle First	Bicycle First
Beacon St at Massachusetts Ave., Boston	17,012	1,827	31	25	6
Beacon St at Park St., Somerville	10,190	1,773	0	N/A	N/A
Broadway at Cross Street East, Somerville	10,372	376	0	N/A	N/A
Cambridge St. at Somerset St., Boston	12,287	1,447	3	2	1
Somerville Ave. at Dane St., Somerville	11,729	1,081	3	3	0
Somerville Ave. at Park St., Somerville	13,520	1,555	0	N/A	N/A

1. *Beacon Street at Massachusetts Avenue, Boston*

The intersection of Beacon Street and Massachusetts Avenue was found to operate under an average daily count of 17,012 and an average daily bicycle count of 1,827 bicyclists, with a distribution as shown in Figure 4.11. The video data revealed 693 through-going bicyclists and 113 right-turning bicyclists for the bike box approach (i.e., southbound approach) for the time period of data collection.

Figure 4.11: Bicycle turning movement counts at Beacon St. and Massachusetts Ave. (11/2/2020 at 12:30 p.m. to 11/3/2020 at 1:15 p.m.)

A total of 31 near misses between vehicles and bicycles were observed, 80% of which featured a vehicle arriving first and a bicycle second. While the large percentage of near misses featuring a vehicle as being first is an indication of potentially less severe crashes, it is important to investigate all of them, as the severity depends also on the vehicle speed and movement and some of the most of the most severe near misses involve instances where the

driver cuts the bicyclist off and, thus, is the first road user. Of those near misses, 77% present a PET that is higher than 3, resulting in mild conflicts, with the rest being categorized as moderate (1<PET<3). All of the near misses that have been reported during the data collection period are near misses between bicyclists crossing the crosswalk and vehicles performing different types of movements. No right-hook near misses were observed. In addition, out of those 31 near misses only 3 appeared to be relevant to the bike box, meaning that the conflict point was either within the bike box or on the crosswalk that is adjacent to it, downstream of the bike box on the southbound approach.

2. *Beacon St at Park St., Somerville*

The intersection of Beacon St. and Park St. was found to operate under an average daily count of 10,190 and an average daily bicycle count of 1,773 bicyclists, with a distribution shown in Figure 4.12. While the overall bicycle demand for that intersection and the through-going bicyclists for two of the three bike box approaches is comparable with the intersection at Beacon Street and Massachusetts Avenue, Boston, described earlier, no near misses were observed based on a PET < 5.0. Notably, no crosswalk-related near misses were observed. One hypothesis that should be investigated in the future is whether the presence of intersection pavement markings discourages the use of crosswalks by bicyclists, as it is perceived as a designated and, therefore, safe space to cross the intersection, which simultaneously encourages compliance with the traffic control devices (i.e., traffic signals); in the absence of such intersection pavement markings, bicyclists are motivated to use the crosswalks, often during the red pedestrian signal.

Figure 4.12: Bicycle turning movement counts at Beacon Street and Park Street (11/16/2020 at 3:00 p.m. to 11/17/2020 at 3:45 p.m.)

3. *Broadway and Cross Street East, Somerville*

The intersection of Broadway and Cross Street operates under an average daily count of 10,372 and an average daily bicycle count of only 376, with a total count of 200 bicycles for the bike box approach during the observation period (Figure 4.13). These bicycle volumes are very low, especially compared to the other intersections that were studied. The observation period resulted in zero bicycle-vehicle near misses, based on a PET < 5.0.
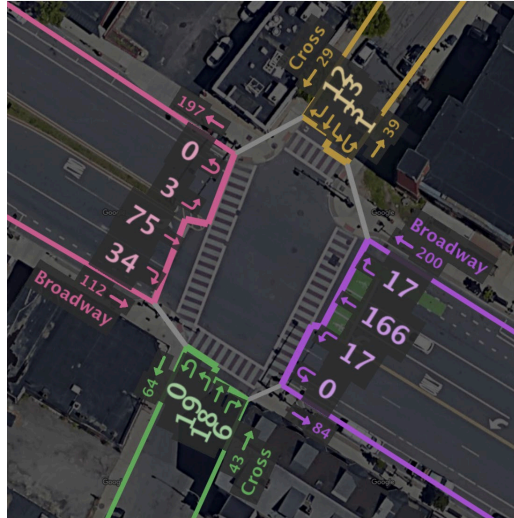
Figure 4.13: Bicycle turning movement counts at Broadway and Cross Street East, Somerville (11/16/2020 at 3:45 p.m. to 11/17/2020, 4:15 p.m.)

4. *Cambridge St. and Somerset St., Boston*

The intersection of Cambridge Street and Massachusetts Avenue operates under an average daily count of 12,287 and an average daily bicycle count of 1,447 bicyclists, with a distribution as shown in Figure 4.14. The video data revealed 533 through-going bicyclists, 248 right-turning bicyclists, and 25 left-turning bicyclists for the bike box approach (i.e., westbound approach) for the time period of data collection.

Figure 4.14: Bicycle turning movement counts at Cambridge Street and Somerset Street, Boston (11/9/2020 at 12:00 p.m. to 11/10/2020 at 12:00 p.m.)

48

Only three bicycle-vehicle near misses were observed during this 24-hour observation period, all of which fell under the mild category (PET>3); two of them featured a vehicle arriving first and a bicycle second, and none of them was associated with the bike box approach (westbound approach). In addition, all of the near misses were observed while bicyclists were crossing the crosswalks, while their PET values for these near misses were 3.4 seconds and higher (with two of them being higher than 4.0). Notably, no intersection crossing markings exist at this intersection; as mentioned earlier the lack of such markings might have motivated bicyclists to utilize the crosswalk for crossing. No right-hook near misses between bicycles and vehicles were observed.

5. *Somerville Ave. and Dane St., Somerville*

The intersection of Cambridge St. and Massachusetts Avenue operates under an average daily count of 11,729 and an average daily bicycle count of 1,081 bicyclists with a distribution, as shown in Figure 4.15. The video data revealed 408 through-going bicyclists, 14 right-turning bicyclists, and 45 left-turning bicyclists for the westbound bike box approach, 440 through-going, 38 right-turning and 12 left-turning bicyclists for the eastbound bike box approach, and 33 through-going, 35 right-turning, and 34 left-turning for the northbound bike box approach for the time period of data collection.
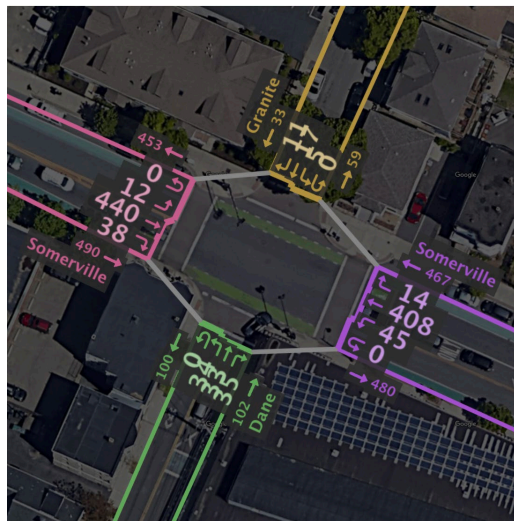
Figure 4.15: Bicycle turning movement counts at Somerville Avenue and Dane Street, Somerville (11/19/2020 at 4:45 p.m. to 11/20/2020 at 5:00 p.m.)

A total of three near misses between vehicles and bicycles were observed, two of which occurred while bicyclists were crossing the crosswalks and featured the vehicle arriving first and the bicycle second; these near misses were at the eastbound approach's crosswalk. Notably, no intersection crossing markings exist for the north-south bicycle movement, which could have motivated the use of the crosswalk for crossing. The third near miss occurred downstream of the northbound approach, between a left-turning vehicle and a through-going bicycle during a permissive left turn (for the vehicle). One of the two crosswalk-related near misses had a PET value of 1.5 seconds, resulting in it being categorized as a moderate conflict; the other two were categorized as mild.

6. Somerville Avenue and Park Street, Somerville

The intersection of Somerville Avenue and Park St. operates under an average daily count of 13,520 and an average daily bicycle count of 1,555, with a distribution shown in Figure 4.16. While the overall bicycle demand for that intersection and the through-going bicyclists for two of the three bike box approaches is comparable to that of the intersection at Beacon Street and Massachusetts Avenue, Boston, described earlier, no near misses were observed based on a PET < 5.0.

Figure 4.16: Bicycle turning movement counts at Somerville Avenue and Park Street, Somerville (11/19/2020 at 4:00 p.m. to 11/20/2020 at 4:45 p.m.)

4.3.2 Motorist Compliance

Observations of vehicle encroachment at 11 intersection approaches with bike boxes in Boston and Somerville have shown that bike box encroachment is indeed a frequent phenomenon; see Figure 4.17 for two examples.

Figure 4.17: Noncompliant motorist behavior at bike boxes

Common design characteristics of all these studied bike boxes are the green-colored pavement and at least one bicycle stencil within the bike box, as well as their location upstream of the crosswalk. In addition, all of them present a "No Right on Red" sign, with

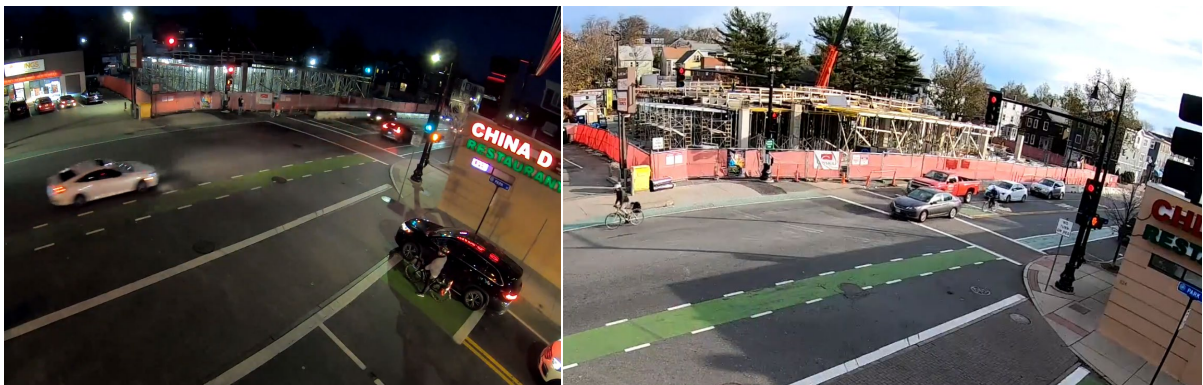the exception of the Somerville Avenue westbound at Park Street, Somerville, which is located on a T-intersection, and the Somerville Avenue westbound at Dane Street, Somerville, which allows a right turn on red. None of these studied bike boxes facilitate transitioning of bike lanes from one side of the roadway upstream to the other one downstream, which is one of the reasons for implementing bike boxes. Finally, all of them have bike lanes upstream, with the exception of Dane Street northbound at Somerville Avenue, Somerville, which has sharrows; yet all of them present designated colored lanes just upstream of the bike box, whether that is a green-colored bike lane spanning the whole length of the upstream link, a non-colored bike lane leading to a colored ingress lane, or just a green-colored ingress lane without a bike lane upstream. The presence of bicycle infrastructure downstream varies significantly more than is the case for the infrastructure upstream, but nevertheless, it does not seem to have an impact on the compliance rate. Finally, none of these sites presents a bike through lane, which is reasonable given that both bike through lanes and bike boxes are expected to mitigate right-hook crashes, so the presence of both might not be warranted, unless a bike box is installed to facilitate other types of bicyclist movements. Table 4.4 presents data collection information period and demand characteristics for the same locations, while Table 4.5 presents some design characteristics for the studied bike boxes that are discussed in relation to the driver compliance rates observed next. Note that the car and bicycle demands reported in the table represent the total demands observed during the corresponding period of data collection.

Table 4.4: Car and bicycle demand at the 11 bike box study approaches

Intersection	Data Collection Period	Car Demand	Bike Demand
Massachusetts Ave. @ Beacon St.	11/2 12:30pm – 11/3 1:15pm	7,062	807
Beacon St. Northbound @ Park St.	11/16 3:00pm – 11/17 3:45pm	3,981	660
Beacon St. Southbound @ Park St.	11/16 3:00pm – 11/17 3:45pm	3,203	731
Park Street @ Beacon Street	11/16 3:00pm – 11/17 3:45pm	1,286	177
Broadway @ Cross St. E.	11/16 3:45pm – 11/17 4:15pm	4,553	12
Cambridge St. @ Somerset St. (Sudbury St.)	11/19 12:00pm – 11/20 12:00pm	3,606	807
Somerville Ave. Eastbound @ Dane St. (Granite St.)	11/19 4:45pm – 11/20 5:00pm	4,944	490
Somerville Ave. Westbound @ Dane St. (Granite St.)	11/19 4:45pm – 11/20 5:00pm	5,354	467
Dane St. @ Somerville Ave.	11/19 4:45pm – 11/20 5:00pm	1,417	102
Somerville Ave. Westbound @ Park St.	11/19 4:00pm – 11/20 4:45pm	5,284	682
Park St. Northbound @ Somerville Ave.	11/19 4:00pm – 11/20 4:45pm	3,968	289

Table 4.5: Subset of design characteristics for bike box locations

Intersection	Bike Box Stop Line	Bike Lane Upstream	Bike Lane Downstream	Bike Box Sign Stop Here on Red	Bike Box Sign No Turn on Red	Bike Box Marking Wait Here
Massachusetts Ave. at Beacon St.	N	Y	Y	N	Y	N
Beacon St. Northbound at Park St.	N	Y	Y	N	Y	N
Beacon St. Southbound at Park St.	N	Y	Y	Y	Y	N
Park Street at Beacon Street	N	Y	N/A	Y	Y	N
Broadway at Cross St. E.	N	Y	Y	N	Y	Y
Cambridge St. at Somerset St.	Y	Y	N	N	Y	N
Somerville Ave. Eastbound at Dane St. (Granite St.)	N	Y	Y	N	Y	Y
Somerville Ave. Westbound at Dane St. (Granite St.)	N	Y	Y	N	N	N
Dane St. at Somerville Ave.	Y	N*	N	Y	Y	N
Somerville Ave. at Park St. Westbound	N	Y	Y	N	N/A	Y
Park St. Northbound at Somerville Ave.	N	Y	N/A	Y	Y	Y

Note: (Y=present, N=not present)
*Sharrow converting into bike lane just upstream of the intersection.

Figure 4.18 presents motorist compliance by lane for each of the 11 bike boxes that were studied, as determined based on whether the motorist is appropriately stopping behind the bike box stop line or the additional stop line in advance of the bike box when applicable. The results reveal an overall compliance rate of approximately 60%. Single-lane bike boxes have compliance rates varying between 49% and 70%. Notably, bike box approaches spanning two lanes do not present higher compliance rates compared to those covering one lane. It is apparent that motorist compliance is higher when the bike box is covering more than two lanes, and it is especially higher for the left and through lanes. This finding is consistent with previous findings from a driving simulator experiment mentioning that compliance rate depends on the turning movement performed by the lane under consideration *(16)* and can be attributed to various reasons that are worth further investigation. One reason this might be occurring is the fact that multilane approaches are part of intersections that are larger in dimension, which allows for more visibility in general and therefore leads to motorists not having an incentive to move closer to the intersection to improve their visibility.
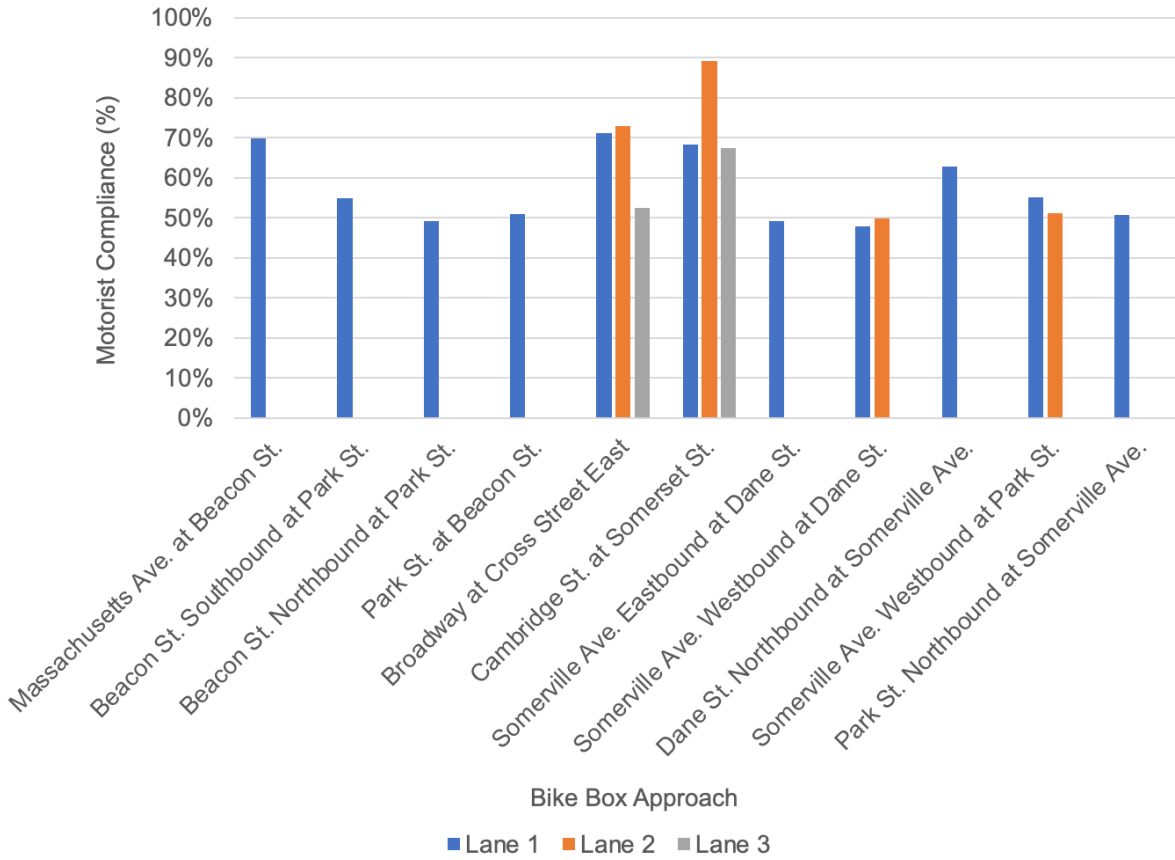
Figure 4.18: Motorist compliance at 11 bike box locations (*Lane 1 is left-most lane)

The results also reveal that left-turning and right-turning vehicles present statistically lower compliance rates than through ones. Given that compliance data were collected by lane rather than turn movement, a statistical analysis was performed to compare compliance rates between left-turn-only lanes and through lanes, and combined through-right turn lanes with through lanes. Lanes serving left movements and lanes serving combined through and right movements both had compliance rates that were lower than lanes serving only through movements with statistical significance. Through lanes had an observed compliance rate of 70.3% with 1,514 observations. Left-turn-only lanes were present at 4 out of the 11 bike box locations and presented a compliance rate of 60.9% with 1,619 observations; the 95% confidence interval of this difference is (-12.7%, -6.1%). Through-right lanes were present at five bike box locations and had a compliance rate of 59.1% with 2,320 observations; the 95% confidence interval of the difference in motorist compliance between through-right and through lanes is (-14.3%, -8.2%). All of the through-right lanes used in the statistical analysis performed here are accompanied by a "No Right Turn on Red" sign, with the exception of the Somerville Avenue westbound at Dane Street in Somerville. A statistical comparison of the impact of the "No Right Turn on Red" sign on motorist compliance revealed a compliance rate of 49.8% for through-right lanes without the sign with 303 observations, and 60.5% for through-right lanes with the sign with 2,017 observations; the 95% confidence interval of the difference in motorist compliance between through-right lanes without a "No Right Turn on Red" sign and with a "No Right Turn On Red" sign is (4.7%, 16.6%).

53

Therefore, the presence of a "No Right Turn On Red" sign increases compliance rate for motorists traveling on through-right lanes.

Several other types of signs and pavement markings can accompany bike box implementations. One example is the sign indicating "Stop Here on Red." Compliance rates at the studied bike box approaches reveal that this sign does not seem to have an impact on compliance rate, as the approaches at which it is installed present some of the lowest compliance rates. The presence of pavement markings "Wait Here" just upstream of the bike box also seem to not be having an impact, as bike boxes featuring that pavement marking present both some of the highest and some of the lowest compliance rates. Interestingly, the bike box located on Massachusetts Avenue and Beacon Street in Boston is the only one featuring a "Yield to Bicyclists on Turn" sign and presents the second-highest compliance rate. The team can, therefore, hypothesize that the presence of such signs is affecting motorist behavior, but further research is required to confirm this hypothesis.

Two of the bike box approaches that present higher compliance rates feature some type of additional stop line, which seems to motivate motorists to not encroach on the bike box: 1) the bike box on Cambridge Street at Somerset Street in Boston includes an additional stop line, as shown in Figure 4.5; and 2) the bike box on Dane Street northbound at Somerville Avenue in Somerville, which has a "Do Not Block" box in advance of the bike box (see Figure 2.18). However, compliance rates at these two intersections are similar to the ones for Massachusetts Avenue at Beacon Street in Boston and Broadway at Cross Street East in Somerville. Further research could explore the impact of advance stop lines on motorist compliance.

The observations regarding specific dimensions of bike box features are inconclusive. In particular, bike box depth and the thickness of the bike box stop line do not show any particular relationship with motorist compliance (see Table 4.6 for specific dimensions for the eight bike boxes, for which data were available). For example, the highest compliance rates are associated with some of the thickest and least thick bike box stop lines. Similar inconclusive observations are made for the other dimensions listed in Table 4.6. This could mean either that those dimensions do not affect compliance or that there is not enough sample size to be able to extract any influence that might exist. Further studies should be done to investigate the impact of specific design features and their dimensions on motorist compliance. In addition, no conclusion can be drawn regarding the impact that the presence of bike lanes upstream has, given that they are present in all but one of the studied bike boxes. Finally, no correlation seems to exist between the type of downstream bicycle infrastructure and motorist compliance rates.

Table 4.6: Bike box dimensions

Intersection	Bike Box Depth (ft)	Bike Box Stop Line Thickness (ft)	Bike Box Setback (ft)	Egress Lane Length (ft)	Ingress Lane Length (ft)
Massachusetts Ave. @ Beacon St., Boston	10.6	1.8	0.0	0.0	27.5
Broadway @ Cross St. E., Somerville	10.7	1.0	4.0	0.0	30.5
Cambridge St. @ Somerset St. (becomes Sudbury St.), Boston	15.8	0.4	-4.3[+]	0.0	105.6
Somerville Ave. Eastbound @ Dane St. (Granite St.), Somerville	10.7	1.1	3.5	0.0	106.7
Somerville Ave. Westbound @ Dane St. (Granite St.), Somerville	10.9	1.0	2.7	56.7	224.5
Dane St. @ Somerville Ave., Somerville	12.7	0.9	3.2	0.0	47.1
Somerville Ave. Westbound @ Park St., Somerville	11.0	1.0	3.9	227.3	162.3
Park St. @ Somerville Ave., Somerville	9.4	1.1	0.0	0.0	73.6

[+]Bike Box is located downstream of the crosswalk.

Figure 4.19 presents the overall compliance for all 11 bike boxes, as well as the total car and bicycle demand for the whole duration of the data collection process by site, which is approximately 24 hours at each site. It should be noted that the compliance rate presented for each site on this figure for bike boxes spanning more than one lane is the overall compliance for all lanes. An investigation of the compliance as a function of the car and bicycle daily demand does not reveal any correlations. This implies that the motorist behavior is primarily related to the design characteristics of the bike box, and the approach and intersection at which it is located, as well as the signal timings at that intersection. It should be noted that this study did not investigate the impact of signal timings on motorist behavior, other than observing compliance during the red signal indication. This could be the focus of future work. Driver familiarity and education on the proper use of such bicycle treatments could also be contributing to the lower motorist compliance rates, although a driving simulator study performed in Massachusetts revealed that familiarity did not affect compliance *(16)*.
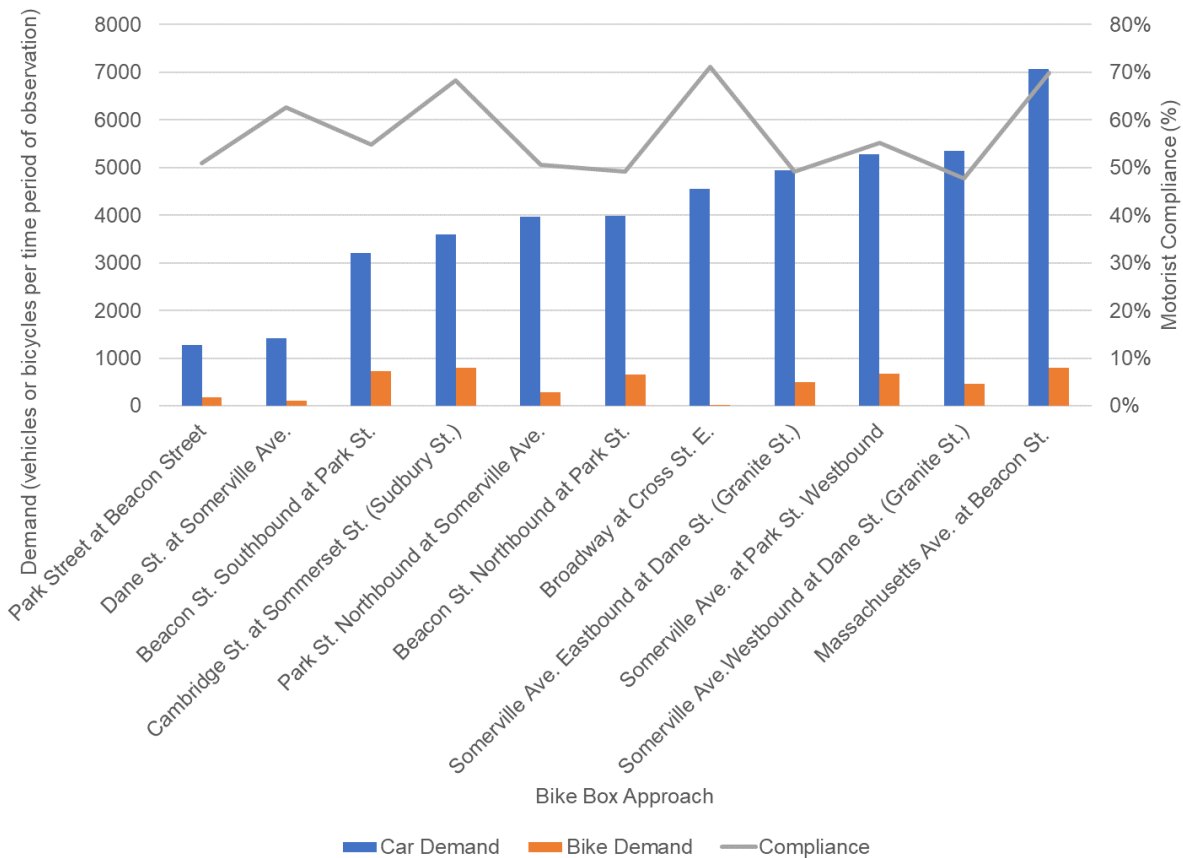
Figure 4.19: Motorist compliance, car, and bicycle demand (during reporting period for each site) for 11 bike box locations (*Lane 1 is left-most lane)

4.3.3 Bike Box Usage by Bicyclists

While a bike box is anticipated to help mitigate intersection right-turn conflicts by improving the visibility of stopped bicyclists, how bicyclists understand, recognize, and utilize bike boxes will significantly affect their effectiveness. In this study, the research team leveraged the detailed bike trajectory data and attempted to answer the critical question of how bike boxes were used by bicyclists. In particular, the team focused on three critical areas near the bike boxes: ingress lane close to the intersection, the bike box region on the right-hand side, and the bike box region on the left-hand side, as shown previously in Figure 2.23.

Figure 4.20 shows the bicycle trajectory heatmaps and bicycle turning movements for all 11 bike boxes at the six intersections. The L and R images for each intersection show the locations of the bicycles when they are waiting at the red signal, color-coded based on predefined regions (Region A/AL/AR: red; Region B: green; Region C: blue) and the subsequent moving direction (Right-turn traffic: red; Through traffic: green; Left-turn traffic: blue), respectively. The center image for each intersection shows the heatmap of the locations of the bicycles.

Figure 4.20: Bicycle trajectory heatmaps for 11 bike boxes at six study intersections

A total of 723 bike trajectories were captured during the red signal phase and intersected with the predefined regions shown previously in Figure 2.23. Figure 4.21 shows the percentage of bicyclists (by movement type) that utilized each of the defined regions within and outside of the bike box. The results indicate that, regardless of the bicyclist turning movement and the bike box design, most of the bicyclists were observed to be waiting in Region B (50.0%) during the red signal, and a total of 80% of bicyclists waited in either Regions A or B. This is in agreement with previous studies, e.g., Dill et al. *(12),* who found that more than 70% of bicyclists in Portland stopped inside the bike box in these two regions (A or B), but only 9% stopped in Region A. From the bicyclists that utilized Region A of the bike box, about 36% were turning left and the rest were through-moving bicyclists.
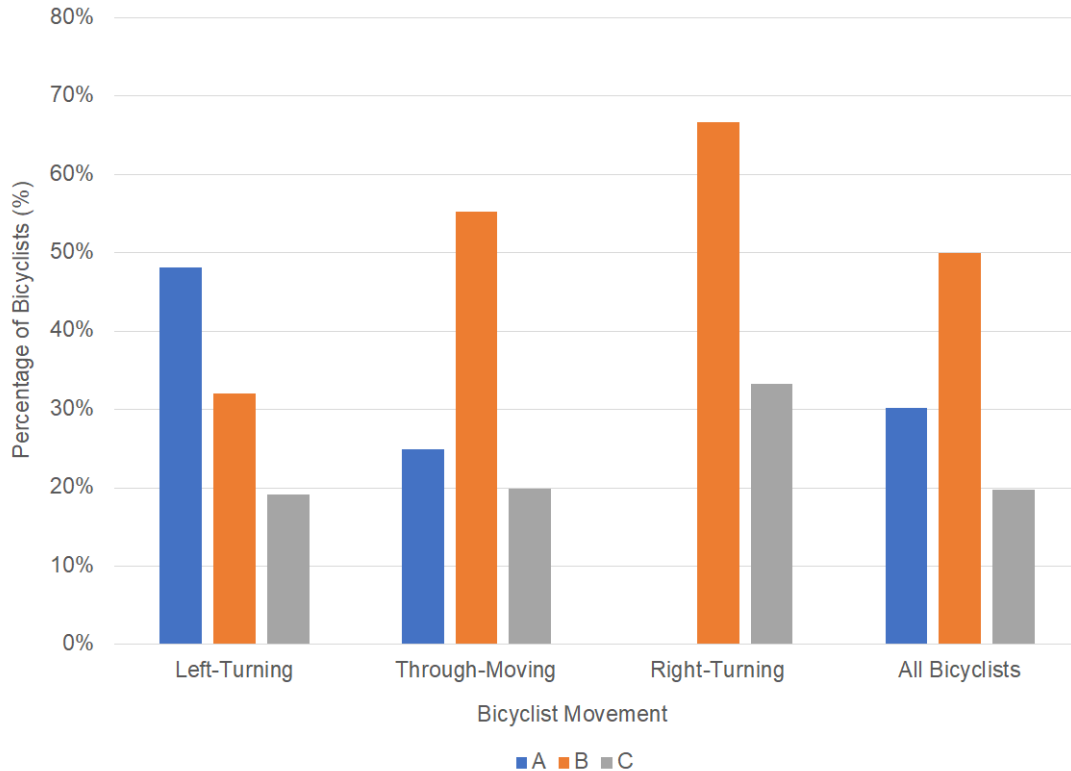
Figure 4.21: Percentage of bicyclists in each region by turning movement

When focusing on specific turning movements, the trajectory data that were analyzed revealed that out of a total of 558 through-going bicyclists, most waited in Region B (55.2%) and fewer in Regions C (19.9%) and A/AL/AR (24.9%). These results indicate a high proper use of bike boxes by through-going bicyclists. That is because the majority of through-moving bicyclists are locating themselves as expected at bike boxes (i.e., in Regions A and B), implying that bike boxes can indeed be effective in avoiding right-hook crashes.

The results for the left-turning bicyclists revealed that 48.1% of the bicyclists used Regions A/AL/AR to wait for the left turn signal. A further investigation revealed that: (1) for the bike box design without a left-only lane (as shown in Figure 2.24(a)), only 46 bicyclists out of a total of 128 left-turning bicyclists used Region A (35.9%); (2) for bike boxes at approaches with with a left-only lane (as shown in Figure 2.24(b)), 30 bicyclists out of a total 34 left-turning bicyclists used Region AL (88.2%) and 3 used Region AR (2.9%). The presence of left-only lanes (and Region AL) significantly encourages bicyclists to take advantage of the bike box when they are turning left. This implies that proper use of bike boxes by left-turning bicycles might be higher at wider approaches (i.e., multiple lanes) since the risk of traversing the bike box width when the green signal is on is higher with more lanes. It also supports the need for alternative infrastructure treatments for left-turning bicyclists such as the two-stage queue turn box. Finally, all three right-turn bicyclists were observed to be waiting in Region B (66.7%) or Region C (33.3%) during the red signal, indicating that in most cases, bike boxes were used properly. Previous studies have found that noncompliant bicyclist behavior has been attributed to habit, lack of awareness of bike box operations, perception of safety, and avoidance of overpassing motorized vehicles and

stopping in front of them *(11)*. Although only a limited number of trajectories were collected for this analysis, it is apparent that there is a need to educate bicyclists on the proper use of bike boxes, especially in terms of positioning themselves ahead of motorized vehicles.

4.4 Recommendations

The majority of the recommendations provided in this section are based on motorist and bicyclist behavior, given that a comprehensive safety analysis was limited by the availability of data (both near-miss and crash data).

Design:
- Additional stop lines and "Do Not Stop" blocks improve motorist compliance to the bike box markings and should be considered at all bike box implementations.
- "No Right Turn on Red" signs can improve bike box compliance for right-turning motorists.
- Two-stage turn queue boxes should be considered to accommodate left-turning bicycles in the absence of a bike signal with an advanced green signal: a) for multilane approaches, since the risk of traversing the bike box width when the green signal is on is higher with more lanes; and b) for single-lane approaches that present lower rates of proper bike box use by left-turning bicyclists.
- Ensure compliance of future bike box implementations with required bike box features as presented in national guidelines, e.g., the NACTO *Urban Bikeway Design Guide (15)*.

Education:
- Bicyclists should be educated on the proper use of bike boxes, especially in terms of positioning themselves ahead of motorized vehicles rather than waiting within the bike lane upstream of the bike box when a bike lane is present.
- Motorists should be educated to improve comprehension of bike boxes, their compliance, and consequent safety outcomes stemming from reduced bike box encroachment and increased yielding to bicyclists' rates.
- Education campaigns should also focus on improving the visibility (e.g., through installation of blank-out signs) and awareness (e.g., through driver education) of "No Right Turn on Red" signs

Data Collection:
- Field data collection occurred during the COVID-19 pandemic, and bicyclist and motorized vehicle demands might not be representative. It would be beneficial to replicate this study after the pandemic in the "new normal" conditions.
- An effort should be made for additional data collection efforts to take place during the warmer months and at other high-trafficked corridors with dense bicycle-friendly infrastructure elements (e.g., in Cambridge) so that larger samples of bicycle trajectories can be obtained for behavioral and near-miss analysis.

- Surveys should be developed and administered to supplement collected data and allow for correlating bicyclist and motorist levels of comprehension and familiarity with bike boxes with their behavior at such locations.

5 Conclusions

This research project consisted of three components aimed at addressing the first three objectives and contributing to the development of recommendations to satisfy the fourth objective: 1) development of an inventory of bike boxes and their design and corresponding intersection design characteristics; 2) analysis of historic crashes and near misses using trajectories of motorized vehicles and bicyclists; and 3) motorized vehicle and bicyclist behavior using field data. Field data used in 2) and 3) were obtained from 11 bike boxes at six intersections for which 24-hour video recordings were available.

5.1 Inventory

The research study revealed that there are at least 91 bike boxes in the Commonwealth of Massachusetts, the majority of which have been installed in the past four years. Detailed design characteristics were obtained with the use of LiDAR scans for 21 of those bike boxes, revealing that bike box depths in Massachusetts are on the lower end of the requirements based on existing guidebooks. The LiDAR scans also revealed great variability in other dimensions such as the bike box setback (i.e., the distance of a bike box from the crosswalk).

The majority of bike boxes are located upstream of the crosswalk; therefore, they have the potential to contribute to increased pedestrian safety. In addition, most of them have used green-colored pavement, but only three of them feature an additional stop line, despite the fact that such lanes have been found to improve motorist compliance. Bike boxes are often accompanied by bike lanes upstream; however, downstream bicycle infrastructure is less common. Another common feature of bike boxes in the Commonwealth is the presence of an ingress bike lane, even in cases where only shadows were present upstream. This is expected to an extent, as ingress lanes are recommended by both MUTCD *(5)* and the NACTO *Urban Bikeway Design Guide* (*15*). These documents also list the presence of a "No Right Turn on Red" sign as required, yet such a sign was found at 72% of bike box approaches that could support one (i.e., not on a T-intersection or not invisible due to construction). Other signs such as "Wait Here" and "Stop Here on Red" are rare, while a bike signal existed for only left-turning vehicles at only one bike box location. Not all of them feature a "No Right Turn on Red" sign, even though it is required based on NACTO guidelines *(15)*.

5.2 Safety Analysis

Given the fact that crashes between motorized vehicles and bicyclists are rare, this research was able to obtain only 18 crashes that occurred at bike box approaches between 2014 and 2020. This limited sample did not allow for a comprehensive statistical analysis, yet some general observations could be made. The results indicated a lower percentage of right-hook crashes on bike box approaches, as compared to all approaches for which data was available;

the team can, therefore, hypothesize that bike boxes have the potential to reduce right-hook crashes.

The majority of the obtained crashes at intersections with bike boxes were attributed primarily to the bicyclist running a red light (~40%) and secondarily due to motorist failure to yield, most frequently during a left-turning movement (22%). These results reveal the need for motorist and bicyclist education, not only with regards to their interactions with bike boxes but in general on how to safely utilize shared roadway space to mitigate conflicts. The otherwise limited crash analysis also revealed that some of the motorist-bicyclist crashes occurred on crosswalks while bicyclists were riding their bikes to cross the roadway. This calls for improved bicycle infrastructure to legitimize bicyclists and encourage them to behave in accordance with control devices.

Similar observations on sidewalk use and the high frequency of near misses between motorized vehicles and bicycles at crosswalks were made using the trajectory data provided by Street Simplified. The analysis of trajectory data from the six intersections showed very few near misses overall and no right-hook near misses. This could be attributed to low bicycle and motorized vehicle demands and potentially the use of the Post Encroachment Time (PET) as the surrogate measure of safety analysis. PET is limited in that it cannot detect braking and acceleration events and works best when users travel on nonparallel paths. Ideally, PET should be used along with the Time to Collision surrogate safety metric, which is better at detecting braking and acceleration events, to provide a full picture of safety outcomes at a specific location.

5.3   Motorist and Bicyclist Behavior at Bike Boxes

This part focused on assessing motorist and bicyclist behavior as expressed via their proper use of bike boxes at signalized intersections. The findings of this study revealed that motorist compliance is lower in Boston and Somerville, Massachusetts, compared to findings from earlier studies reporting compliance rates *(12,16).* This could be attributed to the characteristics of the specific intersections studied, driving culture in the area used for data collection, and potential impacts on motorist behavior that emerged due to the COVID-19 pandemic. In agreement with previous studies, this study also found that motorized vehicles completing turning movements were found to be less compliant than through-moving vehicles. As expected, additional stop lines for bike boxes that are located downstream of crosswalks featured higher motorist compliance rates.

The analysis of bicyclist behavior revealed that the majority of bicyclists tend to utilize the bike box region right in front of the bicycle lane, with the only exception being the left-turning vehicles that were more likely to utilize the main bike box region (i.e., to the left of the bike lane). Left-turning bicycles were more likely to utilize the bike box region, particularly at multilane bike box approaches where a designated left-turn lane exists. It should be noted that without individual surveys, the level of understanding of bike boxes and their usage by bicyclists cannot be investigated. The results of this study also indicate the

need for further exploration of the correlation between bike box and intersection design characteristics and motorist and bicyclist behavior, as well as the need for outreach and education efforts to motivate proper user behavior of both motorists and bicyclists and, therefore, to improve safety outcomes.

Overall, this study contributed to the current body of the literature by 1) offering evidence that motorist compliance rate can be lower at some intersections compared to findings from previous research; 2) confirming research findings from previous studies that reported that motorist compliance is dependent on the turning movement performed; 3) confirming high bicyclist compliance as reported in previous studies; 4) offering additional evidence for the implementation of two-stage turn queue boxes to facilitate left-turning movements; and 5) reiterating the need for education of and outreach to motorists and bicyclists in order to properly utilize bike boxes with the goal of improving safety for all. Ongoing work by the research team focuses on analyzing the interactions between bicyclists and motorists using trajectory data that have already been collected. This effort aims to further understanding of whether certain bike box and, in general, intersection designs result in fewer conflicts between bicycles and cars and are contributing to improving safety.

5.4   Future Work

The inventory was collected based on information from municipalities and the MassDOT districts. It is possible that not all bike boxes that are implemented have been captured in this inventory. It is also likely that additional bike boxes are currently in their planning stages and about to be implemented. In addition, Google Maps was not always sufficient for capturing the design characteristics due to obstacles blocking street views or construction underway. Future work should continue inventorying bike box locations to maintain a current list of bike boxes and their design characteristics in Massachusetts. Furthermore, given that detailed dimensions were obtained for only 21 of the 91 bike boxes, future work could continue the LiDAR scanning of the rest of them to obtain a comprehensive list of bike box implementations and their design specifications in Massachusetts.

Crash analysis was performed with the use of crash data from a five-year period obtained from the IMPACT database, as well as trajectory data from 24 hours of video at six intersections that feature a total of 11 bike boxes. The limited samples that were obtained on both these types of studies show the need for multiyear longitudinal studies and crowdsourced data that will allow for larger sample sizes of near misses. In addition, there is a need to develop appropriate surrogate safety measures to characterize risky locations that otherwise become apparent only when crashes occur. As a first step, the study performed as part of this project using PET could be repeated with the use of TTC to investigate whether differences in the numbers and severity of near misses exist between the two metrics. A comparative analysis between intersections with bike boxes and those without (i.e., control site) in terms of near misses (from additional trajectory data) and motorized vehicle-bicycle crashes should be part of future work. Future work should also incorporate crash data from Emergency Medical Services and the Boston Police Department's Boston Regional

Intelligence Center and cross-check between all of the available databases to better understand the differences between them.

The field data component of this research is limited in that it has focused only on 11 bike box locations in Massachusetts, data for which were collected during the COVID-19 pandemic and the beginning of the winter (November 2020). As a result, motorist and bicyclist demand and population characteristics (e.g., commuters vs. recreational bicyclists) might not be representative of the pre-pandemic or post-pandemic era. Future research can further explore the impact of bike boxes on bicycle and motorist behavior with a larger dataset of bike box locations at a future time with higher bicyclist and motorist demands. In addition, longitudinal field data should be collected to validate before-and-after bike box implementation behavioral observations and assess the impact of educational campaigns on motorist and bicyclist behavior.

This study could not conclude on the impact of bicycle infrastructure and other design features and their dimensions (e.g., stop line thickness, presence of intersection crossing markings, bike box color) on motorist compliance and bicyclist behavior. Future studies should focus particularly on assessing the impact of those attributes on motorist compliance using a larger sample size and simultaneously accounting for bicyclist and vehicle demand. In addition, future work should test the hypothesis that intersection pavement markings legitimize the presence of bicyclists and motivate compliant behavior for both bicyclists and vehicles. Furthermore, the analysis of motorist compliance did not account for signal settings (e.g., duration of red signal indication) or the presence of bike signals and advanced green for bicyclists, which could be further investigated in future studies.

This study did not assess how motorist compliance or bicyclist usage changes as a function of the presence of bicyclists within the bike box or vicinity of the bike box, and vice versa, or whether the stopping location of bicyclists and motorists in the vicinity of the bike box affects yielding rates of right-turning cars to through-going bicycles. Alternative ways of assessing safety outcomes, i.e., metrics other than compliance, should also be considered. Finally, surveys should be used to help supplement collected data and allow for correlating bicyclist and motorist levels of comprehension and familiarity with bike boxes with their behavior at such locations.

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