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PROGRAM

REPORT 766

Recommended Bicycle Lane Widths for Various Roadway Characteristics

TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Christopher J. Hedges
Staff Officer
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This report presents recommendations for bicycle lane widths for various roadway and traffic characteristics, including traffic volume, vehicle mix (i.e., percent trucks), lane width and/or total roadway width, and presence/absence of on-street parking. The conclusions are most applicable to urban and suburban roadways with level grade and a posted speed limit of 30 mph and should be used cautiously for the design of roadways with motor vehicle speeds outside of the range of 25 to 35 mph, and in particular for higher-speed roadways.

This report will provide valuable guidance for traffic and design engineers in areas where bicycle lanes are being considered and implemented.

The 2012 edition of the American Association of State Highway and Transportation Officials' *Guide for the Development of Bicycle Facilities* (AASHTO, 2012), often referred to as the *Bike Guide,* defines a bicycle lane as "a portion of a roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs. It is intended for one-way travel, usually in the same direction as the adjacent traffic lane, unless designed as a contra-flow lane." The AASHTO *Bike Guide* provides general guidance on appropriate bicycle lane widths. The *Bike Guide* states that, under most situations, the recommended width for bike lanes is 5 ft, but under several circumstances wider bicycle lane widths may be desirable, and in several cases a 4-ft-wide bike lane can be used.

Some transportation agencies use the guidance in the AASHTO *Bike Guide* to determine appropriate bicycle lane widths, while others have developed their own policies. Whether at the national, state, or local level, the guidelines that have been developed for bicycle lane widths provide only general guidance on how bicycle lane widths should vary based on the conditions of the roadway. Thus, there was a need to conduct scientifically based research to develop more specific guidance on recommended bicycle lane widths for various roadway conditions.

Under NCHRP Project 15-42, a research team led by MRIGlobal installed temporary pavement markings at several locations to delineate bicycle lanes of varying widths. The lateral positioning of both bicyclists and motorists was measured and used as surrogates to evaluate the safety effects of the allocation of roadway width between parking lanes, bike lanes, buffered spaces, and motor vehicle travel lanes.

The data-collection sites included three midblock locations with on-street parking and two midblock locations where on-street parking was prohibited. The bicycle lane widths evaluated ranged from 3.5 to 6 ft. A supplemental grade study was also performed to evaluate lateral movement of bicyclists pedaling on a moderate upgrade.

The report presents an analysis of the research and design guidance for bicycle lane widths on existing travel lane widths and parking lane widths. The research is based on a review of literature, the current state of practice, and a series of observational field studies.

CONTENTS

SUMMARY

The 2012 edition of the American Association of State Highway and Transportation Officials' *Guide for the Development of Bicycle Facilities* (AASHTO, 2012), often referred to as the *Bike Guide*, defines a bicycle lane as "a portion of a roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs. It is intended for one-way travel, usually in the same direction as the adjacent traffic lane, unless designed as a contra-flow lane." The AASHTO *Bike Guide* provides general guidance on appropriate bicycle lane widths. The *Bike Guide* states that, in most situations, the recommended width for bike lanes is 5 ft, but in some circumstances, wider bicycle lane widths may be desirable, while in other cases a 4-ft-wide bike lane can be used. The guidelines for bicycle lane widths provide only general guidance on how bicycle lane widths should vary based on the conditions of the roadway. There is a need to conduct scientifically based research to develop more specific guidance on bicycle lane widths for various roadway conditions.

The objective of this research was to develop recommendations for bicycle lane widths for various roadway and traffic characteristics. The focus was on developing design guidance for bicycle lane widths for roadways in urban and suburban areas. An observational field study was conducted to evaluate the allocation of roadway width on both bicyclists' and motorists' lateral positioning, taking into consideration various roadway and traffic characteristics. The general methodology of the field study involved installing temporary lane line markings to delineate bicycle lanes of varying widths at midblock locations and observing the behavior of bicyclists and motorists. The final database from the observational field study included data on 4,965 bicyclists, 3,163 passing vehicles, and 994 parked vehicles.

The primary roadway and traffic characteristics that factored most into selecting sites for inclusion in the observational field study were:

- Bicycle volume,
- Traffic volume,
- Vehicle mix (i.e., percent trucks),
- Lane width and/or total roadway width, and
- Presence/absence of on-street parking.

Given the site characteristics and the study scenarios, the ranges in the primary roadway and traffic characteristics analyzed in this research are:

- Bike lane width: 3.5 to 6 ft,
- Parking lane width: 7 to 9 ft,
- Travel lane width: 10 to 18 ft,
- Presence/absence of buffer space,

- Traffic volume: 14,800 to 29,000 vehicles per day (vpd), and
- Percent trucks: 2% to 20%.

Posted speed limit and grade were additional characteristics of interest identified for evaluation in this research; however; all of the sites included in the observational field study had a posted speed limit of 30 mph, and all sites were on a level grade. The effect of grade on bicyclist behavior was evaluated through a supplemental grade study.

The conclusions of the research are as follows and should be considered within the context of the research. In particular, the conclusions are most applicable to urban and suburban roadways with level grades and a posted speed limit of 30 mph and should be used cautiously for the design of roadways with motor vehicle speeds outside of the range of 25 to 35 mph and, in particular, for higher-speed roadways.

General Conclusions

1. A buffered bike lane provides distinct advantages over simply providing a wider bike lane.
2. Narrowing the width of a bicycle lane reduces the variability of the bicyclists' lateral positions; however, this impact is relatively minor, at least for the bicycle lane widths evaluated in this research.
3. As traffic volume increases, bicyclists move away from vehicles in the travel lane and position themselves closer to parked vehicles or the curb.
4. As truck percentage within the vehicle mix increases, bicyclists move away from vehicles in the travel lane and position themselves closer to parked vehicles or the curb.
5. For streets with on-street parking and where the parking lane width is between 7 and 9 ft and the bike lane width is between 4 and 6 ft, the effective bike lane will likely be less than the physical width of a typical adult bicyclist, and the majority of bicyclists will position themselves outside of the effective bike lane.
6. For streets without on-street parking, as long as the adjacent travel lane is at least 10-ft wide and the bike lane is 4 to 5 ft in width, most bicyclists will position themselves in the effective bike lane, and the effective bike lane will be equivalent to the width of the marked bike lane.

Design Guidance

1. Travel lanes between 10 and 12 ft in width are appropriate for streets with a bicycle lane.
2. At sites with travel lane widths between 16 and 18 ft on streets without on-street parking, marking a bicycle lane provides no distinct advantages for the lateral positioning of bicyclists and motorists. While this statement is true with respect to the issues addressed in this particular study, there are other reasons why bike lanes on streets with 16- to 18-ft lanes would be desirable. These include using the bike lane to narrow the travel lane to provide a traffic calming measure; encouraging bicyclists to travel in the correct direction on the street; getting bicyclists off of adjacent sidewalks, where they are generally less safe (Wachtel and Lewiston, 1994); and using the bike lane as a link to a larger bikeway network.
3. In most situations where a bicycle lane is adjacent to on-street parking, the suggested width for the parking lane is 8 ft. An 8-ft parking lane provides sufficient space for a large percentage of vehicles to park within the limits of the parking lane, and it is narrow enough that it allows more of the roadway cross section to be designated for bicyclists in the bicycle lane and motor vehicles in the travel lanes. This is consistent with current recommendations in the AASHTO *Bike Guide*.

4. The AASHTO *Bike Guide* states that under most circumstances, the recommended width for bike lanes is 5 ft. The guide also states that under certain conditions, wider bicycle lanes may be desirable. In particular, the guide states that when adjacent to a narrow parking lane (7 ft) with high turnover, a wider bicycle lane (6 to 7 ft) provides more operating space for bicyclists to ride outside of the door zone of parked vehicles. Based on the data collected in this study, a 6-ft bicycle lane does not provide additional benefits to bicyclists compared to a 5-ft bicycle lane. Most bicyclists will still position themselves within the open door zone of parked vehicles whether in a 6-ft bicycle lane or a 5-ft bicycle lane. A 7-ft bicycle lane may offer distinct advantages for bicyclists compared to bicycle lane widths of 5 and 6 ft; however, data for 7-ft bike lanes were not investigated in this research. Where space permits, the data suggest that installing a narrower bicycle lane with a parking-side buffer provides distinct advantages over a wider bike lane with no buffer.
5. For parking lanes that are 7- to 9-ft wide, assuming the 95th-percentile parked vehicle displacement and an open door width of 45 in., the open door zone width of parked vehicles extends approximately 11 ft from the curb. Therefore, the design of the bike lane should encourage bicyclists to ride outside of this door zone area and account for the width of the bicyclist.

Section 5 of this report provides more detailed design guidance related to bicycle lane widths, taking into account a range of roadway and traffic characteristics, including parking lane width, travel lane width, traffic volume, vehicle mix, and grade.

SECTION 1

Introduction

1.1 Introduction

The 2012 edition of the American Association of State Highway and Transportation Officials' *Guide for the Development of Bicycle Facilities* (AASHTO, 2012), often referred to as the *Bike Guide*, defines a bicycle lane as "a portion of a roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs. It is intended for one-way travel, usually in the same direction as the adjacent traffic lane, unless designed as a contra-flow lane." The AASHTO *Bike Guide* provides general guidance on appropriate bicycle lane widths. The *Bike Guide* states that, in most situations, the recommended width for bike lanes is 5 ft, but in several circumstances, wider bicycle lane widths may be desirable, and in several cases a 4-ft-wide bike lane can be used.

Some transportation agencies use the guidance in the AASHTO *Bike Guide* to determine appropriate bicycle lane widths, while others have developed their own policies. Whether at the national, state, or local level, the guidelines that have been developed for bicycle lane widths provide only general guidance on how bicycle lane widths should vary based on the conditions of the roadway. Thus, there is a need to conduct scientifically based research to develop more specific guidance on bicycle lane widths for various roadway conditions.

1.2 Research Objective and Scope

The objective of this research was to develop a set of recommendations for bicycle lane widths for various roadway and traffic characteristics. The focus was on developing guidance for bicycle lane widths for roadways in urban and suburban areas since these areas are where bicycle lanes are most often considered and implemented. The overall guiding principle of this research was to provide guidance on how wide the bicycle lane should be in cases where the decision to include a bicycle lane has been made. The conclusions and research suggestions were drawn primarily from the research results of this study, while taking into consideration results from previous research.

This research did not compare differences in bicyclist and motorist behaviors on roadways with bicycle lanes versus roadways with shared-lane markings. Therefore, this research does not provide specific guidance on the type of roadway and traffic characteristics where providing bicycle lanes may be preferred or not preferred compared to providing shared-lane markings, except when the conditions are so constrained that it is recommended bike lanes not be marked.

On several roadways where on-street parking was prohibited, data were collected to compare differences in bicyclist and motorist behaviors on roadways with a wide curb lane versus roadways with a bicycle lane. Thus, on roadways where on-street parking is prohibited, this research provides general guidance on the differences in bicyclist and motorist behaviors on roadways with a wide curb lane versus roadways with a bicycle lane.

1.3 Overview of Research Methodology

In Phase I of this study, the research team conducted a literature review and state-of-practice review on bicycle lane widths. The results of this review are summarized in Section 2.

In Phase II, observational field studies were conducted. At several locations, temporary pavement markings were installed to delineate bicycle lanes of varying widths, and the lateral positioning of both bicyclists and motorists was measured and used as surrogates to evaluate the safety effects of the allocation of roadway width between parking lanes, bike lanes, buffered spaces, and motor vehicle travel lanes. The data collection sites included three midblock locations with on-street parking and two midblock locations where on-street parking was prohibited. The bicycle lane widths evaluated ranged from 3.5 to 6 ft. A supplemental grade study was also performed to evaluate lateral movement of bicyclists while pedaling on a moderate upgrade.

1.4 Outline of Report

This final report documents the entire research effort, with the remainder of the document organized as follows:

- Section 2 summarizes the findings of the literature and state-of-practice review.
- Section 3 describes the observational field studies conducted to evaluate the effects of varying lane widths on bicyclists' and motorists' lateral positioning.
- Section 4 describes the supplemental grade study performed to evaluate lateral movement of bicyclists while pedaling on upgrades.
- Section 5 presents design guidance for bicycle lane widths, taking into consideration various roadway and traffic characteristics.
- Section 6 provides conclusions and suggestions for next steps.

For practitioners most interested in the design guidance developed as a result of this research, Section 5 will be of most interest.

SECTION 2

Summary of Literature Review and Design Guidelines

This section provides a summary of available literature related to the design of bicycle lanes. It is divided into two parts: Section 2.1 summarizes safety and design research related to bicycle lanes and shared use lanes, and Section 2.2 summarizes guidance from the AASHTO *Bike Guide* related to the design of bicycle lanes and presents a summary table of recommended bicycle lane widths from other domestic and international guidance documents.

2.1 Safety and Design Research Related to Bicycle Lanes and Shared Use Lanes

The following discussion provides a summary of relevant research related to the design of bicycle lanes.

2.1.1 Safety Evaluations

Traditionally, the safety effectiveness of roadway design elements is evaluated in one of two ways. The first is by comparing the crash frequency at a site with a design element of interest against the crash frequency at a similar site without the design element. The second is by comparing crash frequencies before and after a particular design element has been implemented. However, an evaluation of the safety impact of design elements on bicycle crashes is difficult to ascertain for the following reasons:

- Bike crashes are rare.
- Bike crashes that do not involve a motor vehicle are not recorded in highway crash databases.
- Information on how a particular type of bike facility may have contributed to a bike crash is generally not included in crash reports.

As a result, few authors have been able to directly link crash frequency or the likelihood of a crash to specific bicycle facility designs.

Since direct measures of safety are difficult to obtain for bicycle facilities, surrogate measures often are used to evaluate bicycle facility characteristics (e.g., lane width, markings). Surrogate safety measures include:

- Lateral positioning of the motor vehicle and bicycle traffic (namely the separation distance between the two modes),
- Lateral positioning of the parked vehicle and bicycle traffic (namely the separation distance between the two modes),
- Changes in motor vehicle speed,
- Encroachment of motor vehicle traffic into the oncoming lane when encountering cyclists, and
- Cyclist comfort level.

The separation distances between cyclists and moving vehicles and cyclists and parked vehicles are typically used to assess the likelihood of bicycle/vehicle collisions. Motor vehicle speed is used to assess the severity of potential bicycle/vehicle collisions. Encroachment of a moving vehicle into the oncoming lane is used to assess the likelihood of vehicle/vehicle crashes. Cyclist comfort level is used to assess the likelihood of bicycle/vehicle collisions; however, a strong relationship between cyclist comfort and safety has not been demonstrated. Generally, in the absence of sufficient crash data, these measures can be used to investigate the safety effects of street width allocations and markings for bicycle treatments, including bike lanes and wide curb or shoulder lanes.

2.1.2 Comparing Bike Lanes and Wide Curb Lanes

Bike lanes and wide curb lanes (also referred to as shared lanes) are commonly used to promote bicycling and to create safe roads. Each facility type affects cyclist and driver behavior in different ways. The following paragraphs summarize behavioral differences and similarities resulting from the use of these two facility types.

Bike lanes have a positive impact on safety when compared with unmarked roadways. Bahar et al. (2008) found that the presence of a bike lane reduces bicycle crashes by 36%. This finding is supported by other research. Reynolds et al. (2009) examined the relationship between bicycle infrastructure and cyclist safety through a review of 23 papers from 1975 through 2009. When examining the studies related to roadway segments (rather than intersections), marked bike lanes and bike routes were found to reduce crash rates and injuries by about half when compared to unmodified roadways. The safety effectiveness of specific bicycle facility designs was not described by Reynolds et al.

Hunter and Feaganes (2003) examined the operational effects of converting 14-ft-wide curb lanes to 11-ft travel lanes with 3-ft undesignated lanes. The 3-ft lane was referred to as an "undesignated lane" because it did not meet current bike lane standards in terms of lane width, signing, and marking; however, the lane was intended primarily for bicycle usage. The main findings and conclusions from this study were:

1. The lateral spacing of cyclists from the gutter pan seam was greater with the stripe as compared to with the wide curb lane. The combination of an 11-ft travel lane and 3-ft undesignated lane affected lateral spacing differently for various sites. On average, bicycles rode 7 to 9 in. farther away from the gutter pan seam at three sites where the stripe was added. This would provide a greater margin of safety for cyclists.
2. The lateral spacing of motor vehicles from the gutter pan seam was greater with the stripe than without the stripe. This would be expected with the shift of the travel lane by 3 ft with the addition of the stripe.
3. Overall, the lateral spacing between bicycles and motor vehicles was greater with the stripe than without the stripe; however, the effect was not as clear as for the previous two measures. The addition of the stripe affected lateral spacing differently for various sites. On average, passing motor vehicles were driven 3 to 5 in. closer to bicycles at three of the newly striped sites. This could possibly be indicative of increased comfort level for both road users, where motorists believe cyclists will ride within the striped area, and cyclists believe motorists will not cross into their space in the undesignated lane. Conversely, passing motor vehicles were 4 to 6 in. farther away from bicycles at the comparison sites where the stripe had already been in place for some time.
4. The addition of the stripe reduced the number of motor vehicle encroachments into the adjacent lane on these multilane roads. The effect varied by site. On average, encroachments were reduced by between 15% and 40% at sites where a stripe was newly added.

Based on this information, even 3-ft bike lanes provide benefits over wide curb lanes.

Hunter, Stewart, and Stutts (1999) found that under comparable speed and traffic conditions, the distance from the bicycle to the passing motor vehicle was a direct function of total width (defined as the bike lane width plus the width of the adjacent traffic lane, or simply the width of the wide curb lane when no bike lane was present), regardless of whether the primary bicycle facility was a bike lane or a wide curb lane.

Harkey, Stewart, and Rodgman (1996) evaluated the impact of bike lanes, wide curb lanes, and paved shoulders on motor vehicle and bicycle traffic. Key findings and conclusions from this evaluation include:

- The separation distance between cyclists and motorists does not vary significantly by facility type (i.e., wide curb lane, shared lane, bike lane, paved shoulder). On average, motorists positioned their vehicles approximately 6.4 ft from a cyclist in a wide curb lane; 6.2 ft from a cyclist on a paved shoulder; and approximately 5.9 ft from a cyclist in a bike lane.
- The distance between the cyclist and the edge of the roadway was considerably less along wide curb lanes (1.4 ft) compared to that along facilities with paved shoulders or bike lanes (2.4 ft).
- Motor vehicles moved to the left about 1.4 ft further when passing a cyclist in a wide curb lane than when passing a cyclist riding on a paved shoulder or bike lane facility.
- Encroachment into the adjacent lane to the left by motor vehicles when passing a bicycle was greater on wide curb lanes (22.3%) than along bike lanes or paved shoulders (8.9%).
- Taking into consideration the change in lateral position of the motorist and the number of encroachments, bike lane widths as narrow as 3 ft can provide sufficient space for motorists and cyclists to interact safely; however, 4-ft-wide bike lanes or paved shoulders will optimize operating conditions for motorists and cyclists while minimizing the paved shoulder and right-of-way required.

McHenry and Wallace (1985) analyzed the effectiveness of different wide curb lane widths ranging from 12 ft to 17.6 ft. Their study also compared wide curb lanes to a 4-ft bike lane adjacent to a 10.5-ft travel lane. They found that the optimal width for wide curb lanes was 15 ft, and that bike lanes had advantages over wide curb lanes such as less vehicle encroachment, lower vehicle displacement when passing a bicycle, and less variation in the lateral position of the vehicle and the bicycle. A 12-ft-wide curb lane does not provide enough room to allow vehicle traffic to pass comfortably, and cyclists tend to obstruct vehicle traffic as a result. A 13.8-ft-wide curb lane was more effective than a 12-ft lane, especially when the volume of truck traffic was low; however, a 13.8-ft lane was still perceived as too narrow by both motorists and cyclists. In addition, both the 12-ft and 13.8-ft lane effectively reduced capacity of the travel lane as a result of the difficulty vehicles had in passing cyclists. Expanding the wide curb lane to 17.6 ft caused different problems. Here the motor vehicles had a greater degree of lateral placement, and the 17.6-ft lane width encouraged use by two motor vehicles at intersections when

Table 1. Effects of travel lane width.

	Travel Lane Width			Supporting Study
	12.5 ft or Less	12.5 to 14 ft	Greater than 14 ft	
Vehicle speed while passing	Slows	Slows	Minor/no reduction	Jilla (1974)
Vehicle/bike separation	Narrowest separation	→	Greatest separation	Hunter and Stewart (2009)

one vehicle was turning right. In contrast, a 15-ft-wide curb lane was found to be optimum since it provided a safe degree of space between motor vehicles and cyclists while not providing enough space for motorists to attempt to use the additional space as a travel lane.

Kroll and Ramey (1977) investigated the extent to which motorist and cyclist behaviors were affected by the presence of a bike lane. Observations were made in the field to examine bike and vehicle displacement as functions of speed, lane width, presence of other vehicles, and the presence or absence of a bike lane. Based on their findings, Kroll and Ramey suggested that bike lanes are desirable on streets where the available travel space, defined as the distance between cyclist and roadway centerline, is less than 15 ft. Although the mean separation distance between cyclist and motorist is the same for roadways with and without bike lanes, the variability in separation distance decreases with the presence of bike lanes. Therefore, providing a bike lane appears to lower the likelihood of conflict between the two modes because the presence of a bike lane leads to fewer centerline violations, while the absence of bike lanes leads to more wide swerves and close passes.

Table 1 summarizes the findings of Jilla (1974) and Hunter and Stewart (2009) on the various travel lane widths adjacent to bike lanes. The authors concluded the following:

- Travel lanes of 14 ft and under cause vehicles to slow while passing, creating a safer condition.
- Separation between bikes and passing vehicles increases with overall travel lane width.
- Lane sharing does not reduce roadway vehicle capacity if the travel lane is at least 15-ft wide.

It is also important to note that research conducted by Potts et al. (2006) found that the use of travel lanes narrower than 12 ft on urban and suburban arterials does not increase the expected crash frequency. This finding suggests that geometric design policies should provide substantial flexibility for use of lane widths narrower than 12 ft. However, a few exceptions were present where the data were not clear. This research concluded that no indication is present to suggest that expected crash frequencies increase as lane width decreases for arterial roadway segments or arterial intersection approaches.

2.1.3 Bike Lanes and Parking

Furth et al. (2010) conducted an examination of the lateral positioning of parked vehicles from the curb for a variety of parking lane widths. The distance between parked cars and the curb is an important consideration when bikes are riding adjacent to the parked cars because car doors typically open into the bike lane. A bicyclist colliding into an open door is a common crash type for bicycle riders, and a better understanding of the relationship between parking lane width and the location of parked cars can help control the open door zone and design safety measures. Table 2 summarizes the findings by Furth et al.

Furth et al. (2010) found that where there is no bike lane, the width of the travel lane adjacent to the parking lane has no significant effect on the distance of the parked car tire to the curb. The authors further reasoned that most drivers use the pavement marking, rather than the curb, as guidance when completing a parking maneuver because it is more readily visible in a rearview mirror. They also generalized that a 6.5- to 7.5-ft parking lane is the most appropriate width for U.S. cities.

Duthie et al. (2010) found that a wide curb lane causes significantly more cyclists to travel in the door zone, as compared to a bike lane site. This is likely due to the fact that a bike lane clearly shows cyclists and motorists where to position themselves on the roadway. Duthie et al. also found that a bike lane buffer was very successful in keeping cyclists out of

Table 2. Effect of parking lane width on lateral position of parked vehicles.

Lateral Position of Parked Vehicle	Parking Lane Width		
	6 ft	7 ft	8 ft
95th-percentile distance from curb	0.8 ft	1.24 ft	1.68 ft
Percent of cars over 1 ft from curb	1%	13%	44%

the door zone. From their analysis, several important conclusions were drawn. First, bike lanes are operationally superior to wide curb lanes since they increase the safety and comfort of cyclists and motorists. Second, providing a buffer space between parked cars and bike lanes is very effective. Third, the utilization of on-street parking (either continuous or intermittent) has a significant effect on cyclist lateral position.

Torrence et al. (2009) observed that when the lane adjacent to the motorist was a two-way left-turn lane, as opposed to a through lane for opposing traffic, drivers were 70% more likely to encroach on it when passing a cyclist, since the risk of collision with another vehicle was much less. Motorists were observed to move an average of 1.4 ft away from opposing traffic when not passing a cyclist, and 0.4 ft away when passing. As the motorist moves closer to the cyclist, the cyclist moves closer to parked cars, making the likelihood of being within the door zone greater. The authors also noted that in residential areas, both cyclists and motorists moved farther away from on-street parking.

Van Houten and Seiderman (2005) examined the effects of various pavement markings on the locations of cyclists and parked cars along a section of roadway in Cambridge, Massachusetts. Three pavement marking conditions were evaluated in comparison to the baseline condition: a single lane line marking located 10 ft from the centerline, a lane line plus bike lane symbols with direction arrows, and a bike lane with symbols. The results showed that the first treatment, which was just the lane line, moved the bicycles the farthest from the curb but that parked cars were also farther from the curb, so the distance between the bicycle and the cars remained nearly unchanged. The addition of markings in the second and third scenarios resulted in bicycles and parked vehicles moving back toward the curb, so that the final treatment was not much different than the baseline. However, the additional treatments did result in a decrease in the variation of bicycle location, so that a larger percent of bicycles were traveling at least 9 ft or 10 ft away from the curb. At 9 ft, there is very little overlap in the door zone area and the cyclist's profile, and at 10 ft, the cyclist should be clear of the door zone. This study shows that the presence of a bike lane helps to keep bicycles outside the door zone when compared to a shared lane.

2.1.4 Shared-Lane Marking

The authors of a study of shared-lane markings used in San Francisco compared the effect of adding a bike and chevron symbol (i.e., shared-lane marking) to a bike-in-house symbol on bike routes with no marked bike lane and on-street parking (Alta Planning + Design, 2004). At each site, the shared-lane marking was used for one direction of travel, while the bike-in-house symbol was used in the other direction.

The pavement markings were placed 11 ft from the curb. The distances between the bicycle tire and parked car tire, along with the passing vehicle tire and the bicycle tire, were measured during the before and after conditions. The results showed that the average distance from the bicycle to the parked car increased by 8 in. for both types of pavement markings when no passing vehicle was present. When a passing vehicle was present, the distance from bicycle to parked car increased by 3 and 4 in. for the shared-lane marking and the bike-in-house symbol, respectively. In addition, the distance of the passing car from the bike increased by 2.25 ft for the shared-lane marking and by 2 ft for the bike-in-house symbol. These increases were all statistically significant.

The authors also found that the shared-lane marking significantly reduced the number of cyclists riding on the shoulder and the number of cyclists traveling in the wrong direction. In conclusion, the authors suggested that the proper positioning of the shared-lane marking can help encourage proper lateral positioning of cyclists within the roadway.

2.1.5 Summary of Safety and Design Research Related to Bike Lanes

Table 3 summarizes the behavioral differences and similarities between bike lanes and wide curb lanes.

2.2 Domestic and International Guidelines

This section summarizes design guidance for bicycle lane widths provided in the 2012 AASHTO *Bike Guide*, followed by a summary of other relevant domestic and international guidelines on bicycle lane widths.

2.2.1 AASHTO *Bike Guide* (2012)

The guidance provided in the AASHTO *Bike Guide* that is most relevant to this research is in the area of bicycle facility selection and design criteria for shared roadways and bicycle lanes. By definition, a shared roadway is a roadway open to both bicycle and motor vehicle travel. This may be an existing roadway, a street with wide curb lanes, or a road with paved shoulders. A bike lane is defined as a portion of a roadway designated by striping, signage, and pavement markings for the preferential or exclusive use of cyclists. The AASHTO *Bike Guide* lists several factors to be considered in determining the appropriate facility type, location, and priority for implementation. These factors include:

- Skill level of users,
- Motor vehicle parking,
- Barriers,
- Crash reduction,
- Directness,

Table 3. Behavioral impact of bike lanes and wide curb lanes.

Behavior	Findings	Safer Facility	Supporting Studies
Separation between bikes and motor vehicles	Bike lanes and wide curb lanes produce similar results.	—	Harkey, Stewart, and Rodgman (1996) Kroll and Ramey (1977)
Bike distance from edge of roadway	Compared to wide curb lanes, bike lanes provide greater distance between cyclist and curb.	Bike lane	Harkey, Stewart, and Rodgman (1996)
Vehicle encroachment into adjacent lane when passing	Compared to wide curb lanes, bike lanes result in less encroachment into adjacent lanes.	Bike lane	Harkey, Stewart, and Rodgman (1996) Hunter, Stewart, and Stutts (1999) Hunter and Feaganes (2003)
Driver variability	Compared to wide curb lanes, bike lanes result in less driver variability.	Bike lane	Kroll and Ramey (1977) Torrence et al. (2009)
Bikes in door zone	Compared to wide curb lanes, bike lanes result in fewer cyclists riding in the door zone.	Bike lane	Duthie et al. (2010) Torrence et al. (2009)

- Accessibility,
- Personal safety/security,
- Stops,
- Conflicts,
- Maintenance,
- Pavement surface quality,
- Truck and bus traffic,
- Traffic volumes and speed,
- Bridges,
- Intersection conditions,
- Costs/funding, and
- State and local laws and ordinances.

With respect to the design of bike lanes, the AASHTO *Bike Guide* indicates that bike lanes can be incorporated into a roadway when it is desirable or where there is a high potential for bicycle use to delineate available road space for preferential use by cyclists and motorists, which provides for more predictable movements by both. Bike lanes should typically be one-way facilities and carry bicycle traffic in the same direction as the adjacent motor vehicle traffic. On one-way streets, bike lanes should normally be placed on the right side of the street. The AASHTO *Bike Guide* provides the following guidance on bike lane widths:

- If parking is permitted, the recommended bike lane width is between 5 to 7 ft, and the bike lane is to be placed between the parking area and the travel lane.
- Where parking is permitted, the shared area consisting of the bike lane and parking lane should be a minimum of 12-ft wide, and desirably up to 15-ft wide.
- On high-speed and high-volume roadways or where there is a substantial volume of heavy vehicles, wider bike lanes are recommended.
- When the bike lane is along an urban curbed street where parking is prohibited, the recommended bike lane width is 5 ft from the face of the curb or guide rail to the bike lane stripe, given that there is a usable width of 4 ft.
- For roadways without curb and gutter, the minimum bike lane width should be 4 ft.

The bicycle level-of-service model may be used to determine appropriate shoulder width. This model includes factors such as roadway lane width, lane use, traffic speed and volume, on-street parking, and surface condition.

The AASHTO *Bike Guide* provides more design guidance concerning bike lane lines, markings, and signs, as well as bike lanes at intersections and in relation to turn lanes; however, this research focuses on bike lanes on basic roadway segments, away from the influence of intersections. Thus, the additional details are not covered in this report.

2.2.2 Other Domestic and International Guidelines on Bike Lanes

In addition to the 2012 AASHTO *Bike Guide*, several other domestic and international guidance documents that addressed the design of bicycle lanes were reviewed. These guidelines tend to be very similar to the AASHTO guidance.

Table 4 summarizes the findings and details where the other guidelines vary from the AASHTO guidance. In general, most agencies specify 5 ft as the minimum width for a bike lane; however, several agencies permit bike lanes as narrow as 3 ft. Several agencies also specify minimum or recommended widths for parking lanes in their guidelines, while at least one country (the Netherlands) recommends against bike lanes on roadways with parking.

Table 4. Summary of bike lane width recommendations.

Guide (see References)	Vehicle Lane Width (ft)		Bike Lane Width (ft)		Parking Lane Width (ft)	
	Minimum	Recommended	Minimum	Recommended	Minimum	Recommended
Domestic Guidelines						
AASHTO (2012)			4 (no parking); 5 (w/ parking)	5	7	8
Caltrans* (2005)			5	5	7	7 to 9
Chicago DOT (2002)			5		7	
District of Columbia DOT (2005)	10	10 to 12	5			
City and County of Durham (2006)			5	5 to 6		
City of Minneapolis (2009)			5	5 to 6	8	8 to 10
City of Portland (2010)			6.5**	6.5 to 8.2		
City of San Francisco (2003)			5	5 to 6	7	7 to 9
South Carolina DOT (2003)			4	4 to 6***		
City of Syracuse (1996)			3****			
Virginia DOT (2005)			5		7 (residential); 8 (community)	
Wisconsin DOT (2009)			5	5	8	8 to 10
International Guidelines						
Transportation Association of Canada (1999)			4.5	4.5 to 9		
Netherlands (CROW 2007)			5	5 to 8.2	0*****	0*****
Denmark (Vejdirektoratet, 2006)			3	5		
Haliburton Highlands Cycling Coalition (2008)			3	3 to 5.25		
City of Langley (2004)			5	5 to 6		
Transport for London (2010)	8.2	8.2 to 9.5	4	4 to 5		
Velo Quebec (1992)			3	3 to 7.5		

* Caltrans provides the following additional guidance based on total available width:

Recommended Bike Lane and Parking Lane Widths (Caltrans, 2005)

Total Available Width	Parking Lane Width	Bike Lane Width
12 ft	7 ft	5 ft
13 ft	8 ft	5 ft
14 ft	9 ft	5 ft

** On low-volume streets with no center line, 5-ft "advisory" bike lanes (dotted white lines) are permitted.
*** When speeds exceed 50 mph, 8- to 10-ft lanes should be considered.
**** Cites *ITE Transportation Planning Handbook*: even 3 ft of shoulder space to the right of the edge line can be beneficial to a cyclist, provided that there are no rumble strips.
***** CROW recommends against bike lanes on roadways with parking. An off-road bike path should be considered instead.

SECTION 3

Observational Field Studies

This section describes the observational field studies conducted to evaluate the allocation of roadway width on both bicyclists' and motorists' lateral positioning, taking into consideration various roadway characteristics. The general methodology of the observational field study involved installing temporary lane line markings to delineate bicycle lanes at midblock locations. After a period of time to observe behaviors of bicyclists and motorists, the temporary lane line markings were removed, and new temporary lane line markings were installed along the same midblock location, varying the width of the bicycle lane and in some cases the width of the parking lane. The behaviors of bicyclists and motorists were then observed under the new condition. This process was repeated such that several bicycle lane widths were evaluated at five midblock locations. The scenarios included standard and buffered bicycle lane designs.

All of the study sites had level (or nearly level) grades. A supplemental grade study was conducted to determine how much bicyclists sway or wobble while pedaling on moderate to steep upgrades to evaluate the need for different design guidance for bike lanes on grades (see Section 4).

This section is organized as follows. Section 3.1 briefly describes the site selection process for the observational field studies and presents a general description of the roadway characteristics of the study sites. Section 3.2 describes the study scenarios evaluated at each site. Section 3.3 describes the general data collection methodology. Section 3.4 presents descriptive statistics, the analysis approach, and analysis results of the observational field studies. Section 3.5 summarizes the primary findings from the observational field studies.

3.1 Site Selection and Site Characteristics

The research team contacted representatives in several urban areas throughout the United States to determine if the local transportation agencies/authorities were willing to cooperate in this research and to gather information on potential study sites in the respective cities. The focus was on identifying study locations in urban (and suburban) areas since these areas are where bicycle lanes are most often considered and implemented and a sufficient number of bicyclists are present for data collection and analysis purposes. The nature of this research was highly dependent on finding local transportation agencies/authorities willing to work with the research team and finding appropriate study sites in the respective cities. Study sites in Cambridge (MA) and Chicago (IL) were selected for inclusion in the research.

Study sites in each city were chosen to be as representative as possible of the range of characteristics at typical sites where bicycle lanes are normally planned or installed. When working with the local highway agencies to identify potential data collection sites, sites where bicycle lanes were already planned for installation or were being considered were identified as high-priority locations for inclusion in the study. The roadway characteristics that factored most into the site selection process were:

- Bicycle volume,
- Traffic volume,
- Vehicle mix (i.e., percent trucks),
- Lane width or total roadway width,
- Presence/absence of on-street parking,
- Posted speed limit, and
- Grade.

With the exception of bicycle volume (for which it was critical to find locations with a sufficient level of bicyclists for data collection and analysis purposes), it was desirable to find sites covering a range of these roadway characteristics to draw conclusions and recommendations about each, but some compromises had to be made. For example, all of the potential sites identified during the site selection process had a posted speed limit of 30 mph, but speed limits of

Table 5. Roadway characteristics of data collection sites in Cambridge and Chicago.

City	Chicago	Chicago	Cambridge	Cambridge	Cambridge
Street name	Clark St.	Division St.	Mass. Ave.	Prospect St.	Prospect St.
Direction	NB	EB	WB	SB	NB
Begin cross street	W. Shiller St.	N. Washtenaw Ave.	Wendell St.	Hampshire	Broadway
End cross street	W. Burton Pl.	N. Rockwell St.	Garfield St.	Broadway	Hampshire
Traffic volume (ADT)	14,800	16,600	29,000	15,000	15,000
Percent trucks	16%[3]	20%[3]	7%	2%	2%
Speed limit (mph)	30	30	30	30	30
Presence of on-street parking (Y/N)	Y	Y	Y	N	N
Average travel lane width (ft)	11[1]	12[1]	10[1]	18[2]	16[2]
Number of lanes (directional)	1	1	2	1	1
Curb and gutter (Y/N)	Y	Y	Granite curb, no gutter pan	Granite curb, no gutter pan	Granite curb, no gutter pan
Grade	Level	Level	Level	Level	Level

[1] Average width of the travel lane adjacent to the bicycle lane during the study.
[2] Average width of the travel lane without any bicycle lanes installed.
[3] Most truck traffic consists of single-unit trucks.
Note: NB = northbound, EB = eastbound, WB = westbound, SB = southbound, ADT = average daily traffic.

30 to 35 mph are common on many streets in urban and suburban areas. So although potential data collection sites were not found covering a range of speed limits, the sites that were identified had speed limits common to many streets in urban and suburban areas and were typical of locations where bicycle lanes are installed or are considered for installation.

Five sites were included in the observational study—three sites in Cambridge (Massachusetts Avenue, Prospect Street northbound, and Prospect Street southbound) and two sites in Chicago (Division Street and Clark Street). Table 5 presents site characteristic information for each site. The traffic volumes of the sites ranged from approximately 15,000 to 29,000 vehicles per day (vpd), and the percentage of trucks in the vehicle mix ranged from 2% to 20%. Three of the sites had on-street parking, and two did not. For sites with on-street parking, the width of the travel lane adjacent to the bicycle lane ranged from 10 to 12 ft; and for the two sites where on-street parking was prohibited, the widths of the travel lanes without any bicycle lanes installed were 16 and 18 ft. The speed limit at each site was 30 mph. All of the sites had a level, or nearly level, grade.

3.2 Study Scenarios

At each study site, several scenarios were evaluated by varying the width of the bicycle lane. At study sites with on-street parking, in most cases the vehicle travel lane width was held constant. The longitudinal lane line separating the vehicle travel lane from the bicycle lane was installed using either paint or thermoplastic pavement marking and was not moved. Only the longitudinal lane line closest to the parking lane (or curb) was installed using temporary pavement marking material to vary the width of the bicycle lane. In Chicago, the bicycle lane widths varied from 4 to 6 ft, and the parking lane width varied from 7 to 9 ft. For two scenarios in Chicago, a buffered bicycle lane was also evaluated. On Clark Street there was a 2-ft buffer space between a 7-ft parking lane and a 5-ft bike lane. On Division Street there was a 2-ft buffer space on either side of a 4-ft bike lane. In Cambridge, the bicycle lane widths varied from 3.5 to 5 ft; the parking lane width was held constant at 7 ft; and for the narrower bicycle lane widths of 3.5 ft and 4 ft, a buffer space separated the bicycle lane from the parking lane. These study scenarios are depicted in Figure 1. The study scenarios are numbered for easy referencing throughout the report.

Prospect Street was the only study location without on-street parking. Consistent with the other sites, a longitudinal lane line separating the vehicle travel lane from the bicycle lane was installed using temporary pavement marking material. This lane line was moved to vary the width of the bicycle lane. Bicycle lane widths of 4 ft and 5 ft were evaluated along both directions of Prospect Street. The bike lane width was measured from the center of the longitudinal lane line separating the vehicle travel lane from the bicycle lane to the face of the curb. No gutter pan was present in either direction of travel. In addition, for both directions of travel along Prospect Street, data were collected without any bicycle lane lines present (i.e., simply a wide curb lane). These study scenarios are depicted in Figure 2.

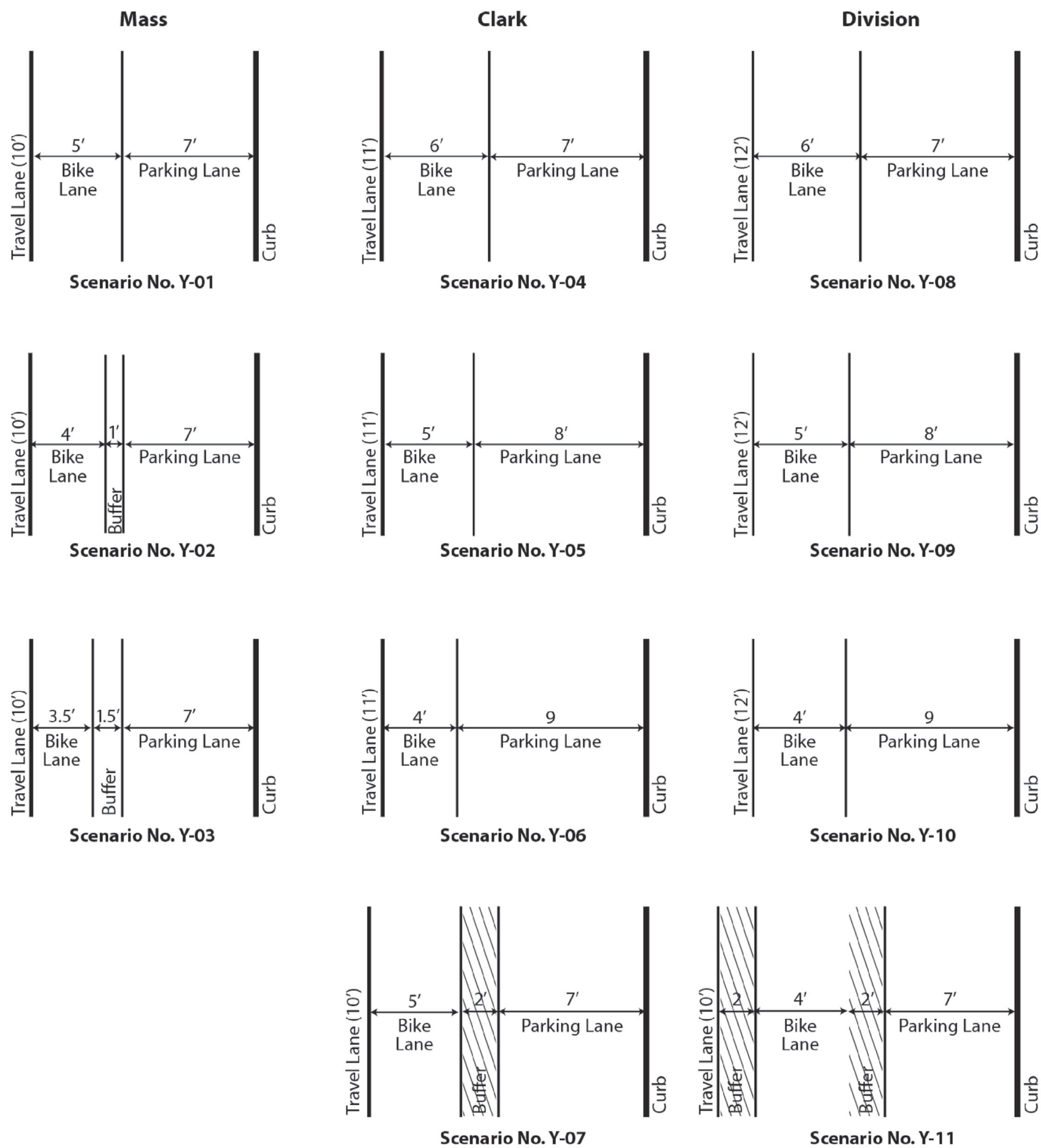


Figure 1. Study sites and scenarios with on-street parking.

Table 6 summarizes the 17 study scenarios evaluated—11 scenarios with on-street parking and 6 scenarios without on-street parking. Table 6 shows the widths of the travel lanes, bicycle lanes, and parking lanes (if applicable) for all study scenarios. Figure 3 shows illustrations of the buffered bike lanes installed on Clark Street and Division Street in Chicago. For these two scenarios, temporary pavement marking materials were not used.

The width of the buffer space was not included as part of the total width of the bicycle lane in the analysis. Also, the specific designs varied depending on the location, as illustrated in Figure 1 and Figure 3. For example, the buffered bike lane on Division Street did not include a longitudinal lane line separating the diagonal cross hatching from the bicycle lane. On Massachusetts Avenue, there was no diagonal cross hatching within the buffer space.

At each study site, temporary pavement markings were installed along one or two city blocks, approximately 300 to 600 ft in length. The temporary pavement marking material was 4-in. wide and white. Two bike lane symbols (and arrows) were painted in the bike lane using a stencil at approximately 10 ft and 200 ft downstream from the beginning cross street. The bicycle lane symbol and arrow were positioned such that they would approximately be in the middle of the narrowest lane. This allowed the symbol to be kept in the same location as the temporary lane lines were moved to vary the width of the bicycle lane.

Given the site characteristics and the study scenarios, the ranges in the primary roadway and traffic characteristics analyzed in this research are as follows:

- Bike lane width: 3.5 to 6 ft
- Parking lane width: 7 to 9 ft
- Travel lane width: 10 to 18 ft
- Presence/absence of buffer space
- Traffic volume: 14,800 to 29,000 vpd
- Percent trucks: 2% to 20%

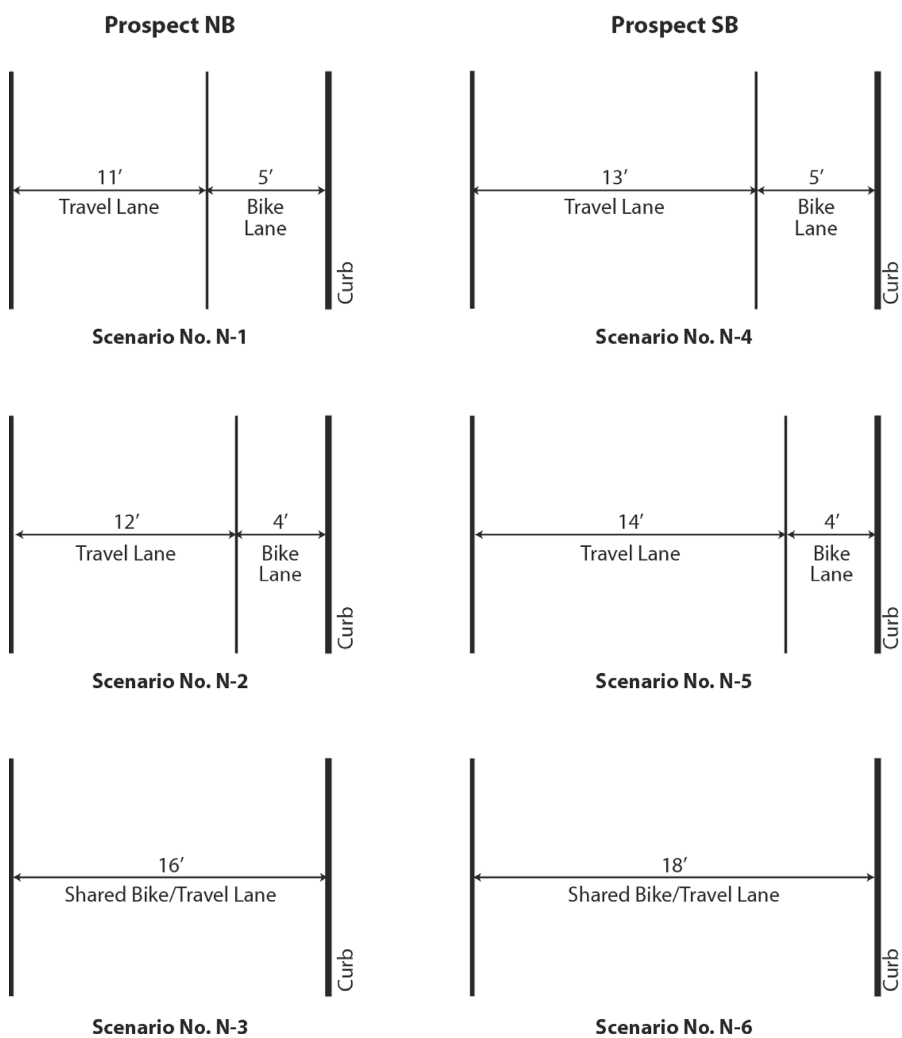


Figure 2. Study sites and scenarios without on-street parking.

Table 6. Location and description of study scenarios.

City, State	Street	Scenario	Width (ft) Travel Lane	Width (ft) Bike Lane	Width (ft) Parking Lane
Sites with On-Street Parking					
Cambridge, MA	Massachusetts Ave.	Y-01	10	5	7
		Y-02		4[1]	
		Y-03		3.5[2]	
Chicago, IL	Clark St.	Y-04	11	6	7
		Y-05		5	8
		Y-06		4	9
		Y-07	10	Buffered[3]	7
Chicago, IL	Division St.	Y-08	12	6	7
		Y-09		5	8
		Y-10		4	9
		Y-11	10	Buffered[4]	7
Sites without On-Street Parking					
Cambridge, MA	Prospect St. (NB)	N-1	11	5	N/A
		N-2	12	4	
		N-3	16	No BL	
Cambridge, MA	Prospect St. (SB)	N-4	13	5	N/A
		N-5	14	4	
		N-6	18	No BL	

[1] 4-ft bicycle lane; 1-ft buffer area.
[2] 3.5-ft bicycle lane; 1.5-ft buffer area.
[3] 5-ft bicycle lane; 2-ft buffer area.
[4] 2-ft buffer area; 4-ft bicycle lane; 2-ft buffer area.
Note: NB = northbound, SB = southbound, BL = bike lane.

Clark Street
(Scenario Y-07)

Division Street
(Scenario Y-11)

Figure 3. Buffered bike lanes in Chicago.

3.3 Data Collection Methodology

For each study scenario, a video camera was positioned to record cyclist and motorist lateral position along the mid-block portion of the study section. Figure 4 through Figure 8 show the perspectives from the camera for the Massachusetts Avenue, Clark Street, Division Street, Prospect Street (northbound), and Prospect Street (southbound) study sites, respectively. Cyclist and motorist behaviors were recorded during morning and afternoon peak periods when bicyclist exposure level was expected to be highest. Video data were collected from April into December during calendar years 2011 and 2012. No crashes were observed at any of the sites during the study.

Reference markings were placed on the pavement within the bicycle lane (or near the curb on Prospect Street for the study scenario without a bicycle lane present). The reference markings were placed near the midblock portion of the study section and were used during video data reduction to ascertain cyclist and motor vehicle lateral position within the roadway cross section.

The video camera was placed approximately 100 ft downstream of the reference markings. The camera was positioned such that the reference markings and the cyclists passing them could be seen in the recorded video. The position and zoom of the camera were also such that the right tires of a vehicle passing a cyclist in the adjacent travel lane could be seen.

During data collection, sketches were made of the project site, noting camera position, reference marking locations,

5-ft Bike Lane
(Scenario Y-01)

4-ft Bike Lane
(Scenario Y-02)

3.5-ft Bike Lane
(Scenario Y-03)

Figure 4. Camera perspective for observational field study scenarios on Massachusetts Avenue in Cambridge.

6-ft Bike Lane
(Scenario Y-04)

5-ft Bike Lane
(Scenario Y-05)

4-ft Bike Lane
(Scenario Y-06)

Buffered Bike Lane
(Scenario Y-07)

Figure 5. Camera perspective for observational field study scenarios on Clark Street in Chicago.

and lane widths (i.e., parking lane, bicycle lane, buffer space, and adjacent travel lane, as applicable). Motor vehicle speed, volume, and classification data were collected during the first scenario at each study site using traffic classifiers.

For sites with on-street parking, the following measurements were taken hourly along the study location to gather parking data while video was being recorded:

- The distance between the curb face and the front right tire (i.e., passenger side) of each parked vehicle
- The distance between the curb face and the rear right tire (i.e., passenger side) of each parked vehicle
- The width of the rear bumper of each vehicle

Empty parking spaces were also noted.

Following video data collection, the recordings were viewed to collect the following measurements, based on the known lateral positions of the reference markings within the cross section of the roadway:

- Cyclist's lateral position: The distance from the front tire of the bicycle to the curb face (at the instant the cyclist passed the reference markings).
- Lateral position of the nearest passing vehicle (in time) in the adjacent travel lane: The distance from the right tire (i.e., passenger side) of the passing vehicle to the curb face (at the instant the motor vehicle passed the reference mark-

6-ft Bike Lane
(Scenario Y-08)

5-ft Bike Lane
(Scenario Y-09)

4-ft Bike Lane
(Scenario Y-10)

Buffered Bike Lane
(Scenario Y-11)

Figure 6. Camera perspective for observational field study scenarios on Division Street in Chicago.

ings). Note: because of the perspective angle and zoom of the camera, it was not feasible to measure the distance from the left tire (i.e., driver side) of the passing vehicle to the curb face to accurately gather data on passing vehicle encroachment into adjacent (motor vehicle) travel lanes.

A final database was assembled that included the relative lateral positions of parked vehicles, bicyclists, and passing vehicles within the roadway cross section. The database was used to analyze the effect of critical roadway characteristics on lateral positions of the respective vehicles (i.e., parked vehicles, bicycles, and passing vehicles) within the parking lane, bicycle lane, and travel lane.

3.4 Data Analysis

The data collected at the various sites under various striping scenarios were analyzed to determine whether selected roadway characteristics affect the placement of bicyclists and vehicles within the cross section of the roadway. This section presents basic descriptive statistics of the measurements collected in the field; the statistical analysis approach, including the definition of the dependent variables used for analysis; and the analysis results.

3.4.1 Descriptive Statistics

Prior to analysis, the data underwent basic quality checks such as removing outliers and unreasonable field measurements

5-ft Bike Lane
(Scenario N-1)

4-ft Bike Lane
(Scenario N-2)

Wide Curb Lane (No Bike Lane)
(Scenario N-3)

Figure 7. Camera perspective for observational field study scenarios on Prospect Street (northbound) in Cambridge.

(e.g., vehicles parked in the travel lane, bicyclist riding in the far left of the travel lane); in total, fewer than 2% of cyclist, passing vehicle, and parked vehicle records were excluded. The final database used for analyses included records for 4,965 bicyclists, 3,163 passing vehicles, and 994 parked vehicles.

Of the field measurements collected at each site, the most relevant for the analysis, in addition to the roadway characteristics described in Table 5, were:

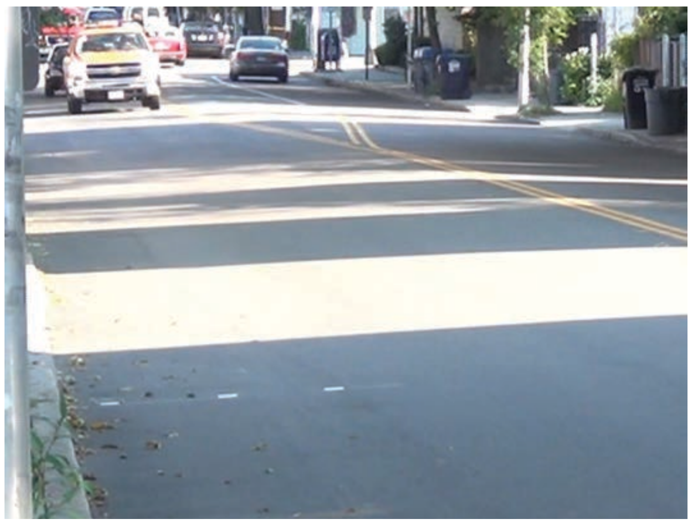
- Total parked vehicle displacement from curb (sites with on-street parking only). This is equivalent to the distance of the left side (i.e., driver side) of the parked vehicle from the curb, calculated as the average distance of the front and rear right tires (i.e., passenger side) to the curb face plus the width of the parked vehicle.
- Distance of bike from curb.
- Distance of passing vehicle from curb, nearest in time to each cyclist measured.

Motor vehicle speed data were also collected at each site but were not included in the analysis.

Overall Relative Positioning of Vehicles and Cyclists. The raw data collected in Cambridge and Chicago were plotted separately for each of the scenarios described in

5-ft Bike Lane
(Scenario N-4)

4-ft Bike Lane
(Scenario N-5)



Wide Curb Lane (No Bike Lane)
(Scenario N-6)

Figure 8. Camera perspective for observational field study scenarios on Prospect Street (southbound) in Cambridge.

Table 6. Figure 9 through Figure 13 show the position of parked vehicles, cyclists, and passing vehicles within their respective lanes. From left to right, where the origin indicates the curb, each plot shows the individual measurements, in feet, of:

- The average distance of the front and rear right tires (i.e., passenger side) to the curb face of each parked vehicle;
- The total parked vehicle displacement from the curb of each parked vehicle;
- The cyclist's lateral position, based on the distance from the front tire of the bicycle to the curb and an assumed physical width of the bicycle of 2.5 ft (i.e., the middle point of the envelope represents the lateral position of the front bicycle tire, and the outside points of the envelop represent the positions of the left and right ends of the handlebar for a typical adult bicyclist);
- The distance from the right tire of the passing vehicle to the curb; and
- The distance from the left tire of the passing vehicle to the curb, assuming a vehicle width of 7 ft based on the dimensions for a passenger car design vehicle in AASHTO's *A Policy on Geometric Design of Highways and Streets* (commonly referred to as the *Green Book;* AASHTO, 2011, Table 2-1b).

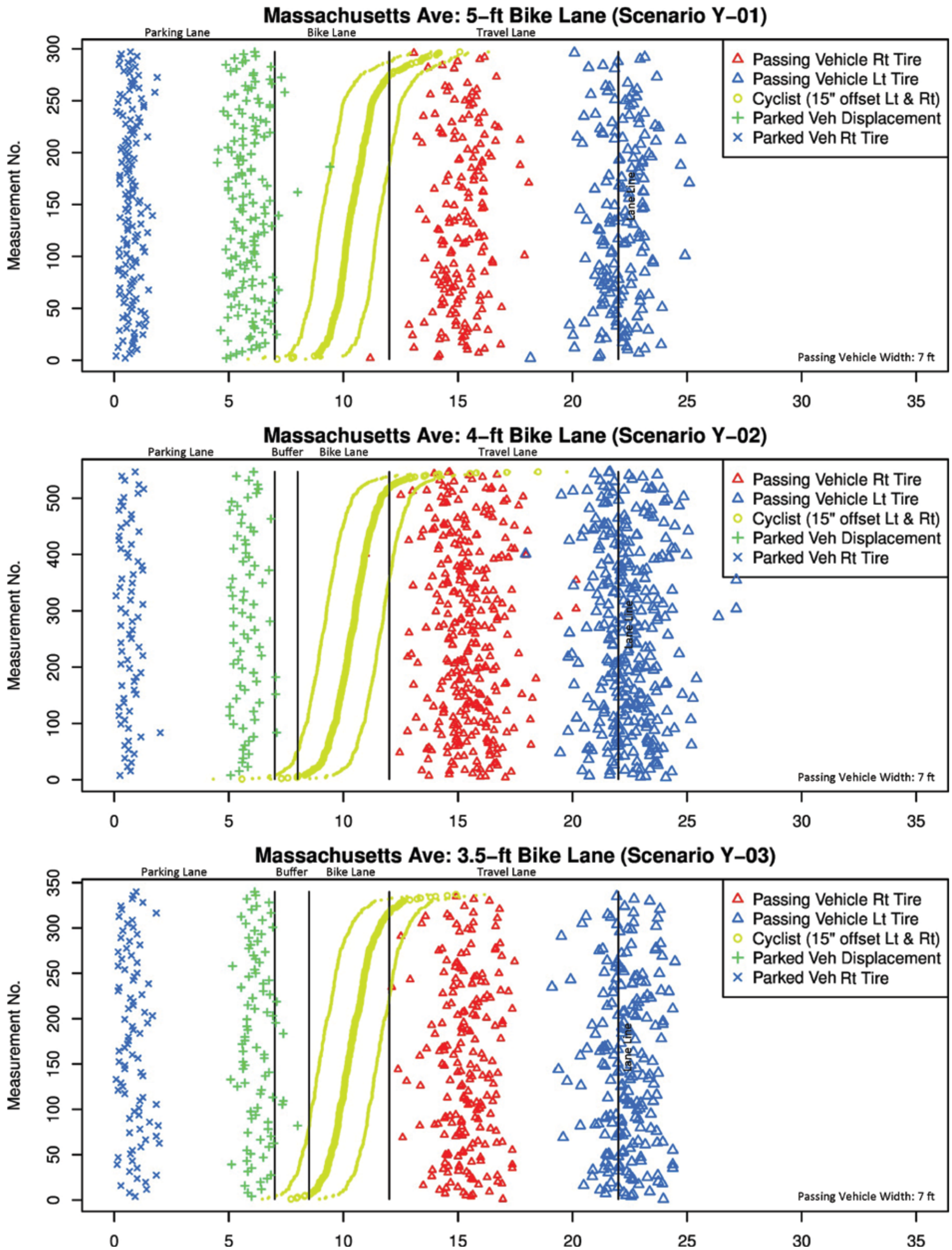


Figure 9. Measurements taken on Massachusetts Avenue in Cambridge (assumed 7-ft width for passing vehicle).

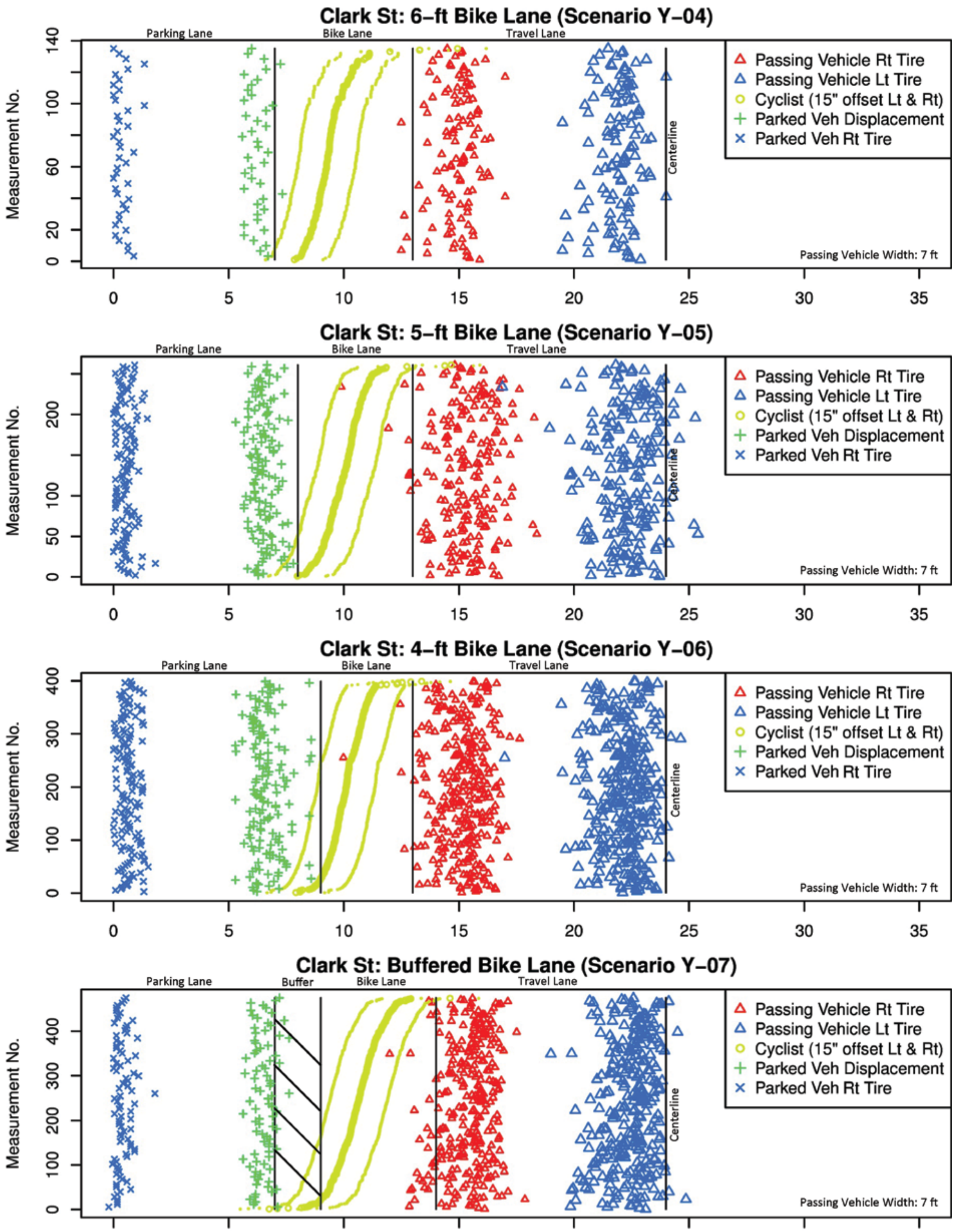


Figure 10. Measurements taken on Clark Street in Chicago (assumed 7-ft width for passing vehicle).

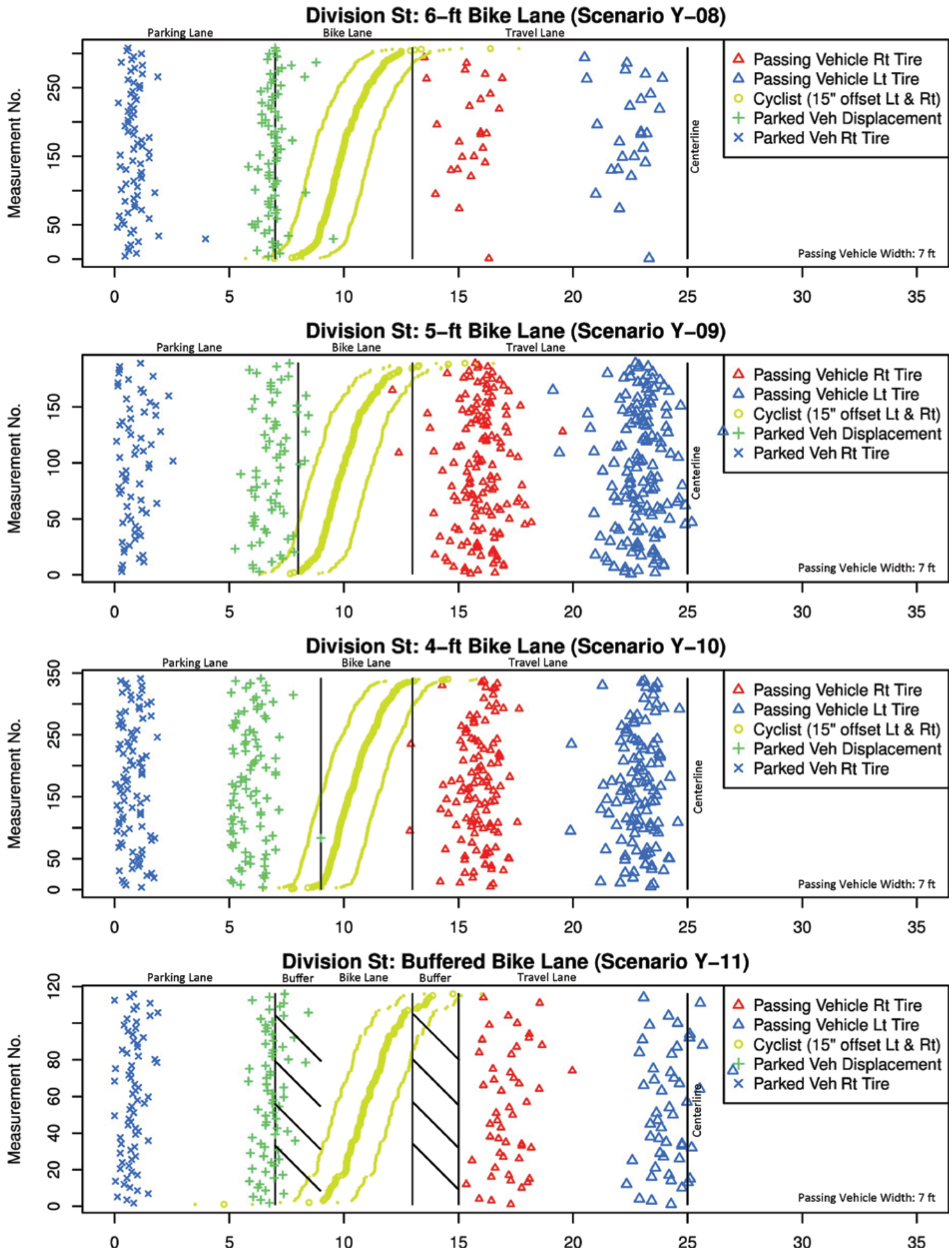


Figure 11. Measurements taken on Division Street in Chicago (assumed 7-ft width for passing vehicle).

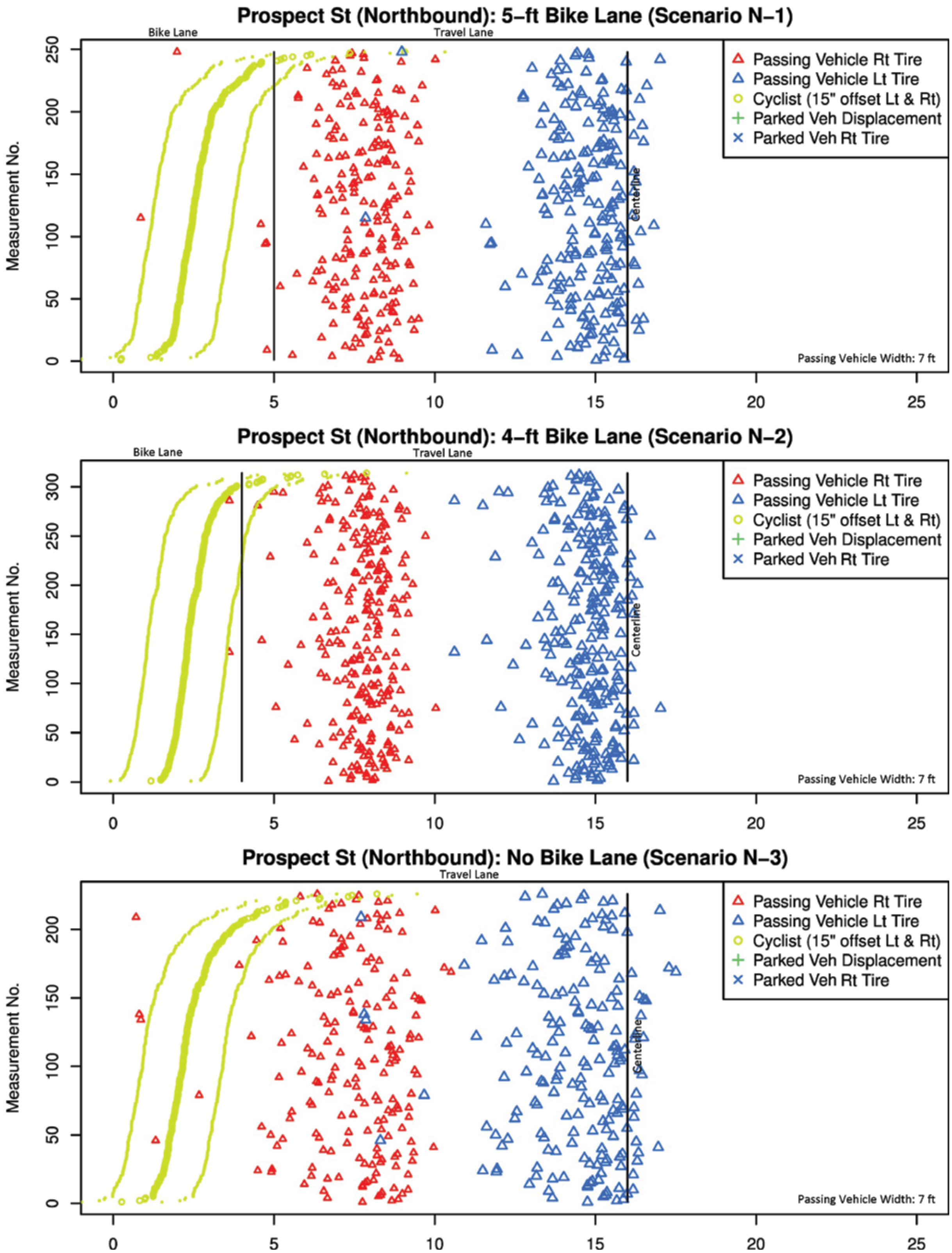


Figure 12. Measurements taken on Prospect Street (northbound) in Cambridge (assumed 7-ft width for passing vehicle).

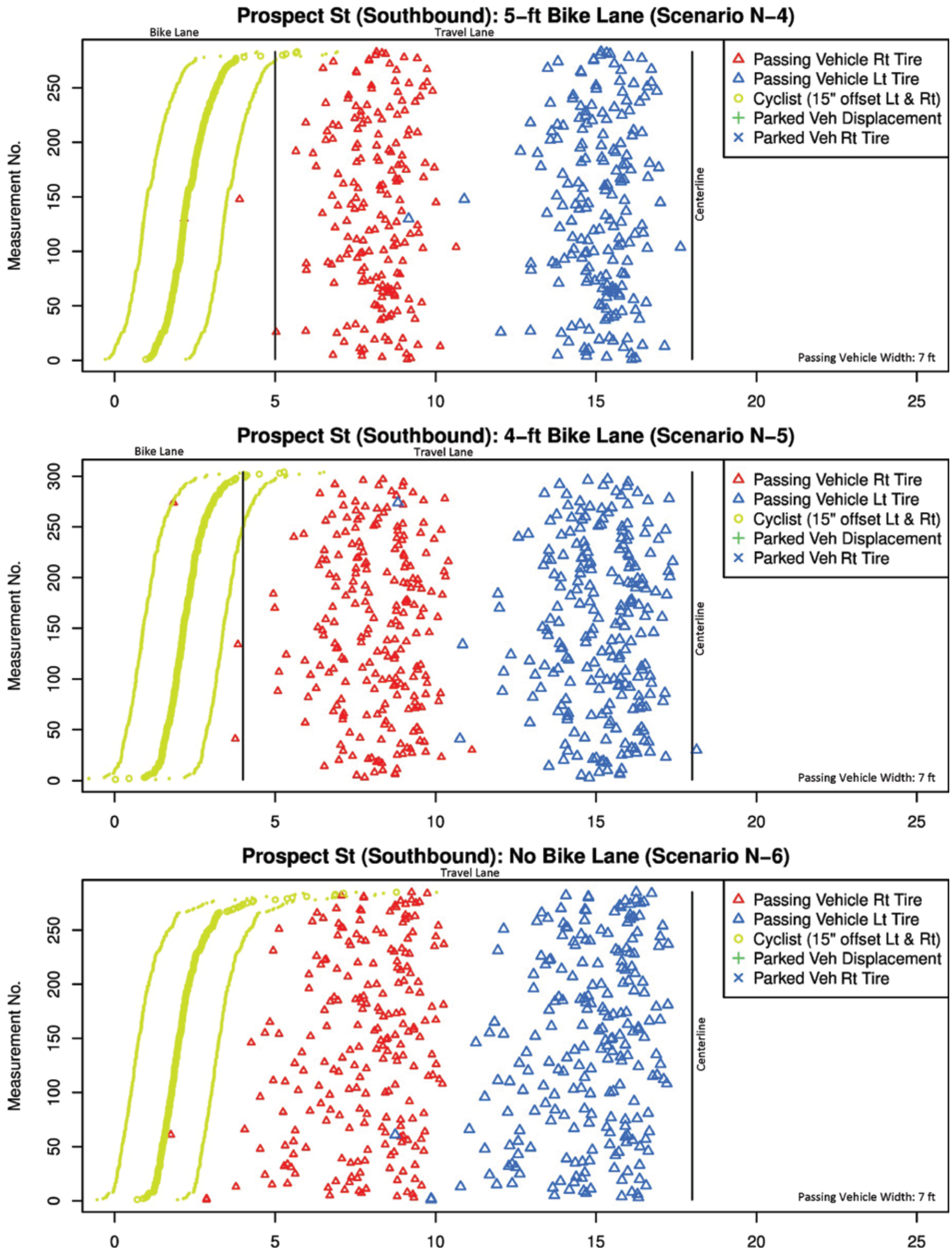


Figure 13. Measurements taken on Prospect Street (southbound) in Cambridge (assumed 7-ft width for passing vehicle).

In each plot, the data are sorted by the cyclist's lateral position, with the minimum distance from the curb lowest on the *y*-axis and the maximum highest on the *y*-axis. This effectively creates a cumulative distribution of the cyclist's position relative to the curb in each graph. Thus, the measurement number on the *y*-axis is not an indication of increasing measurement but simply the order of the measurement in the database after the data were sorted by the cyclist's distance from the curb. As such, the maximum number on the *y*-axis represents the sample size.

Assuming a vehicle width (excluding mirrors) of 7 ft for passing vehicles, several of the figures suggest that encroachment of passing vehicles into adjacent (motor vehicle) travel lanes to the left may be a concern. Encroachment of passing vehicles into adjacent (motor vehicle) travel lanes to the left was not a performance measure that the research team focused on in the analyses (see Sections 3.4.2 and 3.4.3) for reasons described previously, but it deserves some level of attention here. In particular, Figure 9 (scenarios Y-01, Y-02, and Y-03) shows a high rate of vehicle encroachment into the adjacent travel lane. Note that Massachusetts Avenue was the only study site with two travel lanes in the same direction of travel adjacent to the bike lane. All other study sites were two-lane streets. Also, it is important to note that there were a total of five study scenarios (Y-01, Y-02, Y-03, Y-07, and Y-11) where the travel lane adjacent to the bicycle lane was 10-ft wide. From Figures 10 and 11, assuming a vehicle width of 7 ft for passing vehicles, there was a much lower rate of vehicle encroachment of passing vehicles into adjacent (motor vehicle) travel lanes to the left on Clark Street and Division Street than on Massachusetts Avenue. However, based on the research team's field observations, Figures 9 through 13 may overestimate the rate of encroachment of passing vehicles into adjacent (motor vehicle) travel lanes to the left. Therefore, the same data in Figures 9 through 13 are repeated in Figures 14 through 18, this time assuming a vehicle width (excluding mirrors) of 5.67 ft (68 in.). This width is consistent with the average width of parked vehicles measured in the field and dimensions from a sampling of vehicle specifications for passenger vehicles for model years 2013 and 2014. The research team believes that Figures 14 through 18 more accurately represent the behaviors of passing vehicles observed during the field studies with respect to encroachment into adjacent (motor vehicle) travel lanes to the left.

Total Displacement of Parked Vehicles. Basic statistics for this measurement at sites with on-street parking are presented in Table 7. These include, for each scenario, the number of parked vehicles measured, mean, standard deviation, relative standard deviation (standard deviation/mean, in percent), and four percentiles. Percentile values that exceed the parking lane width are highlighted in red. Figure 19 shows the distribution of this measurement in the form of box plots, across all scenarios, but separately for each parking lane width. Since a number of scenarios included buffered lanes of different widths, 7-ft parking lanes were subdivided according to the width and type of the buffer.

Distance of Cyclists from Curb. Basic statistics for this measurement at all sites are presented in Table 8. These include, for each scenario, the number of cyclists measured, mean, standard deviation, relative standard deviation, minimum and maximum distances, and five percentiles. Figure 20 through Figure 24 show this measurement in the form of histograms, separately for each scenario. The positions of the parking lane (where present), buffer space (where present), bike lane (where present), and travel lane are indicated on each plot.

Table 9 (left half) shows the spread of bicyclist lateral positions, separately for each scenario. Here, the spread of bicyclist lateral positions is calculated as the distance between the 5th- and 95th-percentile bicyclist positions. For example, for scenario Y-01 (i.e., the 5-ft bike lane on Massachusetts Avenue), the 5th-percentile bicyclist position is at 9.2 ft and the 95th-percentile bicyclist position is at 11.7 ft. Thus, the spread of bicyclist lateral positions is 2.5 ft (11.7 ft–9.2 ft). The right half of Table 9 shows the average spread of bicyclist lateral positions calculated: (1) by bike lane width, separately across all sites with or without on-street parking, and (2) by bike lane width across all sites (note that bike lane widths of 3.5 and 4 ft were combined). The overall average across all sites is shown to be 2.7 ft. As expected, narrowing the bicycle lane appears to reduce the variability of bicyclist lateral positions (i.e., the spread of bicyclist lateral positions).

Distance of Passing Vehicle from Curb. Basic statistics for this measurement at all sites are presented in Table 10. These include, for each scenario, the number of passing vehicles measured, mean, standard deviation, relative standard deviation, 5th and 10th percentiles, and median. Figure 25 through Figure 29 show this measurement in the form of histograms, separately for each scenario. The positions of the bike lane (where present) and travel lane are indicated on each plot.

A few facts about the study sites are worth highlighting. First, the narrowest travel lane width included in the research was 10 ft; this is the case for all scenarios on Massachusetts Avenue and the buffered bike lane scenarios on Clark Street and Division Street. Second, Massachusetts Avenue was the only study site that included two travel lanes in the same direction of travel as the bicycle lane. All other study sites had only a single travel lane in the same direction of travel as the bicycle lane.

(*text continues on page 41*)

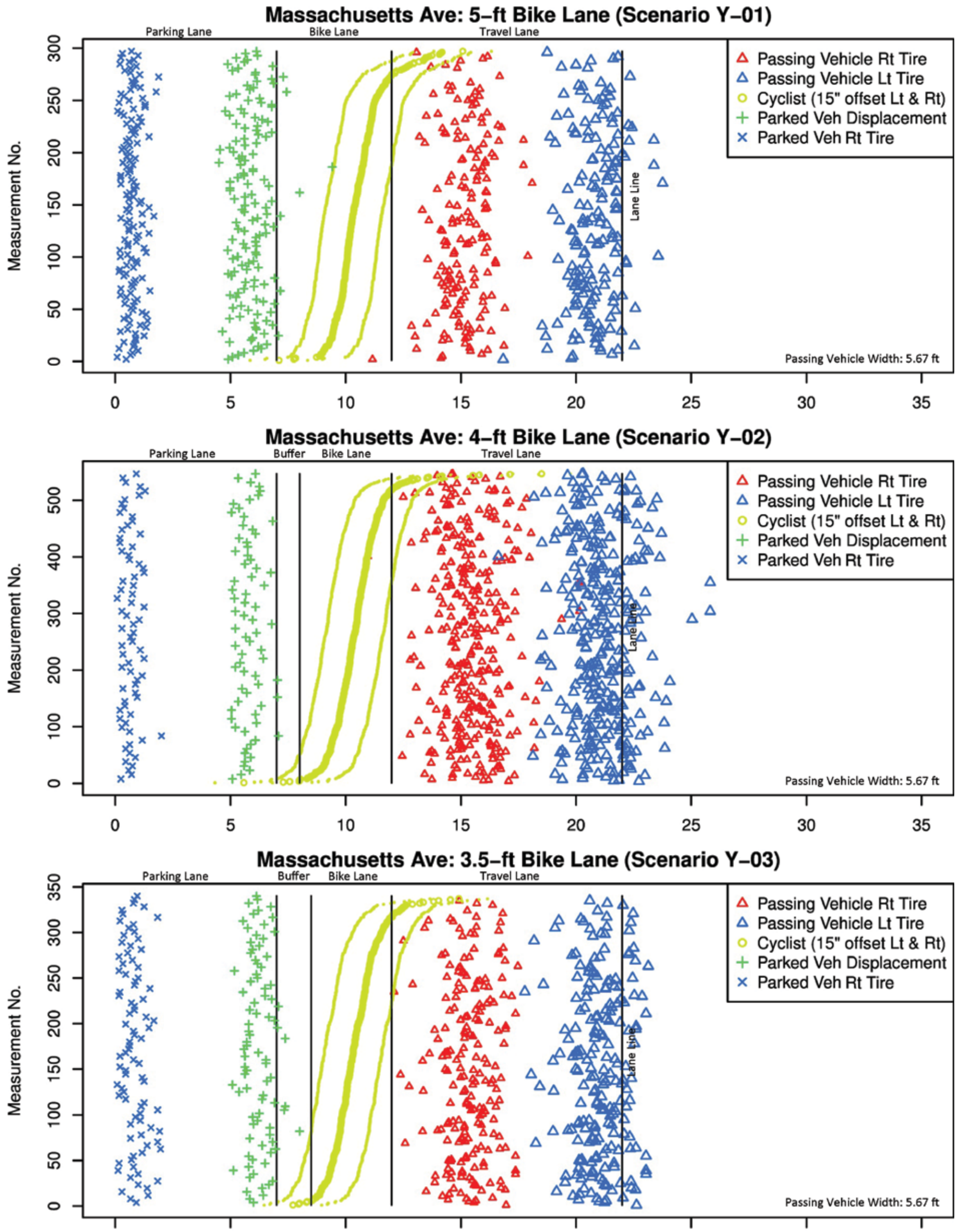


Figure 14. Measurements taken on Massachusetts Avenue in Cambridge (assumed 5.67-ft width for passing vehicle).

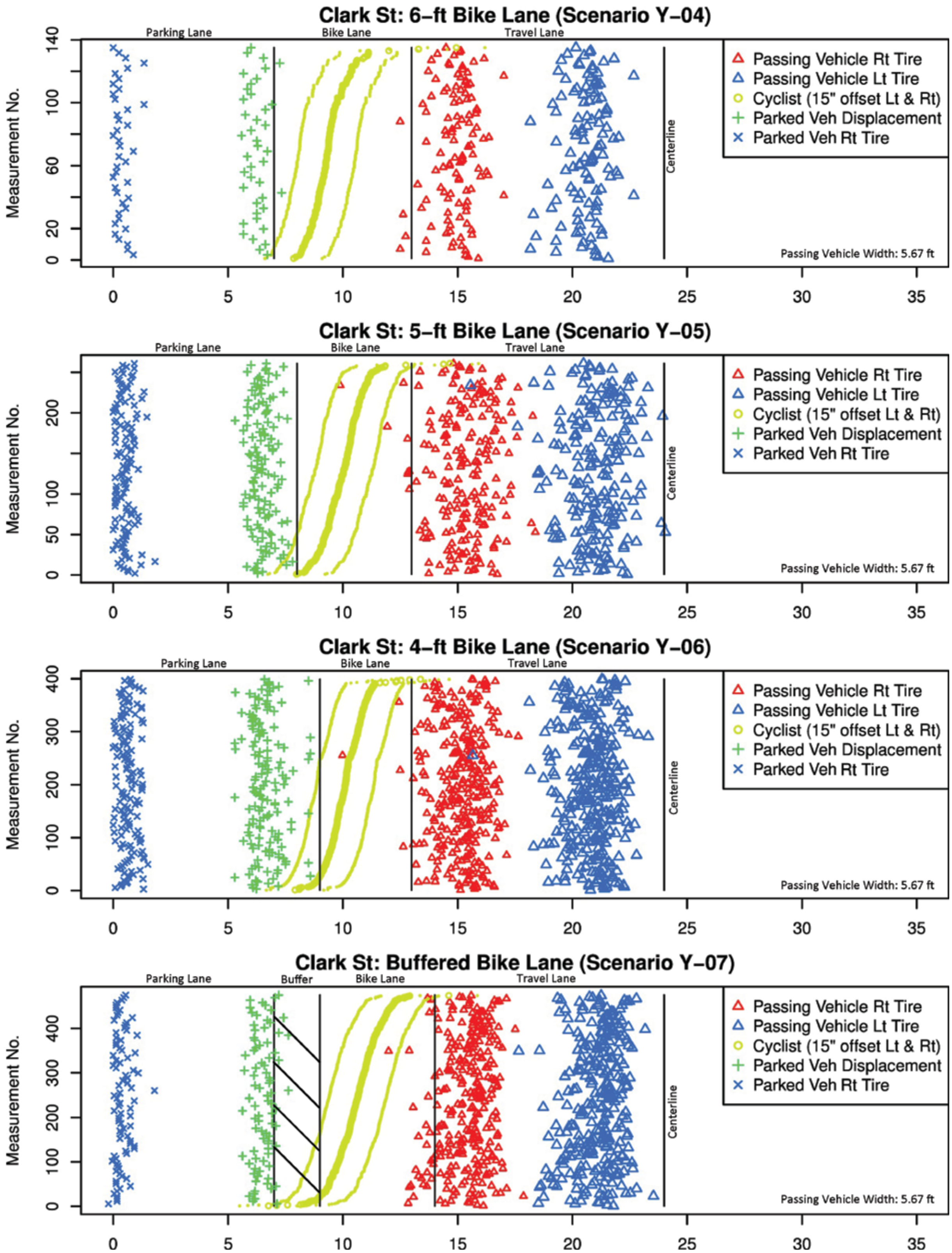


Figure 15. Measurements taken on Clark Street in Chicago (assumed 5.67-ft width for passing vehicle).

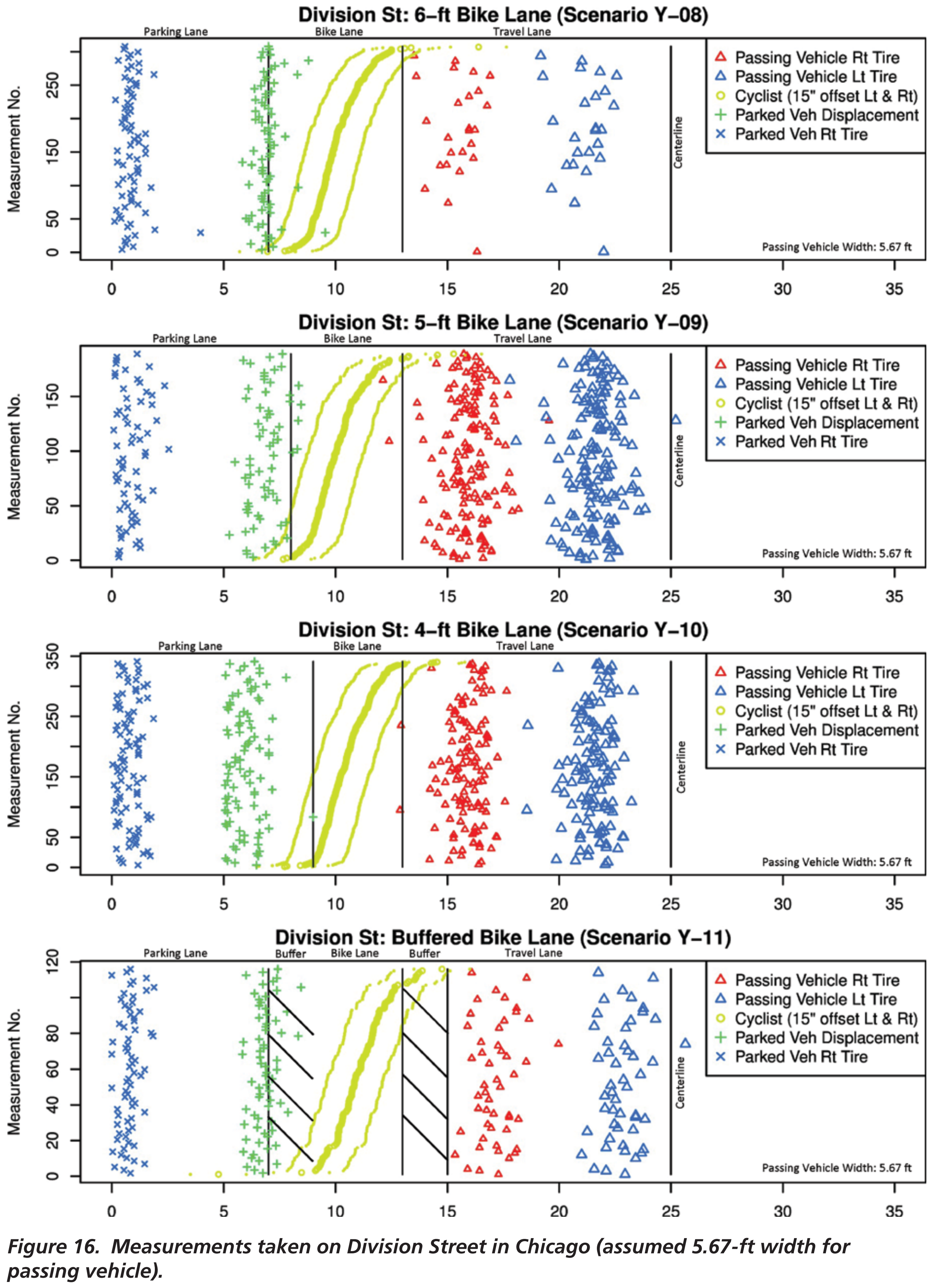


Figure 16. Measurements taken on Division Street in Chicago (assumed 5.67-ft width for passing vehicle).

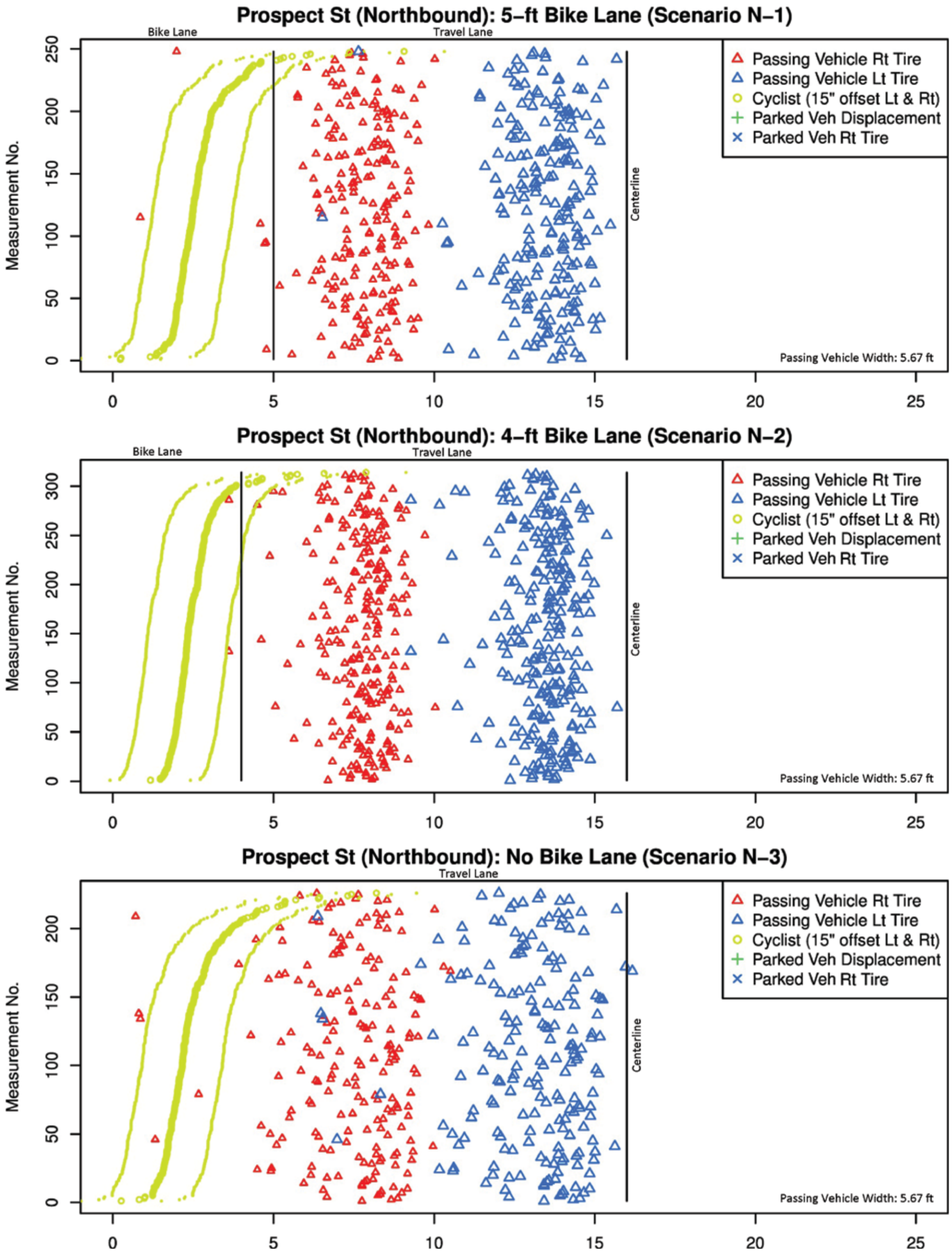


Figure 17. Measurements taken on Prospect Street (northbound) in Cambridge (assumed 5.67-ft width for passing vehicle).

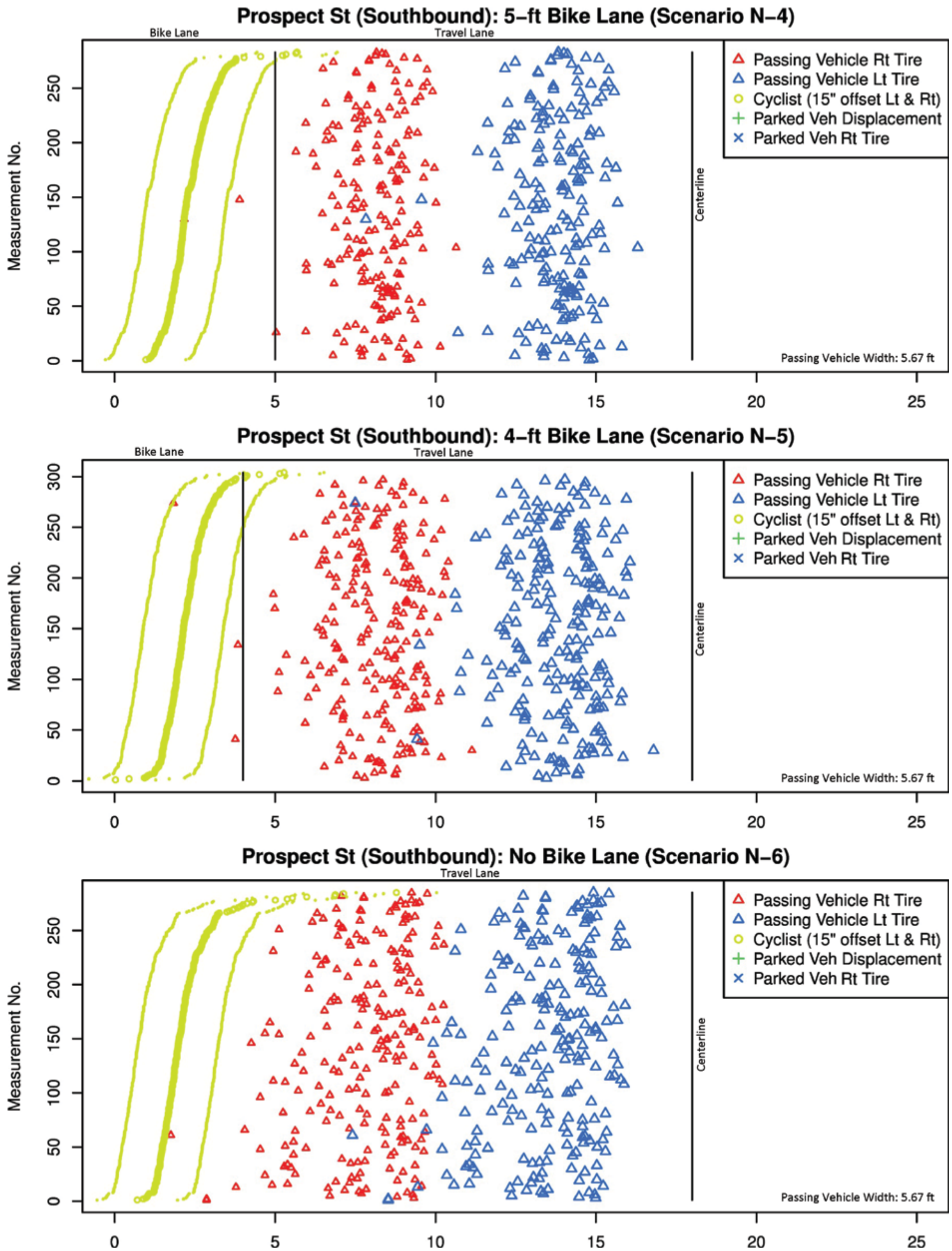
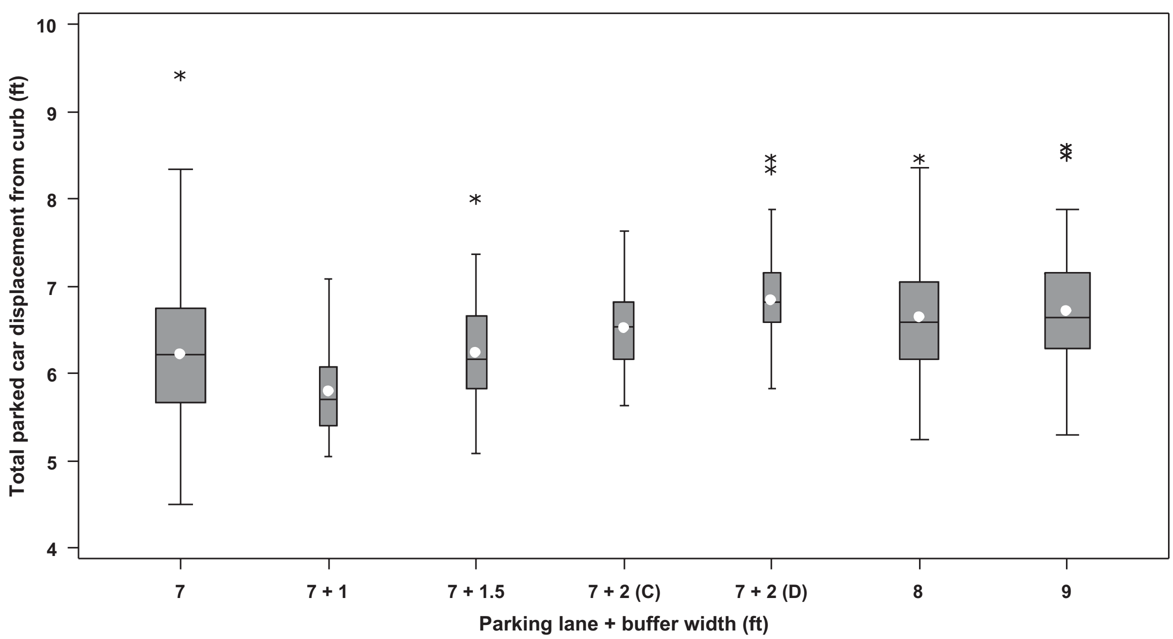


Figure 18. Measurements taken on Prospect Street (southbound) in Cambridge (assumed 5.67-ft width for passing vehicle).

Table 7. Descriptive statistics for parked vehicle displacement.

Street (City)	Parking Lane Width (ft)	Bike Lane Width (ft)	Scenario	Number of Vehicles Measured	Parked Vehicle Displacement—Distance from Curb (ft): Mean	Standard Deviation	Relative Standard Deviation (%)	Percentiles[5]: Median	85th	90th	95th
Massachusetts Ave. (Cambridge)	7.0	5.0	Y-01	145	5.9	0.7	12.3	5.9	6.6	6.8	6.9
		4.0[1]	Y-02	72	5.8	0.5	8.8	5.7	6.3	6.4	6.8
		3.5[2]	Y-03	87	6.2	0.5	8.8	6.2	6.8	6.9	7.1
Clark St. (Chicago)	7.0	6.0	Y-04	41	6.2	0.4	7.0	6.3	6.6	6.7	6.9
	8.0	5.0	Y-05	126	6.5	0.5	7.6	6.5	7.1	7.3	7.4
	9.0	4.0	Y-06	145	6.6	0.7	10.3	6.5	7.2	7.4	7.8
	7.0	Buffered[3]	Y-07	84	6.5	0.4	6.9	6.5	7.0	7.1	7.2
Division St. (Chicago)	7.0	6.0	Y-08	71	6.9	0.4	6.4	6.9	7.1	7.3	7.7
	8.0	5.0	Y-09	65	6.9	0.7	10.6	6.9	7.6	8.0	8.3
	9.0	4.0	Y-10	90	6.8	0.5	6.8	6.8	7.2	7.4	7.6
	7.0	Buffered[4]	Y-11	68	6.8	0.5	8.0	6.8	7.4	7.4	7.8

1 4-ft bicycle lane; 1-ft buffer area.
2 3.5-ft bicycle lane; 1.5-ft buffer area.
3 5-ft bicycle lane; 2-ft buffer area.
4 2-ft buffer area; 4-ft bicycle lane; 2-ft buffer area.
5 Percentile values that exceed the parking lane width are highlighted in red.



	7	7 + 1	7 + 1.5	7 + 2 (C)	7 + 2 (D)	8	9
N	257	72	87	84	68	191	235
Min	5	5	5	6	6	5	5
Mean	6.2	5.8	6.2	6.5	6.8	6.6	6.7
Median	6.2	5.7	6.2	6.5	6.8	6.6	6.6
Max	9.4	7.1	8.0	7.6	8.5	8.5	8.6
Std Dev	0.7	0.5	0.5	0.4	0.5	0.6	0.6

White dot = mean; Star = extreme value; Gray box = mid 50% of data; C = Clark St.; D = Division St.

Figure 19. Distribution of total parked vehicle displacement by parking lane width.

Table 8. Descriptive statistics for bike position from curb.

Street (City)	Bike Lane Width (ft)	Scenario	Number of Cyclists Measured	Distance of Cyclist from Curb (ft)										
				Mean	Standard Deviation	Relative Standard Deviation (%)	Minimum	Percentiles					Maximum
								5th	10th	Median	90th	95th	
Sites with On-Street Parking													
Massachusetts Ave. (Cambridge)	5.0	Y-01	280	10.4	0.8	7.6	7.1	9.2	9.5	10.3	11.3	11.7	12.5
	4.0[1]	Y-02	530	10.4	0.9	8.4	5.6	9.0	9.3	10.4	11.4	11.7	12.5
	3.5[2]	Y-03	327	10.3	0.9	8.3	7.7	8.9	9.3	10.3	11.5	11.8	12.5
Clark St. (Chicago)	6.0	Y-04	134	9.4	0.8	8.6	7.9	8.2	8.4	9.3	10.4	10.9	13.3
	5.0	Y-05	259	10.0	0.8	8.0	8.0	8.6	8.9	10.0	11.0	11.2	12.7
	4.0	Y-06	399	10.1	0.8	7.6	7.9	8.9	9.2	10.1	11.0	11.2	13.4
	Buffered[3]	Y-07	473	10.6	1.0	9.0	6.8	9.0	9.4	10.6	11.8	12.2	12.9
Division St. (Chicago)	6.0	Y-08	306	10.1	1.1	10.5	7.0	8.6	8.9	9.9	11.6	11.9	13.4
	5.0	Y-09	187	10.1	1.1	10.8	7.7	8.4	8.8	9.9	11.6	12.0	13.3
	4.0	Y-10	337	10.5	1.0	9.3	7.7	9.2	9.3	10.4	11.9	12.2	13.1
	Buffered[4]	Y-11	109	10.9	1.2	10.7	4.8	9.3	9.5	10.9	12.5	12.6	13.3
Sites Without On-Street Parking													
Prospect St.—NB (Cambridge)	5	N-1	243	2.6	0.8	29.0	0.2	1.6	1.9	2.5	3.7	4.2	5.3
	4	N-2	305	2.4	0.5	21.9	1.2	1.7	1.8	2.3	3.1	3.5	4.5
	No BL	N-3	215	2.3	0.8	33.3	0.3	1.3	1.6	2.2	3.4	4.0	4.8
Prospect St.—SB (Cambridge)	5	N-4	281	2.3	0.7	29.0	1.0	1.3	1.6	2.2	3.2	3.4	5.3
	4	N-5	301	2.2	0.6	27.5	0.0	1.4	1.5	2.1	3.0	3.3	4.1
	No BL	N-6	279	2.1	0.7	33.1	0.7	1.3	1.4	2.0	3.0	3.3	5.4

[1] 4-ft bicycle lane; 1-ft buffer area.
[2] 3.5-ft bicycle lane; 1.5-ft buffer area.
[3] 5-ft bicycle lane; 2-ft buffer area.
[4] 2-ft buffer area; 4-ft bicycle lane; 2-ft buffer area.
Note: NB = northbound, SB = southbound, BL = bike lane.

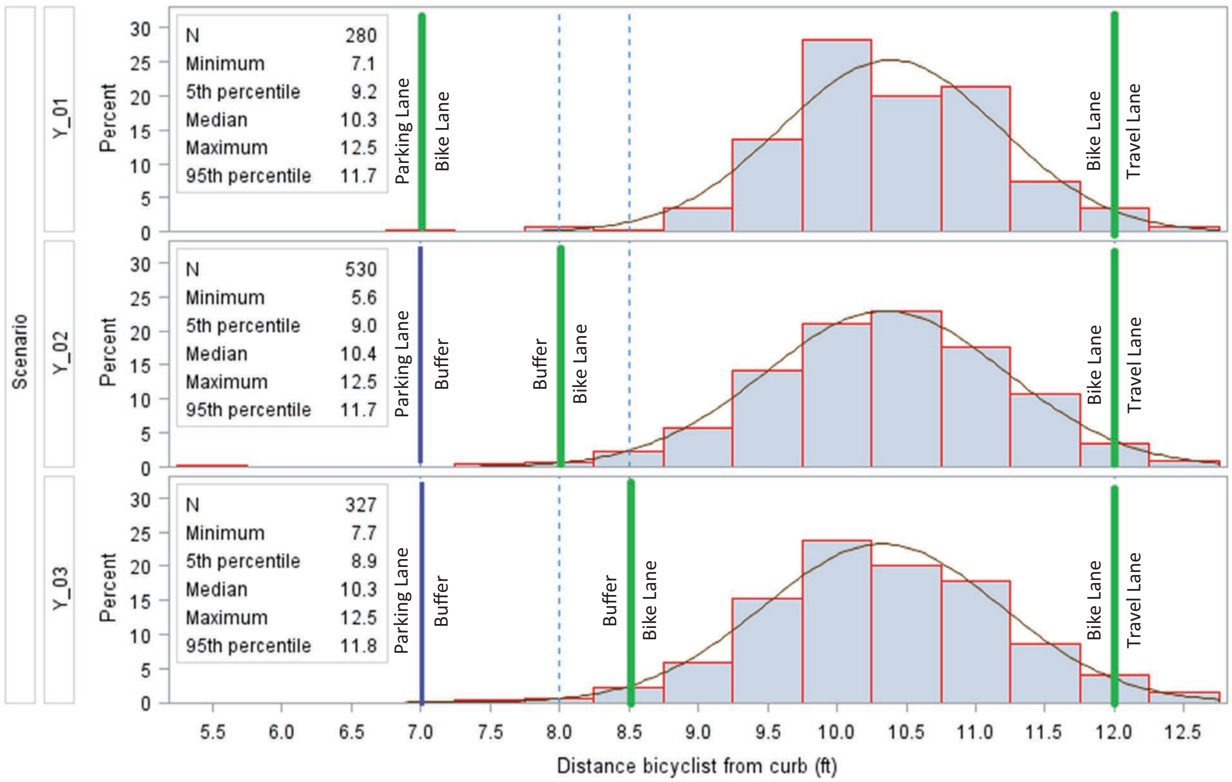


Figure 20. Distribution of distance of cyclists from curb on Massachusetts Avenue.

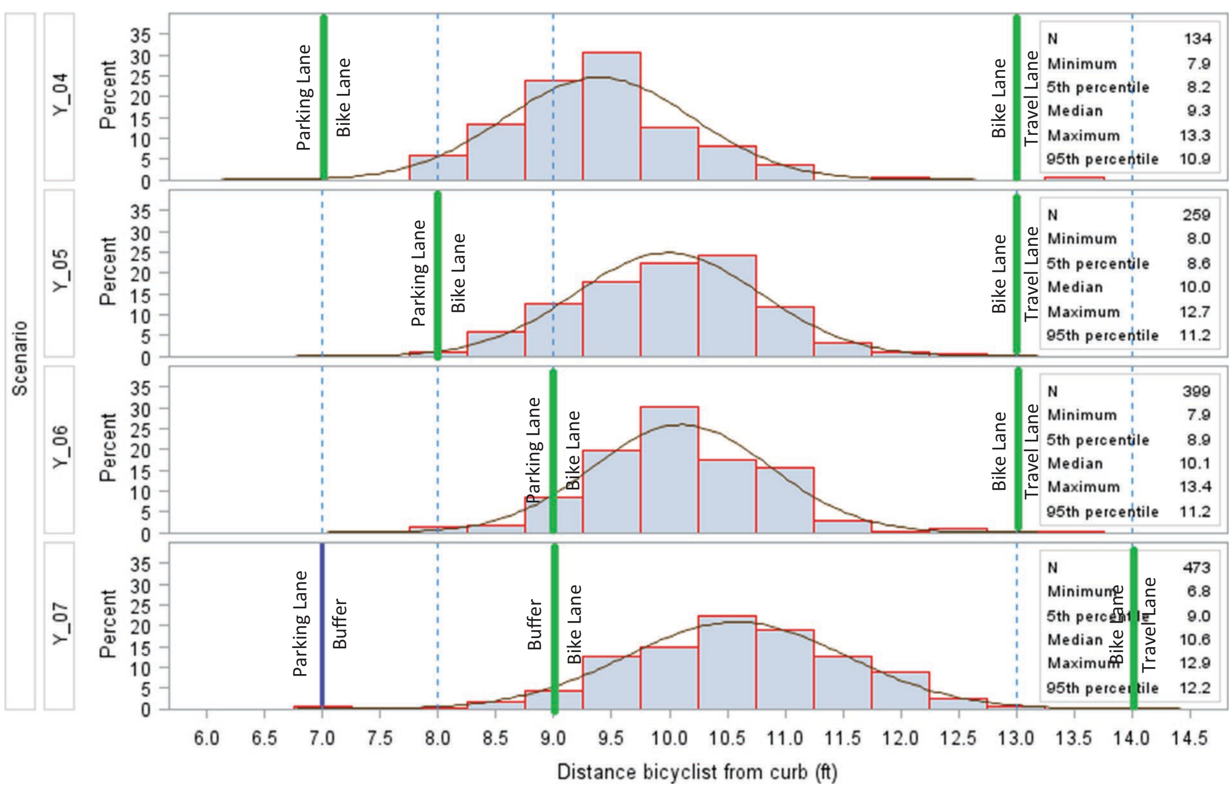


Figure 21. Distribution of distance of cyclists from curb on Clark Street.

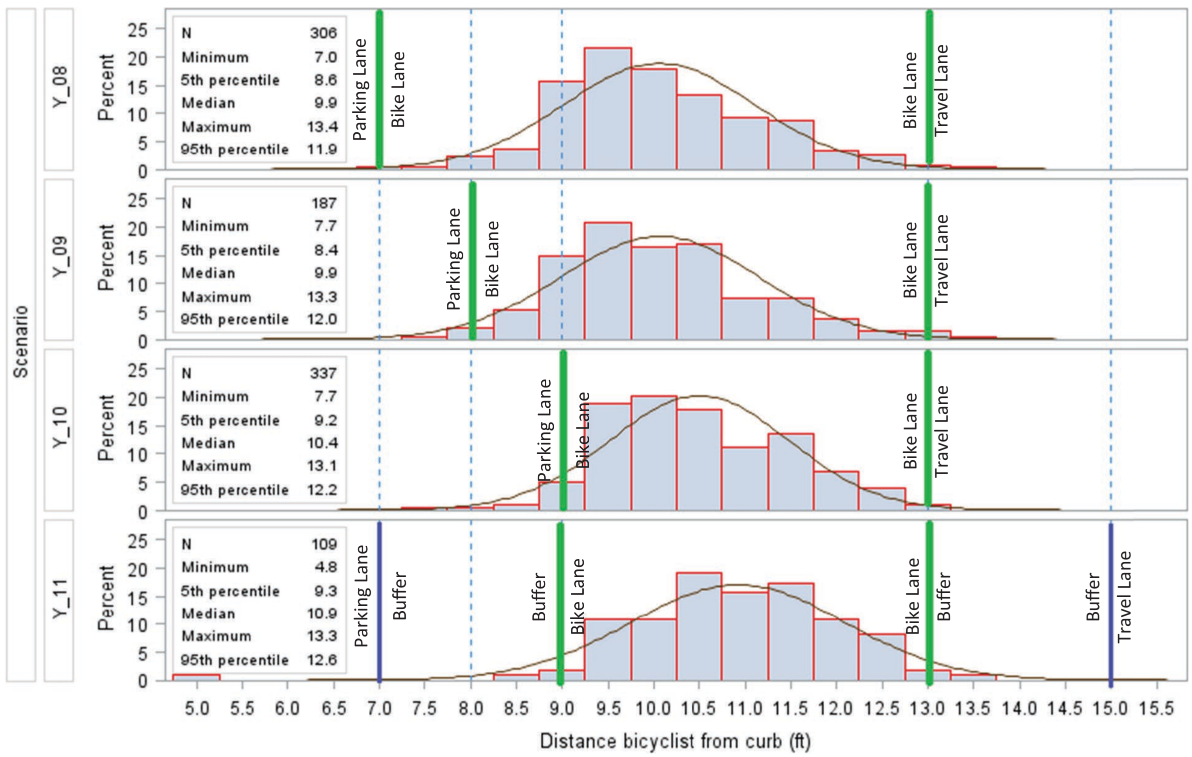


Figure 22. Distribution of distance of cyclists from curb on Division Street.

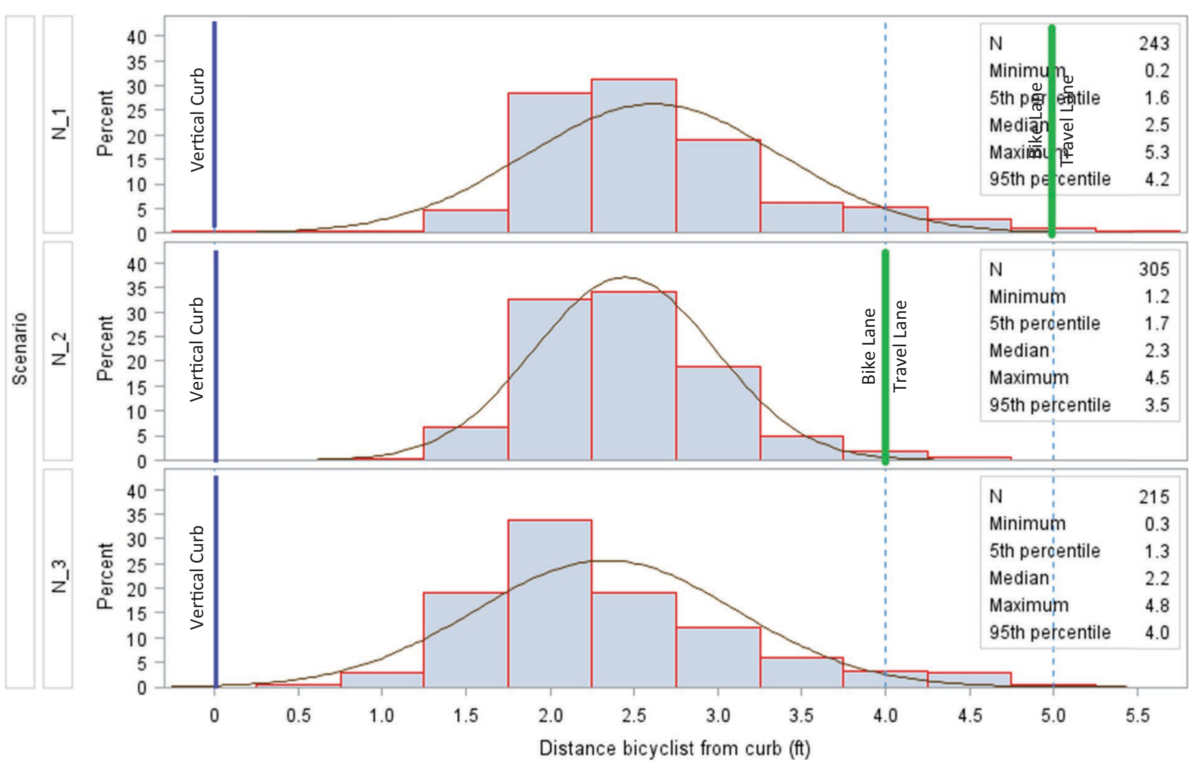


Figure 23. Distribution of distance of cyclists from curb on Prospect Street (northbound).

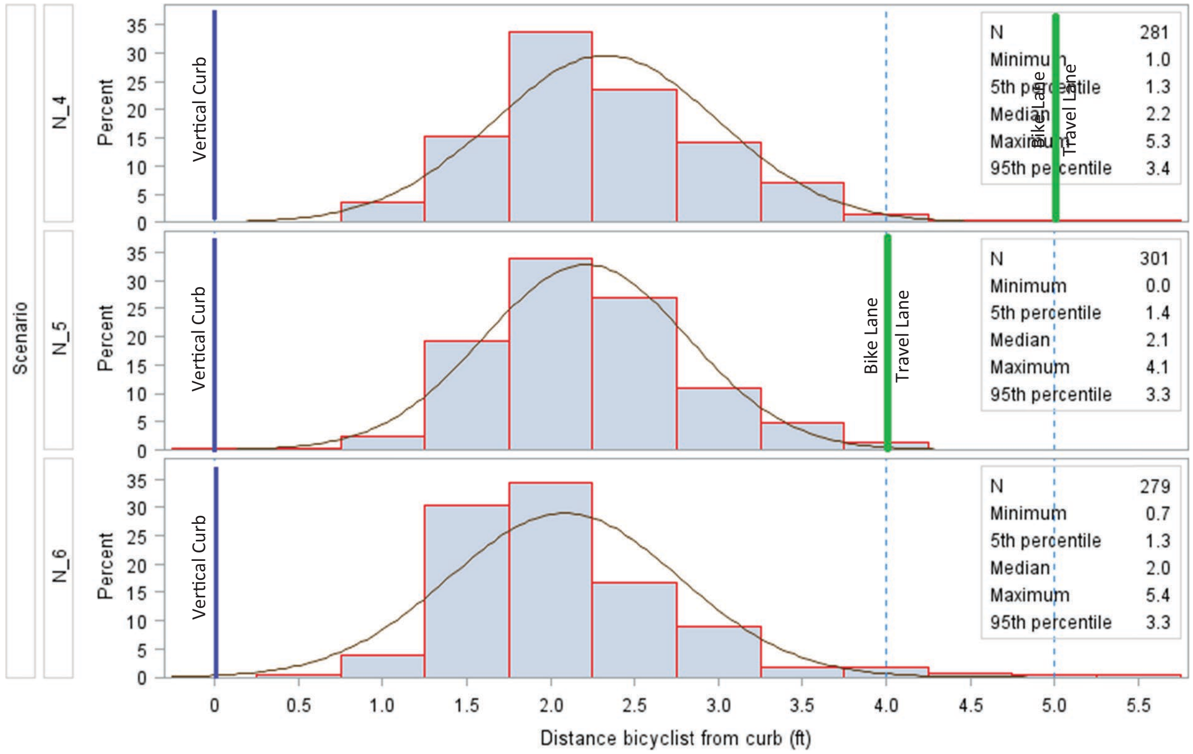


Figure 24. Distribution of distance of cyclists from curb on Prospect Street (southbound).

Table 9. Spread of cyclist lateral positions.

Street (City)	Bike Lane Width (ft)	Scenario	Spread (95th-5th Percentile Positions) (ft)
Massachusetts Ave. (Cambridge)	5.0	Y-01	2.5
	4.0[1]	Y-02	2.7
	3.5[2]	Y-03	2.9
Clark St. (Chicago)	6.0	Y-04	2.7
	5.0	Y-05	2.6
	4.0	Y-06	2.3
	Buffered[3]	Y-07	3.2
Division St. (Chicago)	6.0	Y-08	3.3
	5.0	Y-09	3.6
	4.0	Y-10	3.0
	Buffered[4]	Y-11	3.3
Prospect St.—NB (Cambridge)	5	N-1	2.6
	4	N-2	1.8
	No BL	N-3	2.7
Prospect St.—SB (Cambridge)	5	N-4	2.1
	4	N-5	1.9
	No BL	N-6	2.0
Overall average			**2.7**

Parking Lane	Bike Lane Width (ft)	Average Spread (ft)
Yes	6.0	3.0
	5.0	3.0
	3.5–4.0	2.8
No	5.0	2.4
	4.0	1.9
	No BL	2.4

Bike Lane Width (ft)	Average Spread (ft)
6.0	3.0
5.0	2.8
3.5–4.0	2.6
No BL	2.4

1 4-ft bicycle lane; 1-ft buffer area.
2 3.5-ft bicycle lane; 1.5-ft buffer area.
3 5-ft bicycle lane; 2-ft buffer area.
4 2-ft buffer area; 4-ft bicycle lane; 2-ft buffer area.
Note: NB = northbound, SB = southbound, BL = bike lane.

Table 10. Descriptive statistics for distance of passing vehicles from curb.

Street (City)	Bike Lane Width (ft)	Scenario	Number of Vehicles Measured	Distance of Passing Vehicle from Curb (ft)					
				Mean	Standard Deviation	Relative Standard Deviation (%)	Percentiles		
							5th	10th	Median
Sites with On-Street Parking									
Massachusetts Ave. (Cambridge)	5.0	Y-01	162	15.2	1.0	6.6	13.5	14.1	15.2
	4.0[1]	Y-02	306	15.5	1.3	8.1	13.5	14.0	15.4
	3.5[2]	Y-03	204	15.3	1.0	6.7	13.5	14.2	15.3
Clark St. (Chicago)	6.0	Y-04	111	14.9	0.9	5.7	13.4	13.6	15.1
	5.0	Y-05	200	15.3	1.2	7.9	13.3	13.7	15.4
	4.0	Y-06	300	15.2	1.0	6.5	13.5	13.9	15.3
	Buffered[3]	Y-07	284	15.4	1.0	6.3	13.7	14.1	15.6
Division St. (Chicago)	6.0	Y-08	25	15.5	0.9	6.1	13.6	14.0	15.5
	5.0	Y-09	148	16.0	1.0	6.4	14.2	14.8	16.0
	4.0	Y-10	118	15.9	0.8	5.1	14.3	14.9	16.0
	Buffered[4]	Y-11	47	17.1	0.9	5.1	15.9	16.0	17.2
Sites Without On-Street Parking									
Prospect St.—NB (Cambridge)	5	N-1	207	7.8	1.1	14.6	5.9	6.4	7.9
	4	N-2	241	7.7	1.0	12.6	6.0	6.6	7.9
	No BL	N-3	182	7.4	1.7	23.0	4.6	5.2	7.8
Prospect St.—SB (Cambridge)	5	N-4	185	8.1	1.1	13.8	6.3	6.8	8.2
	4	N-5	226	8.1	1.3	16.3	5.9	6.5	8.3
	No BL	N-6	217	7.8	1.6	20.5	4.8	5.4	7.9

1 4-ft bicycle lane; 1-ft buffer area.
2 3.5-ft bicycle lane; 1.5-ft buffer area.
3 5-ft bicycle lane; 2-ft buffer area.
4 2-ft buffer area; 4-ft bicycle lane; 2-ft buffer area.
Note: NB = northbound, SB = southbound, BL = bike lane.

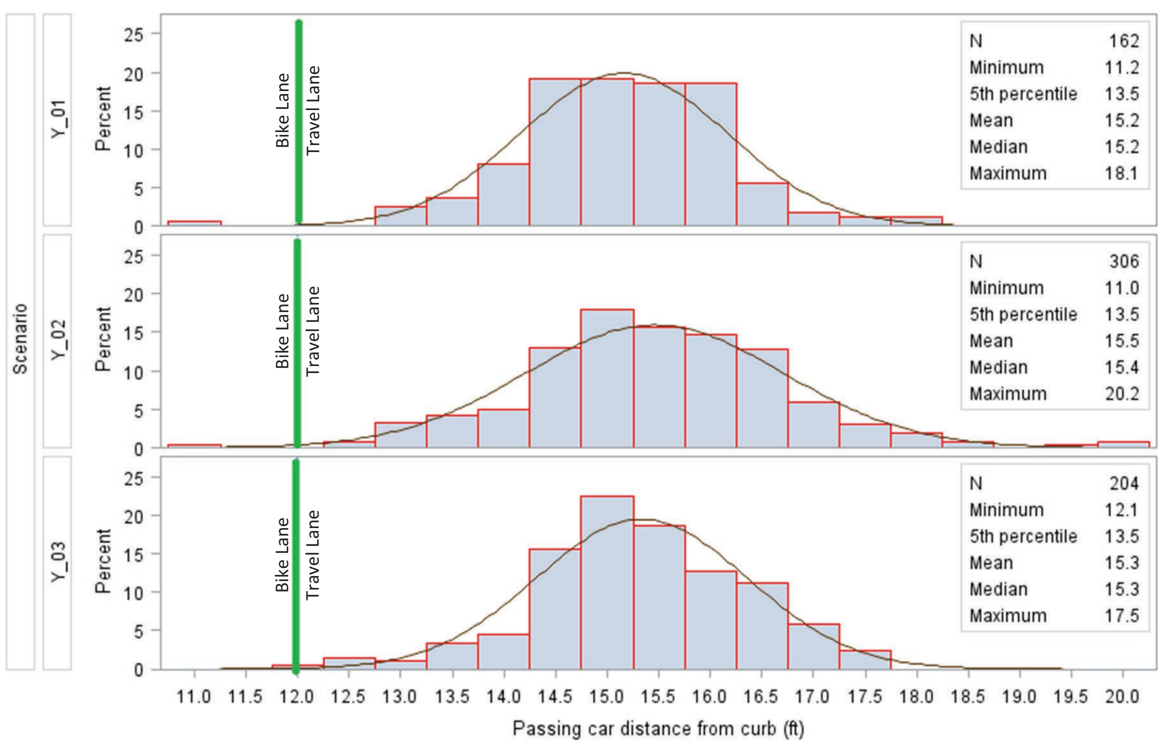


Figure 25. Distribution of passing vehicle distance from curb on Massachusetts Avenue.

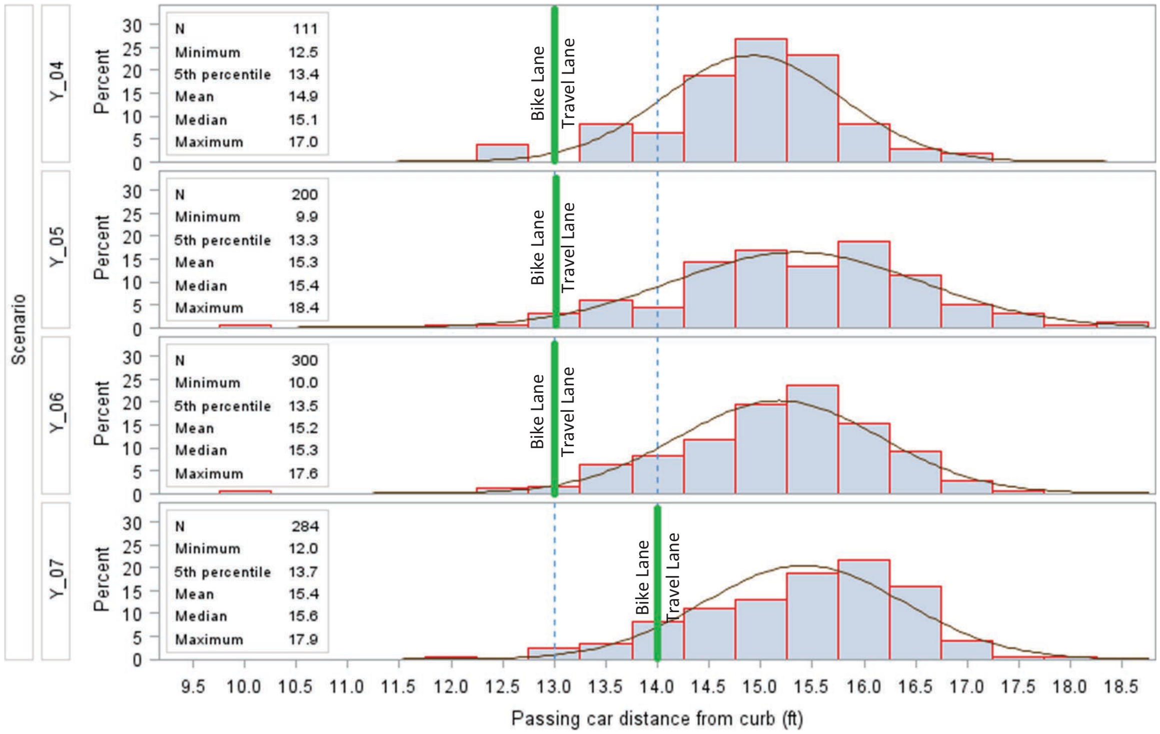


Figure 26. Distribution of passing vehicle distance from curb on Clark Street.

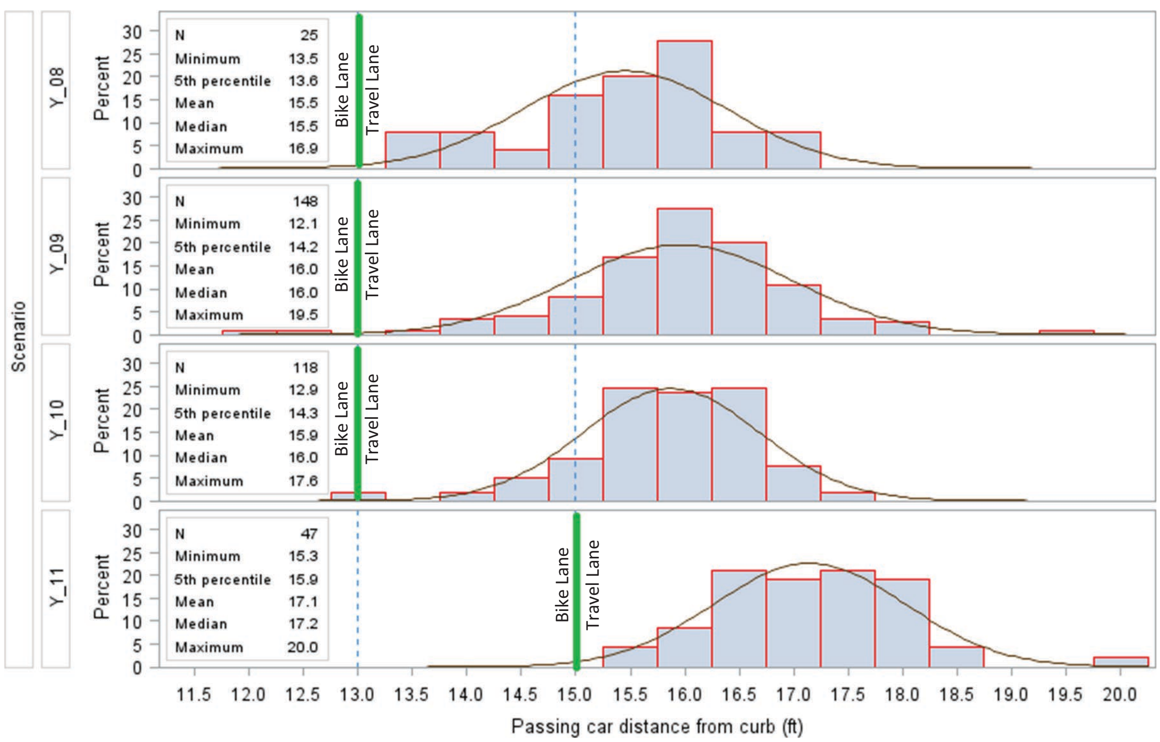


Figure 27. Distribution of passing vehicle distance from curb on Division Street.

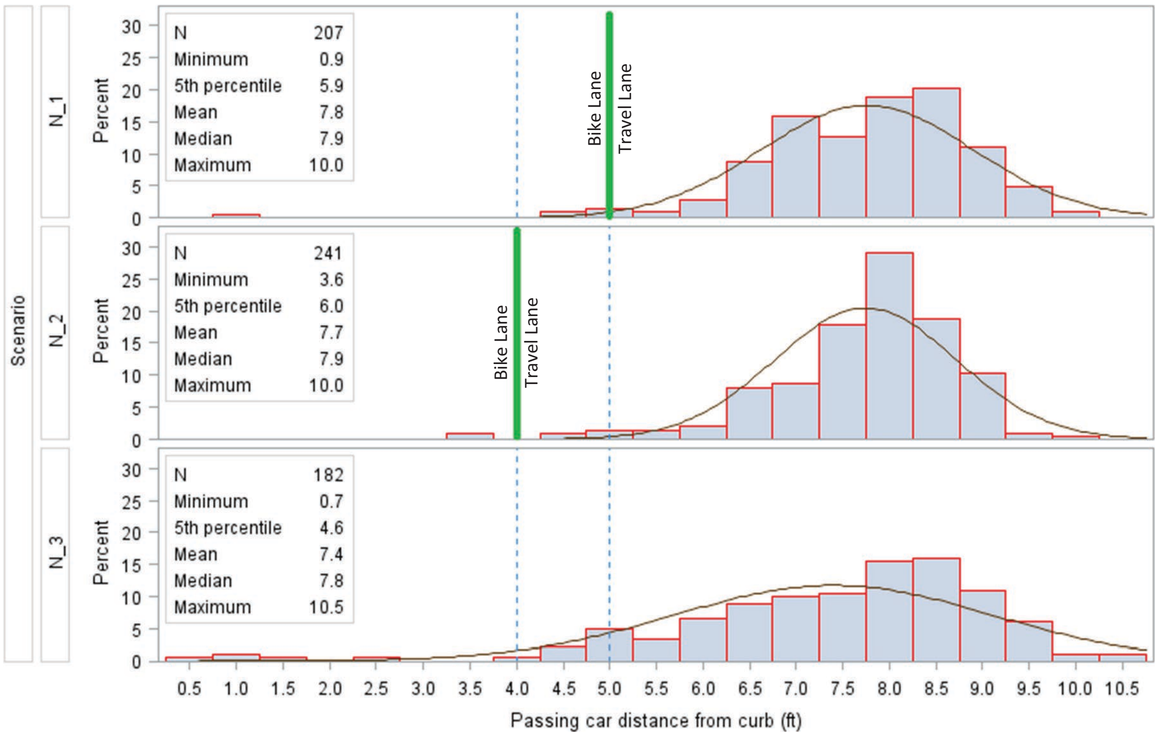


Figure 28. Distribution of passing vehicle distance from curb on Prospect Street (northbound).

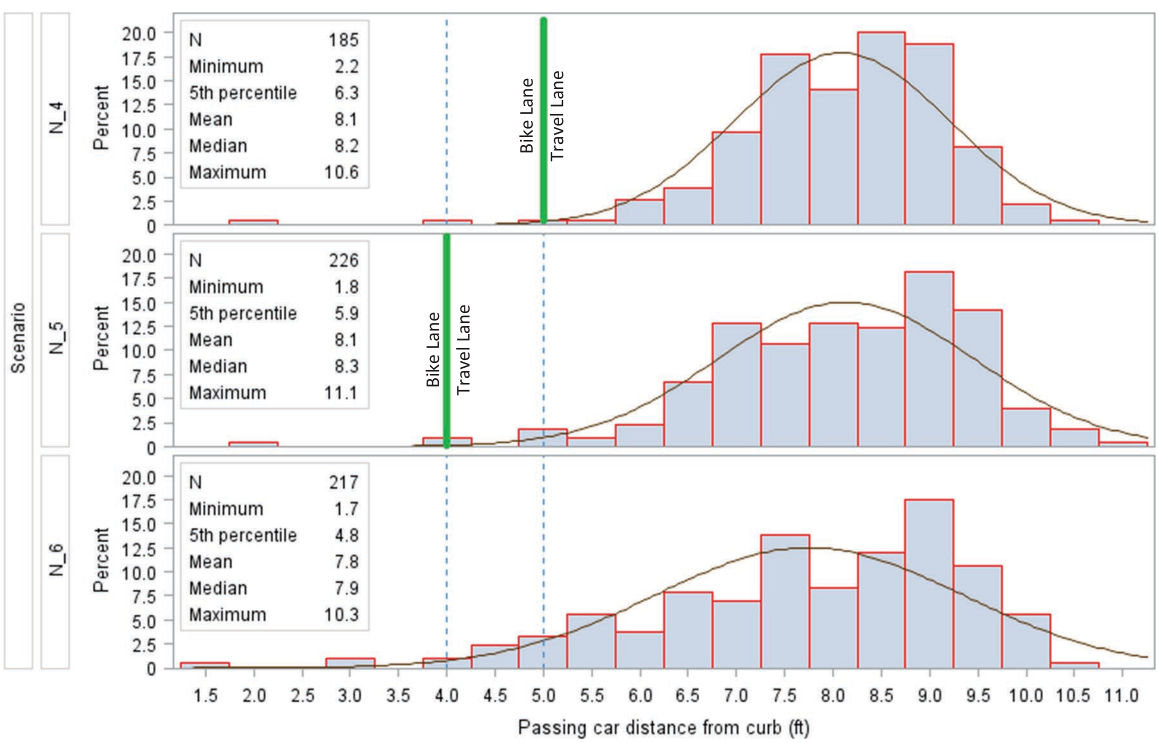


Figure 29. Distribution of passing vehicle distance from curb on Prospect Street (southbound).

A couple of points are worth noting with regard to the position of passing vehicles within the travel lane and relative to the bicycle lane:

1. At sites with travel lanes ranging in width from 10 to 14 ft that were adjacent to bicycle lanes, very few passing vehicles encroached into the bicycle lane, even from the narrowest travel lane of 10 ft. The scenario in which the highest percentage of passing vehicles (approximately 5% to 10%) encroached into the bicycle lane involved a 10-ft travel lane.
2. For scenarios with the narrowest travel lane of 10 ft, half of the passing vehicles on Massachusetts Avenue were positioned 3.3 ft or more from the bicycle lane, half on Clark Street were positioned 1.4 ft or more from the bicycle lane, and half on Division Street were positioned 2.2 ft or more from the bicycle lane. The type of vehicle was not recorded when measuring vehicle position of passing vehicles; however, assuming an overall width of 7 ft for a passenger car based on design vehicle dimensions in the *Green Book*, the data suggest that about half of the vehicles encroached into the adjacent travel lane (in the same direction of travel) on Massachusetts Avenue. Fewer vehicle encroachments into the adjacent travel lane (in the opposite direction of travel) would have occurred on Clark and Division Streets. Possible reasons for the large difference in position of passing vehicles on Massachusetts Avenue as compared to Clark and Division Streets may be that (1) Massachusetts Avenue has two travel lanes in the same direction of travel while the others do not, so consequences may not be as severe when drivers encroach into an adjacent lane of traffic traveling in the same direction; and (2) the percentage of trucks (and buses) on Clark and Division Streets is higher than that on Massachusetts Avenue, so drivers of wider vehicles might position their vehicles closer to the bicycle lane so as not to encroach into the travel lane in the opposite direction of travel.

Motor Vehicle Speed Data. Traffic classifiers were used to collect motor vehicle speeds in the travel lanes at each of the data collection sites. Over a period of 1 to 3 days, speed data were collected in the respective direction of travel at a given study site. Table 11 shows the 85th-percentile speeds measured at each site. Due to the lack of variability in speeds, this variable was not included in subsequent data analyses.

3.4.2 Analysis Approach

From all the field measurements pertaining to the position of parked and passing vehicles and cyclists relative to each other or the curb for the various scenarios, an appropriate single measurement was derived that could be used for analysis. The measurement developed was called "central positioning." This measurement was derived to reflect the relative position of the bike on the roadway, while accounting for both the presence and position of lane line markings on the roadway and the presence and behavior of parked and passing vehicles. This central positioning measure serves as the dependent variable in the statistical analysis discussed in the next section and was defined in a two-step process as follows.

Define an Effective Bike Lane. Figure 30 illustrates how an effective bike lane in which the cyclist is positioned was defined. The top portion of Figure 30 is approximately to scale based on average widths of parking, bicycle, and travel lanes and the distribution of left tire displacement of parked cars observed in this study. Note that this effective bike lane is not meant to be a real bike lane nor does it imply a safe zone for the cyclist; it is simply a portion of the roadway defined so as to be able to perform the analysis. For streets with on-street parking, an effective bike lane is defined based strictly on the behavior of parked vehicles and passing vehicles. For streets where on-street parking is prohibited, an effective bike lane is defined based on the behavior of passing vehicles and the position of the curb. The following measurements and dimensions for each scenario were needed:

- 85th, 90th, or 95th percentile of the total parked vehicle displacement distribution (from Table 7).
- Assumed passenger car open door width. (A 45-in. open car door width was selected to represent a typical open door width of a two-door passenger vehicle based on previous studies and field observations.)

Table 11. Summary of motor vehicle speeds at study sites.

Street	Number of Speed Measurements	85th-Percentile Speed (mph)
Massachusetts Ave.	30,773	30
Clark St.	33,625	33
Division St.	26,548	33
Prospect St. – northbound	8,605	28
Prospect St. – southbound	6,738	29

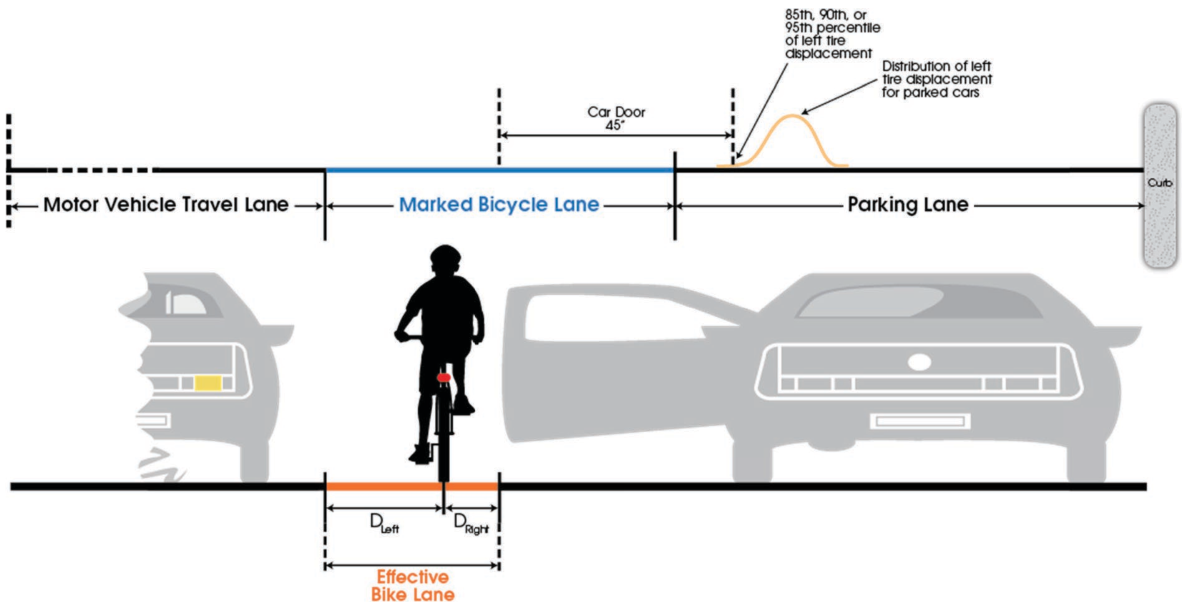


Figure 30. Illustrating the effective bike lane and central positioning.

- Position of the left lane line of the bike lane (i.e., the longitudinal lane line that separates the travel lane and the bike lane).
- 5th percentile of the distribution of passing car distance from curb (from Table 10).

The left and right edges of the effective bike lane were then defined using the rules shown in Table 12, depending on whether the site had on-street parking or a marked bike lane.

Three options were selected to define the right edge of the effective bike lane for sites with on-street parking and marked bike lanes to cover a range of cyclist safety, from conservative (using the 95th-percentile parked car displacement plus a door width) to less conservative (using the 85th-percentile parked car displacement plus a door width). All three options were used and their results compared in the analysis.

A 45-in. open car door width was selected for use in defining the right edge of the effective bike lane. This open door width is based on data for two-door passenger cars for model years 1988 to 1990 reported by Pein (2003). The research team collected similar data on open door widths for several two-door passenger cars for model year 2013 and found that passenger car door dimensions have not changed significantly in the past two decades. Thus, 45 in. was a reasonable choice for representing the open door width for a two-door passenger car. Approximately 15% to 25% of passenger vehicles (including passenger cars, pickups, and sport utility vehicles) are two-door vehicles, while the majority of passenger vehicles are four-door vehicles (Kahane, 2003). The average open door width for four-door vehicles is approximately 38 in. as reported by Pein (2003) and verified by the research team for 2013 model year passenger vehicles. Therefore, a 45-in. open car door

Table 12. Rules used to define an effective bike lane.

Site Type	Scenario	Left Edge of Effective Bike Lane Is The:	Right Edge of Effective Bike Lane Is The:
Without on-street parking Without marked bike lane	N-3 and N-6	5th percentile of the distribution of passing car distance from curb	Curb
Without on-street parking With marked bike lane	N-1, N-2, N-4, N-5	Left lane line of the bike lane	Curb
With on-street parking With marked bike lane	Y-01 through Y-11	Left lane line of the bike lane	Distance from curb of 85th, 90th, or 95th percentile of the total parked vehicle displacement distribution plus 45 in. to account for a fully opened car door

width for use in the analysis is a conservative (i.e., stringent) choice for analysis purposes.

The left edge of the effective bike lane was defined based on the left lane line of the bike lane (for sites with a bike lane) for the following reasons:

- In the presence of a bike lane, it was assumed (although not fully supported by the data) that bicyclists would not ride to the left of the bike lane, in the adjacent travel lane; nor would cyclists position themselves within the buffer space if a buffer is provided between the bike lane and travel lane.
- As illustrated in Figures 25 through 29, rarely did passing vehicles cross over into the bike lane from the adjacent travel lane. In only one scenario (Clark St—buffered bike lane) was the position of the 5th-percentile passing vehicle within the bike lane, and for this scenario, the position of the 5th-percentile passing vehicle was only 0.3 ft within the bike lane. If the position of the 5th-percentile passing vehicles was consistently (or even occasionally) within the bike lane, then it would have been reasonable to define the left edge of the effective bike lane based on the position of passing vehicles; however, this was not the case.

Define the Central Positioning of the Cyclist. The bottom portion of Figure 30 illustrates how the "central positioning" measurement was defined relative to the effective bike lane. For each bike positioned inside or outside the effective bike lane, two distances were defined:

D_{Left} = distance between the left edge of effective bike lane and the cyclist's position, and

D_{Right} = distance between the cyclist's position and the right edge of effective bike lane.

From these two measurements, the final dependent variable was simply calculated as:

$$\text{Central positioning} = \min(D_{Left}, D_{Right}).$$

D_{Left} and D_{Right} can be either (1) both positive (i.e., the cyclist is within the effective bike lane) or (2) one positive and the other negative (i.e., the cyclist is either to the left or right of the effective bike lane, but never (3) both negative. The data will show that a very small percentage of cyclists (about 1%) ride to the left of the effective bike lane (i.e., in the travel lane), while a large percentage of cyclists (up to 45%) ride to the right of the effective bike lane (i.e., in the door zone of parked vehicles) while still riding in the marked bike lane.

Statistical Methodology. A number of complementary approaches were used to analyze the data to investigate whether selected roadway characteristics affect the placement of bicyclists and vehicles within the cross section of the roadway.

1. One approach consists of simply calculating the percentage of cyclists that ride within the effective bike lane and comparing these percentages across the various scenarios. This was done using all three effective bike lane options based on either the 85th, 90th, or 95th percentile of the parked car displacement. While the percentages themselves are not that relevant to the study conclusions, the objective is to assess whether these percentages are affected by the roadway layout—that is, the combination of travel lane width, parking lane width, buffer space, and bike lane width. These comparisons are made without regard to other roadway characteristics such as traffic volume and percent trucks.
2. The effect of parking lane width on the position of parked vehicles relative to the curb is investigated by means of a one-way analysis of variance (ANOVA). The dependent variable considered in the ANOVA is the total parked vehicle displacement, and the single factor is parking lane width (used as a categorical variable at seven levels, as shown in Figure 19). Each scenario (i.e., one of each of the 11 scenarios) is considered a blocking factor in the analysis, and each measured parked vehicle provides replication within each scenario.
3. Another complementary analysis consists of a more rigorous statistical approach. An ANOVA is used to estimate the effect of roadway characteristics, such as traffic volume, percent trucks, presence or absence of a buffer, parking lane width, and travel lane width, on the calculated central positioning (dependent variable). Each scenario is considered a blocking factor in the analysis, and each measured cyclist provides replication within each scenario. Following the ANOVA and depending on whether a factor is statistically significant, a number of relevant comparisons are made to estimate the effect of a particular roadway characteristic on central positioning. In all analyses, a 10% significance level is chosen. Bike lane width, although at first a logical factor to consider in the model, is not included in this model. For any given city block, travel lane width, parking lane width, and bike lane width are highly correlated since their sum is determined by the width of the roadway; therefore, two out of three widths are sufficient to define the roadway width. Additionally, the focus is on establishing the width of the bike lane given a certain situation in the field, and as such, it is preferable to not include bike lane width as a predictor variable in the model.

3.4.3 Analysis Results

The analysis results are presented in the order discussed previously.

Percentage of Cyclists Riding Within the Effective Bike Lane. Using the three selected percentiles (i.e., 85th, 90th, and 95th) from the distribution of total vehicle displacement and assuming a 45-in. open car door width, the percentage of cyclists riding within each of the effective bike lanes was calculated. Naturally, the higher the percentile from the distribution, the fewer cyclists will ride within the effective bike lane. Table 13 displays the following statistics for each of the 11 scenarios with on-street parking and the six scenarios without on-street parking:

- Roadway conditions (columns 2 through 7)
- Location from curb to right edge of effective bike lane based on 85th, 90th, or 95th percentile of total parked vehicle position plus an assumed 45-in. open car door width (columns 8 through 10)
- Location from curb to left edge of effective bike lane (column 11)
- Width of effective bike lane based on 85th, 90th, or 95th percentile of total parked vehicle displacement (columns 12 through 14)
- Percentage of cyclists within the effective bike lane based on 85th, 90th, or 95th percentile of total parked vehicle displacement (columns 15 through 17)

To more thoroughly define the percentage of cyclists riding within the effective bike lane, the widths of the effective bike lanes (shown in columns 12 through 14 of Table 13 for three percentiles of total parked vehicle displacement) need to be considered in conjunction with the cyclist's operating space. Figure 31 illustrates the critical dimensions for an upright adult bicyclist (AASHTO, 2012). The physical width of the bicyclist is 2.5 ft and is based on the physical width (95th percentile) of the handlebars. The minimum operating width of 4 ft is greater than the physical width occupied by the bicyclist because of natural side-to-side movement that varies with speed, wind, and bicyclist proficiency. The preferred operating width of 5 ft allows for even more lateral clearance from nearby obstacles.

When comparing the least conservative measure of the effective bike lane width (i.e., based on the 85th percentile of total parked vehicle displacement) to the physical width of a bicyclist, two of the scenarios evaluated on streets with on-street parking (i.e., scenarios Y-04 and Y-07) had an effective bike lane width greater than 2.5 ft (i.e., the physical width of a bicyclist), while for the other scenarios evaluated on streets with on-street parking, the effective bike lane width was less than the physical width of a typical adult bicyclist. Conceptually this means that, for the majority of scenarios evaluated on streets with on-street parking, the effective bike lane is not wide enough to accommodate either the operating width (4 ft) or the physical width (2.5 ft) of a bicyclist. Also, the boundaries of the effective bike lane are not delineated on the roadway with pavement markings, so it is difficult for bicyclists to envision the effective bike lane and position themselves in the center of it. As is shown later, most bicyclists position themselves to the left or right of the center of the effective bike lane and, in some cases, outside of the limits of the effective bike lane. For the scenarios evaluated on streets where on-street parking is prohibited, the effective bike lane width was always greater than or equal to the minimum operating space (i.e., 4 ft) of a typical adult bicyclist.

Since the effective bike lane widths for the majority of scenarios evaluated on streets with on-street parking were found to be less than the physical dimensions of a bicyclist, the decision was made to calculate the percentage of cyclists riding within the effective bike lane based on the position of the front bicycle tire rather than accounting for the physical, minimum, or preferred operating space of a bicyclist. This approach is consistent with the overall guiding principle of this research, which was to provide guidance on how wide a bicycle lane should be in cases where the decision to include a bicycle lane has been made. It should also be recognized that this approach is part of an effort to develop design guidelines that provide a balanced design to accommodate all roadway users.

The primary findings based on the width of the effective bike lane and the percentage of cyclists positioned within the effective bike lane are as follows:

- For the majority of scenarios evaluated on streets with on-street parking, the effective bike lane widths were narrower than the physical width of a typical adult bicyclist, and for the scenarios evaluated on streets without on-street parking, the effective bike lane widths were always greater than or equal to the minimum operating space of a typical adult bicyclist.
- Across the scenarios with on-street parking, Massachusetts Avenue has the highest percentages of bicyclists that position themselves within the effective bike lane.
- On Clark and Division Streets, with the exception of the 4-ft bike lane scenario on Division Street, the percentage of bicyclists within the effective bike lane is considerably lower for scenarios without any type of buffer.
- In general, on streets with on-street parking, the highest percentages of bicyclists are within the effective bicycle lane when buffers are used.
- On Prospect Street (a street without on-street parking), there is very little difference among scenarios in terms of the percentage of bicyclists within the effective bike lane, and the percentage of bicyclists in the effective bike lane is very high (close to 100%).

Effect of Parking Lane Width on Position of Parked Vehicles. The one-way ANOVA showed that parking lane width

Table 13. Percentage of cyclists riding within effective bike lane by scenario.

Scenario	Street (City)	Width (ft) Of: Parking Lane	Width (ft) Of: Buffer[1]	Width (ft) Of: Bike Lane	Width (ft) Of: Buffer[2]	Width (ft) Of: Travel Lane	Location (ft) from Curb of Right Edge of Effective Bike Lane Using: 85th Percentile[a]	Location (ft) from Curb of Right Edge of Effective Bike Lane Using: 90th Percentile	Location (ft) from Curb of Right Edge of Effective Bike Lane Using: 95th Percentile	Location (ft) From Curb of Left Edge of Effective Bike Lane	Effective Bike Lane Width (ft) Using: 85th Percentile	Effective Bike Lane Width (ft) Using: 90th Percentile	Effective Bike Lane Width (ft) Using: 95th Percentile	Percent Cyclists Within Effective Bike Lane Using: 85th Percentile	Percent Cyclists Within Effective Bike Lane Using: 90th Percentile	Percent Cyclists Within Effective Bike Lane Using: 95th Percentile
Sites with On-Street Parking—A 45-in. Car Door Was Assumed																
Y-01	Massachusetts Ave. (Cambridge)	7	0.0	5.0	0	10	10.3	10.5	10.7	12.0	1.7	1.5	1.3	47.5	37.9	34.3
Y-02			1.0	4.0			10.0	10.2	10.6	12.0	2.0	1.8	1.4	63.6	58.1	38.1
Y-03			1.5	3.5			10.5	10.7	10.8	12.0	1.5	1.3	1.2	36.1	33.0	25.1
Y-04	Clark St. (Chicago)	7	0.0	6.0	0	11	10.4	10.5	10.7	13.0	2.6	2.5	2.3	10.4	7.5	4.5
Y-05		8		5.0			10.8	11.0	11.2	13.0	2.2	2.0	1.8	13.9	8.9	5.8
Y-06		9		4.0			11.0	11.2	11.6	13.0	2.0	1.8	1.4	11.5	5.8	1.8
Y-07		7	2.0	5.0		10	10.8	10.8	11.0	14.0	3.2	3.2	3.0	41.6	40.0	35.7
Y-08	Division St. (Chicago)	7	0.0	6.0	0	12	10.9	11.0	11.5	13.0	2.1	2.0	1.5	21.6	18.0	10.8
Y-09		8		5.0			11.4	11.7	12.0	13.0	1.6	1.3	1.0	12.3	7.0	3.7
Y-10		9		4.0			11.0	11.2	11.4	13.0	2.0	1.8	1.6	30.0	25.8	21.4
Y-11		7	2.0	4.0	2	10	11.1	11.2	11.6	13.0	1.9	1.8	1.4	43.1	39.4	29.4
Sites Without On-Street Parking																
N-1	Prospect St.—NB (Cambridge)	0	0.0	5.0	0	11	0.0	0.0	0.0	5.0	5.0	5.0	5.0	98.8	98.8	98.8
N-2				4.0		12	0.0	0.0	0.0	4.0	4.0	4.0	4.0	98.7	98.7	98.7
N-3				0.0		16	0.0	0.0	0.0	4.6	4.6	4.6	4.6	99.1	99.1	99.1
N-4	Prospect St.—SB (Cambridge)	0	0.0	5.0	0	13	0.0	0.0	0.0	5.0	5.0	5.0	5.0	99.3	99.3	99.3
N-5				4.0		14	0.0	0.0	0.0	4.0	4.0	4.0	4.0	99.0	99.0	99.0
N-6				0.0		18	0.0	0.0	0.0	4.8	4.8	4.8	4.8	99.3	99.3	99.3

[a] All percentiles pertain to the distribution of total parked vehicle displacement from curb.
[1] Buffer between parking lane and bike lane.
[2] Buffer between bike lane and travel lane.
Note: NB = northbound, SB = southbound.

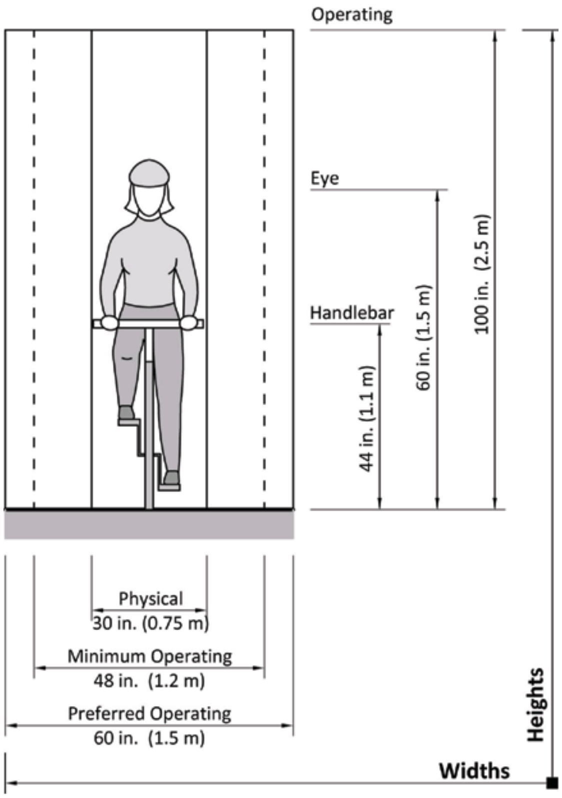


Figure 31. Bicyclist operating space (AASHTO, 2012).

had no statistically significant effect (*p*-value of 0.50) on the position of parked vehicles. (Descriptive statistics were shown earlier in Table 7 and Figure 19.) The mean parked vehicle displacement from the curb was estimated for each category of parking lane plus buffer space width using the model from the ANOVA. The mean, standard error of the mean, and lower and upper 95% confidence limits of the mean are shown in Table 14.

Differences between selected pairs in mean displacement of parked vehicles are shown in Table 15. Three parking lane widths were compared to each other: 7-ft, 8-ft, and 9-ft widths. The estimated mean difference in vehicle displacement is shown in column 2 and its 95% confidence interval in the last two columns. The *p*-values associated with the *t*-values and degrees of freedom indicate that none of the pairwise differences in parked vehicle displacement is statistically significantly different from zero. (All *p*-values exceed 0.3.)

Table 14. Estimated total parked vehicle displacement as a function of parking lane plus buffer width.

Width of Parking Lane + Buffer (ft)	Estimated Mean Distance from Curb (ft)	Standard Error of Estimate (ft)	95% Confidence Limits of Estimate (ft)	
			Lower	Upper
7	6.33	0.22	5.72	6.94
7 + 1	5.79	0.38	4.73	6.85
7 + 1.5	6.23	0.38	5.17	7.30
7 + 2 (Clark St.)	6.52	0.38	5.46	7.58
7 + 2 (Division St.)	6.83	0.38	5.77	7.89
8	6.70	0.27	5.94	7.45
9	6.73	0.27	5.97	7.48

Although vehicles seem to park farther away from the curb as parking lane width increases, this increase in displacement from the curb, which ranges from 0.03 to 0.4 ft, is not statistically significant at the 5% or even 30% significance level. It should also be noted that, as shown in Table 7, a higher percentage of vehicles parked outside the designated 7-ft parking lane, while only a few vehicles parked outside the designated 8-ft parking lane. In the presence of a 9-ft parking lane, all vehicles parked within the boundaries of the designated parking lane.

The primary findings related to parked vehicle displacement and parking lane widths are as follows:

- For parking lane widths of 7, 8, and 9 ft, the width of the parking lane does not significantly affect the position of parked vehicles relative to the curb; however, the trend is in the direction one would expect. The narrower the parking lane width, the closer the parked vehicles are to the curb.
- For parking lane widths of 7, 8, and 9 ft, a higher percentage of vehicles parked outside the boundaries of the designated 7-ft parking lane, only a few vehicles parked outside

Table 15. Comparison of parked vehicle displacement between selected parking lane widths.

Parking Lane Comparison	Estimated Mean Difference in Vehicle Displacement (ft)[a]	Standard Error of Difference (ft)	Degrees of Freedom	*t*-Value	*p*-Value	95% Confidence Limits of Difference (ft)	
						Lower	Upper
7 ft to 8 ft	−0.36	0.35	4.03	–1.04	0.36	–1.33	0.60
7 ft to 9 ft	−0.40	0.35	4.00	–1.13	0.32	–1.37	0.57
8 ft to 9 ft	−0.03	0.38	3.98	–0.08	0.94	–1.09	1.03

[a] The difference is calculated as the first in the pair minus the second in the pair shown in the first column.

the boundaries of the designated 8-ft parking lane, and no vehicles parked outside the boundaries of the designated 9-ft parking lane.

Effect of Roadway Characteristics on the Calculated Central Positioning of Cyclists. Three sets of ANOVAs were run to estimate the effect of roadway characteristics on the calculated central positioning (dependent variable). Given the site characteristics and the study scenarios, the ranges in the primary roadway characteristics that could be analyzed were:

- Bike lane width: 3.5 to 6 ft,
- Parking lane width: 7 to 9 ft,
- Travel lane width: 10 to 18 ft,
- Presence/absence of buffer space,
- Traffic volume: 14,800 to 29,000 vpd, and
- Percent trucks: 2% to 20%.

Given the number of study sites, the ranges of traffic volume (ADT) and percent trucks were such that these two roadway characteristics were dichotomized as follows for analysis purposes:

- Low ADT: 15,000 to 17,000 vpd.
- High ADT: 29,000 vpd.
- Low percent trucks: <10%.
- High percent trucks: 16% to 20%.

Presence of a buffer was defined as "yes" if either one or two buffers were present. Travel lane and parking lane widths were used as continuous variables (i.e., covariates) in the models.

The first set of three ANOVAs (based on the 85th, 90th, and 95th percentile of the total parked vehicle displacement when defining the effective bike lane), in which central positioning was modeled as a function of ADT, percent trucks, presence of buffer, parking lane width, and travel lane width, showed that neither parking lane width nor travel lane width was statistically significant. (The *p*-values ranged from 0.65 to 0.71 for travel lane width and from 0.77 to 0.91 for parking lane width.) These two variables were excluded one at a time from the models.

The second set of three ANOVAs, in which central positioning was modeled as a function of ADT, percent trucks, and presence of buffer, showed that all three categorical factors were statistically significant. The Type 3 tests for fixed effects are shown in Table 16, separately for each percentile used in defining the effective bike lane. In all cases, the three factors are highly significant, as indicated by the *p*-values shown in the last column.

The least-squares mean central positioning was then estimated for each level of each factor and compared between the two levels of a given factor. To estimate the effect of an assumed worsening of the roadway conditions for the cyclists, the differences in central positioning were calculated as follows for the three roadway characteristics:

- Change in ADT from low to high.
- Change in percent trucks from low to high.
- Change from presence of buffer space to no buffer space.

The difference in central positioning can be interpreted as a cyclist displacement to one side or the other within the effective bike lane affected by the change in the factor considered. The results are shown in Table 17. The *p*-values in column 8 show the statistical significance of the difference between the two central positioning estimates. The last two columns provide a 95% confidence interval for the difference.

The interpretation of the results in Table 17 is illustrated using the first row in the table.

- At low ADT, the estimated central positioning of the cyclist is on average 0.65 ft; this indicates that the cyclists ride, on

Table 16. ANOVA results—Type 3 tests for fixed effects.

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	*F*-Value	*p*-Value
USING 85TH PERCENTILE OF PARKED VEHICLE DISPLACEMENT				
ADT	1	13	93.7	<.0001
Percent trucks	1	13	309.3	<.0001
Buffer	1	13.1	5.7	0.0328
USING 90TH PERCENTILE OF PARKED VEHICLE DISPLACEMENT				
ADT	1	13	95.2	<.0001
Percent trucks	1	13	297.2	<.0001
Buffer	1	13.1	8.2	0.0134
USING 95TH PERCENTILE OF PARKED VEHICLE DISPLACEMENT				
ADT	1	13	87.2	<.0001
Percent trucks	1	13	278.8	<.0001
Buffer	1	13.1	6.0	0.0288

Table 17. Estimated cyclist displacement in effective bike lane as a function of changes in ADT, percent trucks, and presence of buffer.

Factor: Change from _ to _	Estimated Mean Central Positioning (ft)		Estimated Mean Displacement of Cyclist[a] (ft)	Standard Error of Mean Displacement (ft)	Degrees of Freedom	*t*-Value	*p*-Value	95% Confidence Limits of Mean Displacement (ft)	
	1st in Pair	2nd in Pair						Lower	Upper
USING 85TH PERCENTILE OF PARKED VEHICLE DISPLACEMENT									
ADT: low to high	0.65	–1.47	2.12	0.22	13	9.68	<.0001	1.64	2.59
Truck %: low to high	0.89	–1.71	2.59	0.15	13	17.59	<.0001	2.28	2.91
Buffer: yes to no	–0.20	–0.62	0.42	0.18	13.1	2.39	0.03	0.04	0.81
USING 90TH PERCENTILE OF PARKED VEHICLE DISPLACEMENT									
ADT: low to high	0.62	–1.71	2.33	0.24	13	9.76	<.0001	1.82	2.85
Truck %: low to high	0.84	–1.94	2.78	0.16	13	17.24	<.0001	2.43	3.13
Buffer: yes to no	–0.27	–0.83	0.55	0.19	13.1	2.86	0.01	0.14	0.97
USING 95TH PERCENTILE OF PARKED VEHICLE DISPLACEMENT									
ADT: low to high	0.48	–2.05	2.53	0.27	13	9.34	<.0001	1.94	3.11
Truck %: low to high	0.74	–2.31	3.05	0.18	13	16.7	<.0001	2.65	3.44
Buffer: yes to no	–0.52	–1.05	0.54	0.22	13.1	2.46	0.03	0.07	1.01

[a] The mean displacement is calculated as the central positioning corresponding to the first in the pair minus the second in the pair.

average, within the effective bike lane (since the estimate is positive) at 0.65 ft from either its left or right edge.

- At high ADT, the estimated central positioning of the cyclist is on average −1.47 ft; this indicates that the cyclists ride, on average, outside the effective bike lane (since the estimate is negative), at 1.47 ft to the right of its right edge. [Remember that only about 1% of cyclists ride to the left of the effective bike lane (i.e., in the travel lane) while a large percentage of cyclists (up to 45%) ride to the right of the effective bike lane (i.e., mostly in the car door area.)]
- The effect of changing from low to high ADT is estimated by the difference between the two central positioning estimates, that is, 0.65 − (−1.47) = 2.12 ft. Therefore, one can conclude that the effect of the higher ADT displaces the cyclists by an average of 2.12 ft toward the curb. (This average ranges from 1.64 to 2.59 ft, the 95% confidence interval shown in the last two columns of in Table 17.)

The primary findings related to the effect of roadway characteristics on the calculated central positioning (dependent variable), based on the results shown in Table 17, are summarized in the following.

Of the five roadway characteristics analyzed—traffic volume, percent trucks, presence of buffer space, parking lane width, and travel lane width—the latter two did not significantly affect the central positioning of a bicyclist within the roadway cross section. However, traffic volume, percent trucks, and presence of buffer space significantly affected the central positioning of a bicyclist in the roadway cross section, as follows:

- Traffic volume
  - When the traffic volume was between 15,000 and 17,000 vpd, bicyclists rode inside the effective bike lane an average of 0.65 ft from the closest edge.
  - When the traffic volume was 29,000 vpd, bicyclists positioned themselves to the right of the effective bike lane by an average of 1.47 ft.
  - As traffic volume increased, bicyclists moved away from vehicles in the travel lane and positioned themselves closer to the parked vehicles or the curb. The mean displacement of a bicyclist due to increased traffic volume was estimated at 2.12 ft and ranged from 1.64 to 2.59 ft.
- Percent trucks
  - When the truck percentage was below 10%, bicyclists rode inside the effective bicycle lane an average of 0.89 ft from the closest edge.
  - When the truck percentage was between 16% and 20%, bicyclists positioned themselves to the right of the effective bike lane by an average of 1.71 ft.
  - As truck percentage increased, bicyclists moved away from vehicles in the travel lane and positioned themselves closer to parked vehicles or the curb. The mean displacement of a bicyclist due to increased percent truck volume was estimated at 2.59 ft and ranged from 2.28 to 2.91 ft.
- Presence of a buffer
  - In the presence of a buffer, bicyclists positioned themselves to the right of the effective bike lane (i.e., within the door zone) by an average of 0.2 ft, regardless of the width of the bicycle lane.
  - The same held true in the absence of a buffer; however, bicyclists positioned themselves even closer to the

parked vehicles within the door zone by an average of 0.62 ft, regardless of the width of the bicycle lane.
  – The presence of a buffer effectively moved bicyclists away from parked vehicles by an average of 0.42 ft, ranging from 0.04 to 0.81 ft.

These results all pertain to the top portion of Table 17 (i.e., when the effective bike lane is defined using the 85th percentile of parked vehicle displacement). This is the least conservative definition of effective bike lane in this study. All the results hold whether using the 85th, 90th, or 95th (most conservative) percentile of parked vehicle displacement. Average cyclist displacement due to a change in traffic volume or percent trucks increases by less than 0.5 ft going from the least conservative to the most conservative definition of effective bike lane. That change is less pronounced (0.13 ft) for the presence of a buffer effect.

3.5 Summary of Key Findings

The primary findings based on the descriptive statistics and the analyses from the observational field studies conducted to evaluate the allocation of roadway width on both bicyclists' and motorists' lateral positioning, taking into consideration various roadway characteristics, can be summarized as follows:

- For the majority of scenarios evaluated on streets with on-street parking, the effective bike lane widths were narrower than the physical width of a typical adult bicyclist (i.e., 2.5 ft). For the scenarios evaluated on streets without on-street parking, the effective bike lane widths were always greater than or equal to the minimum operating space (i.e., 4 ft) of a typical adult bicyclist.
- The general trend in the data suggests that drivers park their vehicles closer to the curb as the parking lane narrows from 9 ft to 7 ft; however, the results are not statistically different. For the same parking lane widths, a higher percentage of vehicles parked outside the boundaries of the designated 7-ft parking lane, only a few vehicles parked outside the boundaries of the designated 8-ft parking lane, and no vehicles parked outside the boundaries of the designated 9-ft parking lane.
- For parking lanes 7- to 9-ft wide, based on the 95th-percentile parked vehicle displacement and assuming an open door width of 45 in., the open door zone width of parked vehicles extends approximately 11 ft from the curb.
- At sites with travel lanes ranging in width from 10 to 14 ft that were adjacent to bicycle lanes, very few passing vehicles encroached into the bicycle lane, even from the narrowest travel lane of 10 ft.
- Most bicyclists positioned themselves within the designated bicycle lane, but some bicyclists rode to the left in the travel lane adjacent to the bicycle lane, while others rode to the right of the bicycle lane (i.e., in the parking lane or buffer area) on streets with on-street parking.
- On streets with on-street parking, in most cases less than 50% of bicyclists positioned themselves within the effective bike lane, and in general, the percentage of bicyclists positioned within the effective bike lane was low (e.g., between 10% and 20%).
- On streets without on-street parking, most bicyclists (i.e., approximately 98% to 99%) were positioned within the effective bike lane regardless of whether a marked bike lane was installed.
- In general, on streets with on-street parking, the highest percentages of bicyclists were within the effective bicycle lane when buffers were used.
- Traffic volume, percent trucks, and presence of buffer space significantly affected the central positioning of a bicyclist in the roadway cross section:
  – As traffic volume increased from low (i.e., 15,000 to 17,000 vpd) to high (i.e., 29,000 vpd), bicyclists moved away from vehicles in the travel lane and positioned themselves closer to the parked vehicles or the curb. The estimated mean displacement of a bicyclist due to increased traffic volume was 2.12 ft (based on the 85th percentile of parked vehicle displacement) and ranged from 1.64 to 2.59 ft (95% confidence interval).
  – As truck percentage increased from low (i.e., <10%) to high (i.e., 16% to 20%), bicyclists moved away from vehicles in the travel lane and positioned themselves closer to parked vehicles or the curb. The estimated mean displacement of a bicyclist due to increased percent truck volume was 2.59 ft (based on the 85th percentile of parked vehicle displacement) and ranged from 2.28 to 2.91 ft (95% confidence interval).
  – The presence of a buffer effectively moved bicyclists away from parked vehicles by an average of 0.42 ft (based on the 85th percentile of parked vehicle displacement) and ranged from 0.04 to 0.81 ft (95% confidence interval).

SECTION 4

Supplemental Grade Study

During the process of developing guidelines for bike lane widths under various conditions, it was desirable to understand how roadway grade affects cyclist position. Specifically, the question of how much a cyclist drifts and sways back and forth while pedaling up a moderate to steep grade was of interest. Understanding the operating characteristics of cyclists pedaling up hills is important in determining whether wider bicycle lanes may be appropriate on upgrades.

4.1 Description of Field Study

A small study was conducted near the MRIGlobal campus in Kansas City, Missouri, in which six volunteers (four males and two females) rode their bicycles up a moderate grade. The volunteers were recruited from the MRIGlobal staff and were not members of the Transportation Research Center to avoid any potential bias. They ranged in skills from regular commuters to those who bicycle only recreationally. The participants used their own bicycles (from high-end road to inexpensive mountain bikes) during the study. Table 18 specifies the age and skill level of each participant and type of bicycle used during the testing.

A low-volume roadway with an upgrade of 3% to 4% was selected for the study. A temporary 4-in. longitudinal line was painted on the roadway surface 5 ft from the edge of the curb face, beginning approximately 80 ft from the bottom of the hill and extending for 60 ft along the roadway. A video camera was positioned downstream of the study section to record cyclists traversing the 60-ft section. Reference markings were placed at 10-ft increments along the study section, permitting six measurements of cyclist lateral position per rider traversing the section once. One at a time, cyclists started from the bottom of the grade and pedaled up to and through the 60-ft study section. Each cyclist completed the course five times. The roadway was not closed for the study. Participants were directed to bicycle up the grade within the bike lane as they naturally would. Figure 32 shows video frames of a bicyclist traversing the study section as part of the supplemental grade study.

Following the field study, the video recordings were viewed to document the lateral position (relative to the curb) of each cyclist at 10-ft increments along the study section. Thus, a database of 180 records of lateral position (6 riders × 5 traversals × 6 measurements of lateral positioning) was assembled. From the lateral position of each cyclist relative to the curb at the six locations along the study section, two variables were derived to capture the cyclists' sway and drift along the section of road. The two indicators are defined and their estimates provided in the following.

4.2 Data Analysis

Six measurements of lateral position were taken over a 60-ft section of the upgrade roadway for each rider during each run. From these, sway and deviation from a straight-line trajectory were defined as follows:

- **Sway:** For each rider and run, sway was calculated as the difference between the maximum and minimum of the six lateral positions from the curb.
- **Deviation from a straight-line trajectory:** For each rider and run, a straight-line trajectory was defined by the line connecting the lateral position at the first and last reference markings. The deviations at marking numbers 2 through 5 from that line were then calculated and averaged.

The distribution of sway is shown separately for each cyclist in Figure 33, and the distribution of deviation from a straight-line trajectory is shown separately for each cyclist in Figure 34. Basic descriptive statistics (minimum and maximum, mean, median, and standard deviation) for each indicator are shown at the bottom of each box plot. The horizontal lines in each

Table 18. Descriptives of supplemental grade study participants.

Participant	Age	Skill Level	Bike Type
1	44	Moderate	Hybrid
2	66	High	Road
3	28	Moderate	Road
4	70	Low	Mountain
5	34	High	Cruiser
6	30	Moderate	Mountain

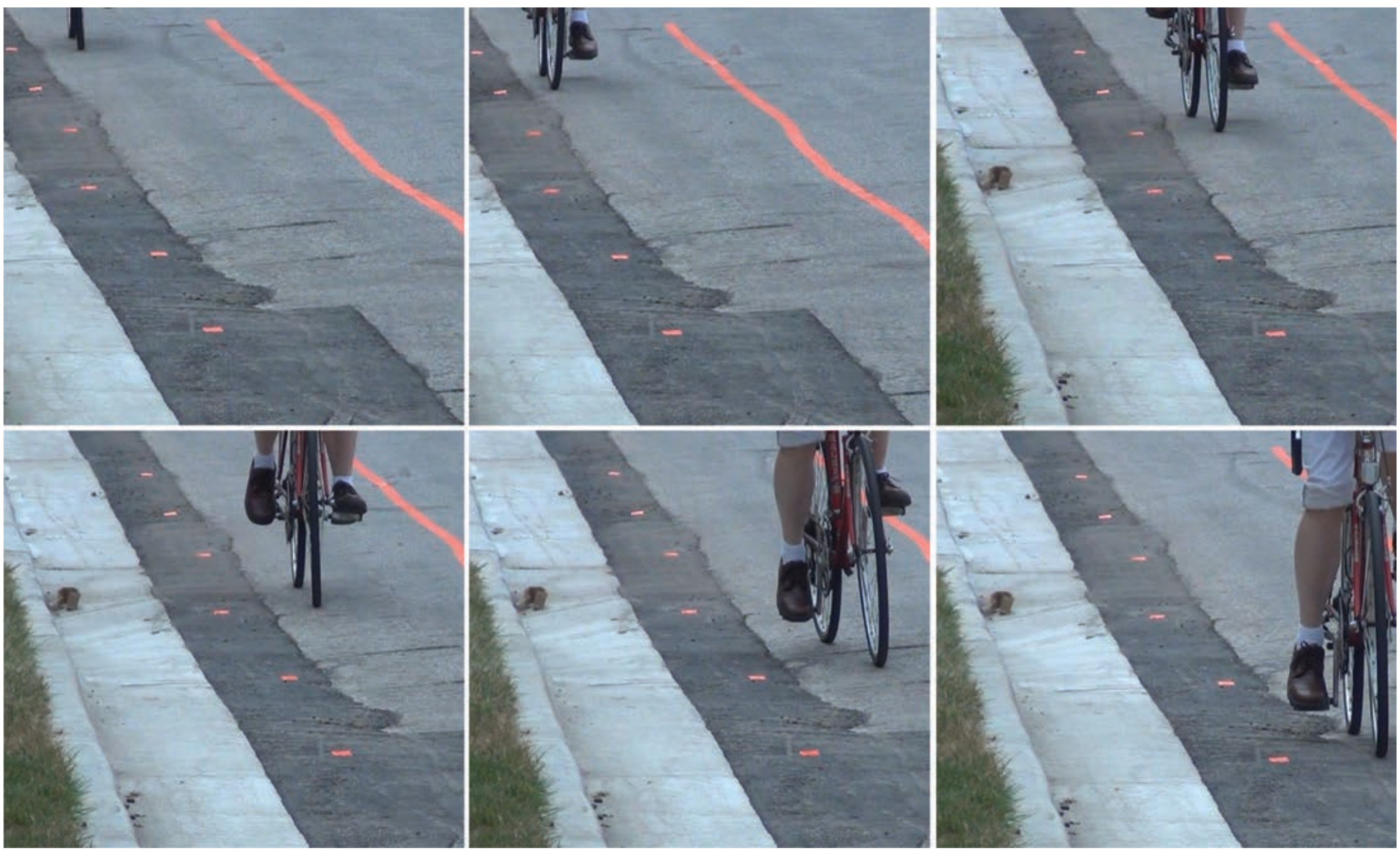
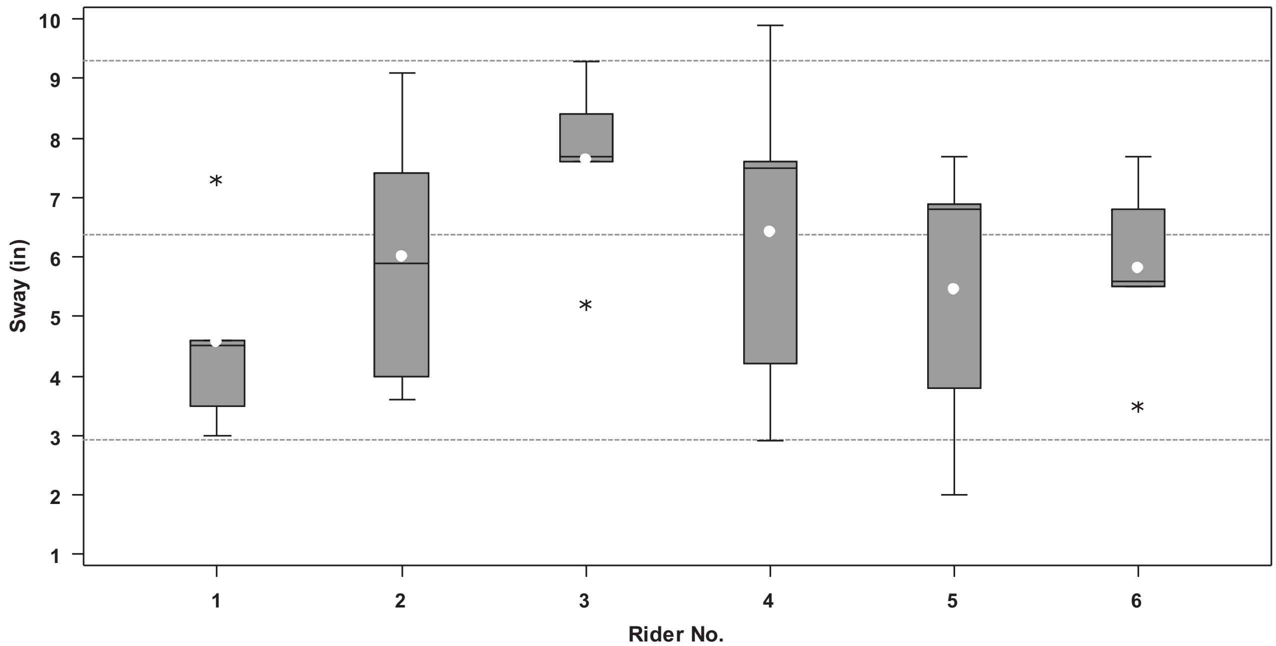


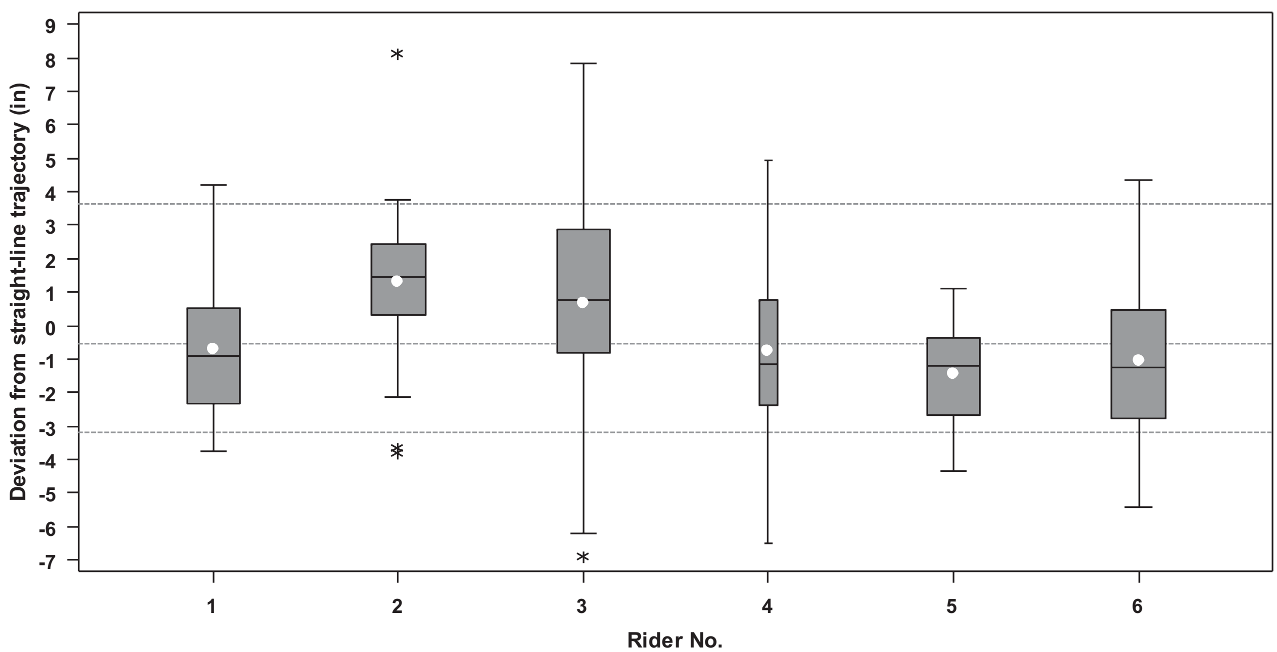
Figure 32. Video frames of a bicyclist traversing the upgrade during the supplemental grade study.



N	5	5	5	5	5	5
Min	3.0	3.6	5.2	2.9	2.0	3.5
Mean	4.6	6.0	7.6	6.4	5.4	5.8
Median	4.5	5.9	7.7	7.5	6.8	5.6
Max	7.3	9.1	9.3	9.9	7.7	7.7
Std Dev	1.66	2.31	1.52	2.83	2.43	1.58

White dot = mean; Star = extreme value; Gray box = mid 50% of data
Horizontal dashed lines represent overall 5th, 50th, and 95th percentile sway (2.9 in.; 6.4 in.; and 9.3 in.)

Figure 33. Distribution of cyclists' sway.



N	20	20	20	19	20	20
Min	-3.8	-3.8	-6.9	-6.5	-4.3	-5.4
Mean	-0.7	1.3	0.7	-0.7	-1.4	-1.1
Median	-0.9	1.4	0.8	-1.1	-1.2	-1.2
Max	4.2	8.1	7.8	4.9	1.1	4.3
Std Dev	1.95	2.63	3.51	2.65	1.56	2.54

White dot = mean; Star = extreme value; Gray box = mid 50% of data
Horizontal dashed lines represent overall 5th, 50th, and 95th percentile deviation from straight-line trajectory (-3.2 in., -0.6 in., and 3.6 in.)

Figure 34. Distribution of cyclists' deviation from straight-line trajectory.

box plot mark the 5th, 50th (median), and 95th percentiles. Thus 90% of the sway measurements fall between 2.9 and 9.3 in.; 90% of the deviations from straight-line trajectory fall between −3.2 and 3.6 in.

Overall mean estimates and 95% confidence intervals of both indicators were calculated, taking into account rider variability; the results for each are as follows:

- Average back-and-forth sway was 6 in., with a 95% confidence interval of 4.9 to 7.1 in.
- Average deviation from a straight-line trajectory was −0.3 in., with a 95% confidence interval of −1.4 to 0.81 in.

4.3 Summary of Key Findings

The primary findings from the supplement grade study conducted to understand the operating characteristics of cyclists on a moderate to steep upgrade are summarized as follows:

- Cyclists do sway back and forth while pedaling up moderate to steep grades.
- There is considerable variability in the amount of sway among riders.
- The largest observed deviation from a given straight-line trajectory was approximately 8 in., but generally, cyclists deviated only 3 to 4 in. from their straight-line trajectory.

SECTION 5

Design Guidance

This section provides general design guidance related to bicycle lane widths, taking into account a range of roadway and traffic characteristics. The design guidance is based primarily on the results of this research but also takes into consideration the results of previous research. The design guidance primarily pertains to the installation of bicycle lanes on roadways in urban and suburban areas. In the absence of similar data and analyses for rural areas, it is likely that the design guidance is applicable to rural areas; however, application of the design guidance to rural areas should be done with caution. This section addresses suggested bicycle lane widths as they relate to the following roadway and traffic characteristics:

- Parking lane width
- Travel lane width
- Traffic volume
- Vehicle mix
- Grade

Recall that the 2012 AASHTO *Bike Guide* indicates that a bicycle lane should range in width between 4 and 8 ft depending on conditions. Under most circumstances, the recommended width for bicycle lanes is 5 ft, but wider lanes may be desirable under conditions such as being (1) adjacent to narrow parking lanes with high turnover, (2) in areas with high bicycle use and without on-street parking to allow bicyclists to ride side by side or to pass each other, (3) on high-speed and high-volume roadways, or (4) on roadways with a substantial volume of heavy vehicles (i.e., trucks). Bicycle lanes as narrow as 4 ft may be used for roadways with no curb and gutter and no on-street parking or on extremely constrained, low-speed roadways with curbs but no gutter where the preferred bicycle lane width cannot be achieved. The AASHTO *Bike Guide* also states that the recommended width of a marked parking lane is 8 ft, and the minimum width is 7 ft.

The 2011 AASHTO *Green Book* states that the desirable minimum width of a parking lane is 8 ft; however, parking lane widths of 10 to 12 ft may be desirable to provide better clearance from the traveled way and to accommodate use of the parking lane during peak periods as a through-travel lane. Parking lane widths of 10 to 12 ft are also sufficient to accommodate delivery vehicles and allow a bicyclist to maneuver around an open door of a parked motor vehicle. The *Green Book* also notes that 7-ft parking lanes have been successfully used on urban collector streets within residential neighborhoods, where only passenger vehicles need to be accommodated in the parking lane.

The suggested design guidance based on the results of this research is presented in the following. It is important to note that throughout this research and analyses, where a buffer space is present, its width is not included in the width of the bicycle lane. Also, no data were included in the analyses that considered the position of two (or more) bicyclists riding side by side or one bicyclist passing another bicyclist in the bike lane. Therefore, the design guidance presented is intended for designing facilities to accommodate a bicyclist riding alone or more than one bicyclist riding in single file behind another. Finally, in developing the design guidance, equal weight is given to designing bicycle lanes to reduce the risk of bicycle crashes involving open doors of parked vehicles and bicycle crashes involving passing vehicles (i.e., moving vehicles in the travel lanes).

Bicycle Lane Width

This research investigated bicycle lanes ranging in width from 3.5 to 6 ft. In general, there was no practical difference in bicyclist positioning when operating within the bicycle lanes of these varying widths. When adjacent to an on-street parking lane, a majority of the cyclists positioned themselves within the open door zone of parked vehicles, regardless of the width of the bicycle lane. Thus, in the context of design guidance presented in the current *Bike Guide*, there is no evidence to suggest that a 6-ft bicycle lane provides any additional benefits to bicyclists in terms of drawing or moving bicyclists away from the door zone of parked vehicles compared to a bicycle lane width of 5 ft, or even as narrow as 3.5 ft or 4 ft. It should be noted, however, that the effect of increasing the bicycle lane width up to 6 ft without making a corresponding reduction in parking lane width (or buffer width) was not fully considered. Similarly, when adjacent to a vertical curb (without a gutter), there was no practical difference in bicyclist positioning when operating within bicycle lanes of 4 ft as compared to 5 ft.

The width of the bicycle lane does slightly affect the spread of bicyclist lateral positions, in that narrowing the bicycle lane reduces the variability of bicyclist lateral positions; however, the impact is relatively minor. For example, the average spread of bicyclist lateral positions within a 6-ft bike lane was 3.0 ft, while the average spread of bicyclist lateral positions within a 3.5- to 4.0-ft bike lane was 2.6 ft. Thus, narrowing the bicycle lane by 2 ft reduced the average spread of bicyclist lateral positions by 0.4 ft.

Therefore, in terms of accommodating bicyclists within a bicycle lane, there does not appear to be a distinct advantage of providing a wider bicycle lane compared to a narrower bicycle lane, at least when considering bicycle lane widths between 3.5 and 6.0 ft. Widening or narrowing the bicycle lane does not necessarily move bicyclists away from the door zone of parked vehicles, nor does it practically effect the spread of bicyclist lateral positions within the bicycle lane.

However, evidence suggests that providing a buffer space between the parking lane and the bicycle lane is desirable. When a buffer was provided between a bike lane and a parking lane, bicyclists positioned themselves further away from the door zone of parked vehicles, and as a result, a higher percentage of bicyclists were within the effective bike lane compared to when no buffer space was provided. The recommended buffer space is at least 1.5- to 2-ft wide and preferably marked with white diagonal cross hatching or chevron markings. The Manual on Uniform Traffic Control Devices requires that a buffer space wider than 4 ft be marked with chevrons (or diagonal cross hatching), while the National Association of City Transportation Officials requires chevrons or diagonal cross hatching for a buffer space of 3 ft or wider.

The study scenarios evaluated in this research did not include any scenarios with a buffer space wider than 2 ft. In each scenario that included a buffer, a buffer was present between the parking lane and the bicycle lane. In one scenario (Y-11), a buffer was also present between the bicycle lane and the travel lane. Based on the scenarios evaluated, the placement of the buffer spaces across the scenarios, the distribution of the bicyclists within the roadway cross section, and the placement of passing vehicles, evidence suggests that it is more desirable to install the buffer space between the parking lane and bike lane where on-street parking is permitted. In addition, data suggest that for parking lanes widths of between 7 and 9 ft and a buffer space of only 1 to 2 ft, a sizable portion (40% to 60%) of bicyclists may still position themselves within the door zone of parked vehicles. Thus, when adjacent to narrow parking lanes, it is desirable to provide a wider buffer space up to a maximum of 4 ft. Caution should be used in marking too wide of a buffer space since this may result in motor vehicles using the buffered bike lane even if it is properly marked.

In summary, providing a buffer space between a parking lane and bike lane offered distinct advantages over simply providing a wider bike lane.

Parking Lane Width

This research investigated parking lanes ranging in width from 7 to 9 ft. From a bicyclist's perspective, the primary interest was to determine if the parking lane width influenced how close drivers parked their vehicles to the curb, which affects the overall displacement of the vehicle from the curb and potential placement of an open car door. Although a general trend in the data suggests that drivers park their vehicles closer to the curb as the parking lane narrows from 9 ft to 7 ft, the results are not statistically different. The data also show that for parking lane widths of 7 ft, approximately 5% to 15% of parked vehicles extend beyond the limits of the parking lane. Therefore, to accommodate a larger percentage of drivers, a parking lane width of 8 ft is suggested for when a bicycle lane is adjacent to the on-street parking. An 8-ft parking lane allows more of the roadway cross section to be designated for use by bicyclists and motor vehicles in a bicycle lane and the travel lanes compared to a 9-ft parking lane. When the roadway cross section is limited or if there is a desire to install a buffered bike lane, a 7-ft parking lane may be used adjacent to a bicycle lane.

For parking lanes 7- to 9-ft wide, the open door zone width of parked vehicles extends approximately 11 ft from the curb, assuming the 95th-percentile parked vehicle displacement and an open door width of 45 in. Thus, where bike lanes are adjacent to parking lanes 7- to 9-ft wide, the design of the bike lane should encourage bicyclists to ride outside of this door zone area (and account for the width of the bicyclist).

Travel Lane Width

This research investigated travel lanes ranging in width from 10 to 18 ft. The widest travel lane adjacent to a bicycle lane was 14 ft. During the field data collection, few passing vehicles were observed encroaching into the bicycle lanes for most of the study scenarios, even from the narrowest 10-ft travel lane. Similarly, few passing vehicles likely encroached into adjacent travel lanes to the left, especially when encroachment involved crossing the centerline of the roadway. Thus, based on these field observations, travel lanes between 10 and 12 ft in width were found to be appropriate when adjacent to a bicycle lane. This is consistent with previous research (Potts et al., 2006) that indicates the use of travel lanes narrower than 12 ft on urban and suburban arterials does not necessarily increase expected crash frequencies and that geometric design policies should provide flexibility for use of lane widths narrower than 12 ft.

With respect to wide curb lanes, this research investigated travel lanes of 16 and 18 ft in width on streets without on-street parking. Marking a bicycle lane of 4 or 5 ft in width on such a facility may have some advantages in distinguishing allocation of roadway width and minimizing the potential for operation of two motor vehicles side by side, but there was no practical difference in the bicyclists' positioning between the scenario with a 4- or 5-ft marked bicycle lane (narrowing the travel lane to 11 to 14 ft) and a scenario with a wide curb lane and no marked bicycle lane. On streets without on-street parking and travel lanes of 16 and 18 ft in width, whether a marked bicycle lane is provided or not, the effective bike lane is, for practical purposes, the same, and almost all bicyclists will position themselves within the effective bike lane.

Traffic Volume

This research included study sites with traffic volumes ranging between 14,800 and 29,000 vpd. The data show that as traffic volume increases, bicyclists move away from vehicles in the travel lane and position themselves closer to parked vehicles or the curb. In the analyses that were performed, the traffic volumes were categorized as lower ADT (15,000 to 17,000) and higher ADT (29,000). It was found that bicyclists positioned themselves approximately 1.5 to 2.5 ft closer to parked vehicles or the curb at the higher ADT level compared to the lower ADT level. As such, on streets with ADTs above 20,000 vpd, additional displacement of bicyclists due to traffic volume should be considered when determining the allocation of street width between parking lanes, bicycle lanes, and travel lanes. In particular, consideration should be given to designating additional street width to bicyclists and/or providing a buffer to account for the additional displacement of bicyclists at higher traffic volumes.

Vehicle Mix

This research included study sites with the percentage of trucks in the vehicle mixes ranging from between 2% and 20%. Similar to traffic volume, the data show that as truck percentage in the vehicle mix increases, bicyclists move away from vehicles in the travel lane and position themselves closer to parked vehicles or the curb. In the analyses that were performed, the truck percentages were categorized as low (<10%) and high (16% to 20%). It was found that bicyclists positioned themselves approximately 2.5 to 3.0 ft closer to parked vehicles or the curb at the higher truck percentage level compared to the lower truck percentage level. As such, on streets with truck percentages above 10%, additional displacement of bicyclists due to trucks should be considered when determining the allocation of street width between parking lanes, bicycle lanes, and travel lanes. In particular, consideration should be given to designating additional street width to bicyclists and/or providing a buffer to account for the additional displacement of bicyclists at higher truck percentages.

Grade

This research included a supplemental grade study in which cyclists pedaled up a moderate grade of 3% to 4%. The average observed back-and-forth sway of the cyclists was approximately 6 in., while their deviation from a straight-line trajectory was typically between 3 and 4 in. Given that so few bicyclists position themselves within 6 in. of the outside edge of a marked bicycle lane, there is not sufficient evidence to suggest the need to widen a bicycle lane on moderate to steep upgrades to account for potential back-and-forth sway of cyclists while pedaling up the grade.

Allocation of Total Roadway Width

Based on the research results, Table 19 provides guidance for suggested lane widths for total roadway widths measuring 44 to 54 ft curb to curb, based primarily on the percentage of bicyclists riding within the effective bike lane and the estimated central positioning of bicyclists, while accounting for traffic volume, truck percentages, and the presence/absence of a buffer. The suggested lane widths are not the direct result of a single analysis performed as part of this research but are based on the combined information collected during the research.

Table 19 is most applicable to urban and suburban two-lane undivided roadways, with constrained roadway width and on-street parking, and with a posted speed limit 30 mph. The roadway could function either as an arterial or collector roadway. For all locations, engineering judgment needs to be exercised when selecting the final allocation of roadway width, taking into consideration the safety, mobility, and accessibility of all roadway users. The results of this research are most applicable to assist in providing design guidance for allocation of lane widths for total roadway widths mea-

Table 19. Suggested lane widths for urban and suburban two-lane undivided roadways with on-street parking and constrained roadway widths.

Widths (ft)—One Direction of Travel						Curb to Curb (ft)	Travel Conditions[1]
Parking Lane	Buffer	Bike Lane	Buffer	Travel Lane	Curb to CL		
8	3*	4	2	10	27	54	All conditions
7	3*	4	2	10	26	52	All conditions
7	2*	4	2	10	25	50	High volume or high truck percentage
7	3	5	0	10	25	50	Low volume and low truck percentage
7	1.5	4	1.5	10	24	48	High volume or high truck percentage
7	3	4	0	10	24	48	Low volume and low truck percentage
7	2	5	0	10	24	48	Low volume and low truck percentage
7	2	4	0	10	23	46	All conditions
7	0	5	0	10	22	44	All conditions
7	1**	4	0	10	22	44	All conditions

* May consider combining buffers to create a 4-ft buffer between parking and bike lanes.
** Caution that striping of double white lines may cause confusion.
1 The suggested threshold for distinguishing between low and high traffic volume is 20,000 vpd, and the suggested threshold for distinguishing between low and high truck percentage is 10% trucks in the vehicle mix.
Note: CL = center line.

suring 44 to 54 ft curb to curb. The guidance generally reflects that a buffer space provides distinct advantages over simply providing a wider bike lane and that providing a buffer space on both sides of the bike lane may help bicyclists to ride within the effective bike lane on roads with higher traffic volumes or truck percentages.

Table 19 does not provide design guidance for total roadway widths greater than 54 ft or less than 44 ft. For total roadway widths greater than 54 ft, designers have more flexibility to provide wider lane widths and need less guidance due to the availability of space (e.g., additional width can be allocated to the travel lane or parking lane). On the other hand, for total roadway widths less than 44 ft, conditions are so constrained that based on the analysis results, it is suggested that bike lanes not be marked but rather a shared lane be provided adjacent to a parking lane and/or the roadway be marked with a shared-lane marking. Table 19 does not provide guidance on where it might be more appropriate to install or use a shared-lane marking rather than a bike lane. Also, Table 19 does not consider or address cross sections with a two-way lane, left-turn lane, or multiple lanes in the same direction of travel, although the general suggestions are still applicable. Concepts for designing Complete Streets could also be considered when determining the final allocation of roadway width.

Table 19 provides several design options for total roadway widths of between 44 and 50 ft. For total roadway widths of 52 ft or more, design decisions concerning allocation of lane widths can be made independent of traffic volumes and truck percentages, and the same is true for total roadways widths of 46 ft or less. However, for total roadway widths of between 48 and 50 ft, several different suggested lane widths are provided depending on the expected traffic volumes and truck percentages for the roadway. The design guidance provides suggested lane widths for four categories of traffic volumes or truck percentages—that is, low and high traffic volumes and low and high truck percentages. The range of traffic volume and truck percentage categories used to evaluate the effect of roadway characteristics on the central positioning of bicyclists should be used as a rule of thumb for distinguishing values for low and high volumes and truck percentages in Table 19, as follows:

- Low volume: 15,000 to 17,000 vpd,
- High volume: 29,000 vpd,
- Low truck percentage: <10%, and
- High truck percentage: 16% to 20%.

For example, a threshold value of 20,000 vpd may be reasonable to distinguish between low and high traffic volumes. Similarly, a threshold value of 10% trucks in the vehicle mix appears to be a reasonable value to distinguish between low and high truck percentages.

The design guidance shown in Table 19 suggests that the combined width of the buffer area(s) and bike lane be a minimum of 5 ft and a maximum of 9 ft. Caution should be used in designing a buffer area and bike lane with a combined width greater than 9 ft because it may promote the use of this portion of the roadway by motor vehicles, even when properly marked and designated as a bike lane.

Table 19 suggests that suggested parking lane widths on roadways measuring 44 to 54 ft curb to curb should be 7 ft. The *Green Book* states that 7-ft parking lanes have been used on urban collector streets within residential neighborhoods, but in most other situations, the desirable minimum width of a parking lane is 8 ft (as was also suggested based on the results of this research). Given that a buffer and in some cases two buffers are suggested in conjunction with the designated bicycle lane under constrained conditions, providing a 7-ft parking lane adjacent to a buffered bicycle lane on a wider range of facility types than simply urban collector streets within residential neighborhoods seems appropriate.

Finally, for streets where on-street parking is prohibited, the analysis results from this research indicate that the minimum bike lane width should be 4 ft, measured from the face of curb or vertical surface to the center of the bike lane line, for roadway widths of 32 ft or greater (measured curb to curb) and may be appropriate for roadway widths as narrow as 28 ft. For roadways with higher volumes or higher truck percentages, a bike lane width of 5 ft is desirable. It is also worth mentioning that although this research did not evaluate bike lane widths as narrow as 3 ft, Hunter and Feaganes (2003) concluded that marking a 3-ft bike lane provides benefits over a wide curb lane. Along sections of roadway with curb and gutter or guardrail, the usable width of the bike lane should be considered when determining the desired width for the bike lane.

Limitations of the Research

This design guidance needs to be considered within the context of the research. In particular, it should be noted that the suggested allocations of roadway widths are based on data collected along streets with posted speed limits of 30 mph. The speeds of motor vehicles in the travel lane adjacent to a bike lane likely affect the comfort and positioning of bicyclists within the bike lane. Therefore, the suggested allocations of roadway widths should be used cautiously for the design of roadways with motor vehicle speeds outside of the range of 25 to 35 mph and, in particular, for higher-speed roadways.

In addition, data were collected only at five sites in two cities. It would have been desirable to collect data at more sites in additional cities. This would have permitted a wider range of roadway characteristics to be evaluated and analyzed. As such, a limited dataset was used to generalize results and make them applicable to other communities/cities.

It should also be recognized that physical and financial constraints typically exist, so agencies must do the best that they can within their means and with available resources. This is to say, if physical and financial constraints did not exist, from a motorist and bicyclist's perspective, it would be desirable to provide 12-ft travel lanes, 7-ft bike lanes with buffers, 10-ft parking lanes, and so forth. Such lane widths and cross sections would provide additional separation between vehicles/bicycles within adjacent lanes; however, such wide cross sections could also result in undesirable consequences such as increased speeds of motor vehicles and increased crossing distances for pedestrians. However, all agencies must deal with the realities of financial limitations, and particularly during the construction or reconstruction of urban and suburban streets, right-of-way constraints limit the amount of total roadway width that can be allocated to accommodate a range of users. Thus, decisions must be made regarding allocation of roadway width to comfortably serve all roadway users. While it may not always be practical to provide an ideal design, cross section, or allocation of total roadway width, the reality is that, in some situations, lane widths may be what would be less than preferred in an effort to balance the needs of all roadway users. For example, the resulting effective bike lane widths may be less than the physical, minimum, or preferred operating space of a bicyclist as defined in the current edition (2012) of the AASHTO *Bike Guide*, or the minimum shy distance separating a vehicle from another vehicle (or bicyclist) as recommended in the *Roadside Design Guide* (AASHTO, 2011) may not be achievable, especially under constrained conditions.

Finally, it should be emphasized that the objective of this research was to develop a set of suggestions for bicycle lane widths for various roadway and traffic characteristics under the overall guiding principle to provide suggestions on how wide the bicycle lane should be in cases where a decision to include a bicycle lane has been made. It should be made very clear, as evident by the data collected and analysis results, that the design guidance presented herein does not eliminate the potential risk to bicyclists striking open car doors of parked vehicles or being struck by passing vehicles, nor does the design guidance eliminate the potential for encroachment of passing vehicles into adjacent (motor vehicle) travel lanes to the left. When a facility is designed, whether it meets or does not meet current guidelines, it is important to fully understand the risks associated with all road users. This report sheds light on the risks faced by road users for a certain range of roadway and traffic characteristics where bicycle lanes may be provided.

Given the objective, scope, and limitations of this research, it is understood that some of the design guidance suggested from this research could be viewed as controversial. The basic question that has to be posed is, "Particularly for constrained or fixed roadway widths, which facility type is most desirable from a bicyclist perspective: a shared lane, a marked shared lane, or a bicycle lane?" This research did not answer this basic question, but rather focused on providing design guidance for a bicycle lane given the decision that a bicycle lane will be installed. Proceeding from this research, roadway designers and transportation agencies have several options concerning the use of the suggested design guidelines. They can (1) accept the design guidance suggested and incorporate the design guidance for bicycle lanes within their local design practices, (2) interpret the data and analysis results differently than what has been presented and develop their own design guidance for bicycle lanes, or (3) reject the suggestions (and potentially focus on designs for a shared lane or a roadway with a shared-lane marking, or where on-street parking is permitted, eliminate the parking in favor of a dedicated bicycle lane). However the results of this research and design guidance are viewed, it should be remembered that as stated in the Foreword of the AASHTO *Green Book*, good highway design involves balancing safety, mobility, and preservation of scenic, aesthetic, historic, cultural, and environmental resources. A design policy is not intended to supersede the need for application of sound principles by knowledgeable design professionals but is intended to provide sufficient flexibility to encourage independent designs tailored to particular situations, and engineering judgment is to be exercised to select appropriate design values.

SECTION 6

Conclusions and Future Research

The objective of this research was to develop suggestions for bicycle lane widths for various roadway and traffic characteristics. The focus was on developing design guidance for bicycle lane widths for roadways in urban and suburban areas. An observational field study was conducted to evaluate the allocation roadway width on both bicyclists' and motorists' lateral positioning, taking into consideration various roadway and traffic characteristics. The general methodology of the field study involved installing temporary lane line markings to delineate bicycle lanes of varying widths at midblock locations and observing the behavior of bicyclists and motorists. The final database from the observational field study included data on 4,965 bicyclists, 3,163 passing vehicles, and 994 parked vehicles.

The primary roadway and traffic characteristics that factored most into selecting sites for inclusion in the observational field study were:

- Bicycle volume,
- Traffic volume,
- Vehicle mix (i.e., percent trucks),
- Lane width or total roadway width, and
- Presence/absence of on-street parking.

Given the site characteristics and the study scenarios, the ranges in the primary roadway and traffic characteristics analyzed in this research were:

- Bike lane width: 3.5 to 6 ft,
- Parking lane width: 7 to 9 ft,
- Travel lane width: 10 to 18 ft,
- Presence/absence of buffer space,
- Traffic volume: 14,800 to 29,000 vpd, and
- Percent trucks: 2% to 20%.

Posted speed limit and grade were additional characteristics of interest identified for evaluation in this research; however, all of the sites included in the observational field study had a posted speed limit of 30 mph and were on a level grade. The effect of grade on bicyclist behavior was evaluated through a supplemental grade study.

This section presents the conclusions from the study and suggestions for future research. Section 5 provided general design guidance related to bicycle lane widths taking into account the range of roadway and traffic characteristics evaluated in this research.

6.1 Conclusions

The conclusions here should be considered within the context of the research. In particular, the conclusions are most applicable to urban and suburban roadways with a level grade and a posted speed limit of 30 mph and should be used cautiously for the design of roadways with motor vehicle speeds outside of the range of 25 to 35 mph and, in particular, for higher-speed roadways.

General Conclusions

1. A buffered bike lane provides distinct advantages over simply providing a wider bike lane.
2. Narrowing the width of a bicycle lane reduces the variability of the bicyclists' lateral positions; however, this impact is relatively minor, at least for the bicycle lane widths evaluated in this research.
3. As traffic volume increases, bicyclists move away from vehicles in the travel lane and position themselves closer to parked vehicles or the curb.
4. As truck percentage within the vehicle mix increases, bicyclists move away from vehicles in the travel lane and position themselves closer to parked vehicles or the curb.
5. For streets with on-street parking and where the parking lane width is between 7 and 9 ft and the bike lane width is between 4 and 6 ft, the effective bike lane will likely be less

than the physical width of a typical adult bicyclist, and the majority of bicyclists will position themselves outside of the effective bike lane.

6. For streets without on-street parking, as long as the adjacent travel lanes is at least 10-ft wide and the bike lane is 4 to 5 ft in width, most bicyclists will position themselves in the effective bike lane, and the effective bike lane will be equivalent to the width of the marked bike lane.

Design Guidance

1. Travel lanes between 10 and 12 ft in width are appropriate for streets with a bicycle lane.
2. At sites with travel lane widths of between 16 and 18 ft on streets without on-street parking, marking a bicycle lane provides no distinct advantages for the lateral positioning of bicyclists and motorists. While this statement is true with respect to the issues addressed in this particular study, there are other reasons why bike lanes on streets with 16- to 18-ft lanes would be desirable. These include using the bike lane to narrow the travel lane to provide a traffic calming measure, encouraging bicyclists to travel in the correct direction on the street, getting bicyclists off of adjacent sidewalks where they are generally less safe (Wachtel and Lewiston, 1994), and using the bike lane as a link to a larger bikeway network.
3. In most situations where a bicycle lane is adjacent to on-street parking, the suggested width for the parking lane is 8 ft. An 8-ft parking lane provides sufficient space for a large percentage of vehicles to park within the limits of the parking lane, and it is narrow enough that it allows more of the roadway cross section to be designated for bicyclists in the bicycle lane and motor vehicles in the travel lanes. This is consistent with current recommendations in the AASHTO *Bike Guide* and *Green Book*.
4. The AASHTO *Bike Guide* states that under most circumstances, the recommended width for bike lanes is 5 ft. The guide also states that under certain conditions, wider bicycle lanes may be desirable. In particular, the guide states that when adjacent to a narrow parking lane (7 ft) with high turnover, a wider bicycle lane (6–7 ft) provides more operating space for bicyclists to ride outside of the door zone of parked vehicles. Based on the data collected in this study, a 6-ft bicycle lane does not provide additional benefits to bicyclists compared to a 5-ft bicycle lane. Most bicyclists will still position themselves within the open door zone of parked vehicles whether in a 6-ft bicycle lane or a 5-ft bicycle lane. A 7-ft bicycle lane may offer distinct advantages for bicyclists compared to bicycle lane widths of 5 and 6 ft; however, data for 7-ft bike lanes were not investigated in this research. Where space permits, the data suggest that installing a narrower bicycle lane with a parking-side buffer provides distinct advantages over a wider bike lane with no buffer.
5. For parking lanes 7- to 9-ft wide, assuming the 95th-percentile parked vehicle displacement and an open door width of 45 in., the open door zone width of parked vehicles extends approximately 11 ft from the curb. Therefore, the design of the bike lane should encourage bicyclists to ride outside of this door zone area and should account for the width of the bicyclist.
6. Taking into consideration the percentage of bicyclists riding within the effective bike lane and the estimated central positioning of bicyclists, which accounts for traffic volume, truck percentages, and the presence/absence of a buffer, Table 19 provides suggested lane widths for total roadway widths measuring 44 to 54 ft curb to curb. Where bicycle lanes are designed according to the guidance from Table 19, it should be recognized that bicyclists will still likely position themselves within the door zone of parked vehicles.

6.2 Future Research

Suggestions for future research topics related to bicycle lane widths are as follows:

1. The primary roadway and traffic characteristics evaluated in this research to develop guidelines for bicycle lane widths were parking lane width, travel lane width, traffic volume, and vehicle mix (i.e., percent trucks). Future research could be conducted to develop recommended bicycle lane widths based on vehicle speeds (or posted speed limits) and grade (which was addressed in this research on a limited basis).
2. This research found a relationship between bicyclist position and traffic volume and vehicle mix (i.e., percent trucks). Both traffic volume and vehicle mix were dichotomized into high and low categories. It would be desirable to more fully evaluate the impact of a wider range of traffic volume and vehicle mix on bicyclist lateral position. Some value may also be added by analyzing bicyclist lateral position relative to individual vehicle types (e.g., passenger cars, trucks, buses).
3. This research found that including a buffer space provides distinct advantages over simply providing a wider bike lane; however, only a limited number of buffered bike lane designs were evaluated. Additional research could investigate a wider range of buffered bicycle lane designs to develop better design guidance for such lanes and, in particular, bicycle lanes with buffers on both sides that potentially balance the threat of passing vehicles and the open doors of parked vehicles.
4. In this research, for streets with on-street parking, an effective bike lane was defined based on the behavior of parked

vehicles and passing vehicles, and for streets where on-street parking was prohibited, an effective bike lane was defined based on the behavior of passing vehicles. Future research could be conducted to determine the relationship between effective bike lane widths, the physical and operational widths of bicyclists, and bicycle crashes, including bicycle crashes in the presence of passing vehicles and parked vehicles (where applicable).

5. The frequency and severity of bicyclists colliding with open doors of parked vehicles should be assessed in future research. A safety analysis should be conducted to quantify the proportion of bicycle crashes that involve an open door of a parked vehicle compared to bicycle crashes that involve passing vehicles (i.e., moving vehicles in the travel lanes). In addition, the injury severity of such crashes should be assessed. This would help to better assess the magnitude of the problem associated with bicycle crashes involving an open door of a parked vehicle relative to bicycle crashes involving passing vehicles.
6. This research focused on developing design guidance for bicycle lane widths for roadways in urban and suburban areas, taking into consideration the roadway and traffic characteristics in those areas. A similar research effort should be conducted to develop design guidance for bicycle lane widths in rural areas, taking into consideration their roadway and traffic characteristics.
7. Future research should investigate the impacts of travel lane widths and bicycle lane widths on encroachment into adjacent travel lanes. This research did not collect data for vehicle classification and width for passing vehicles but rather assumed two vehicle widths to estimate a range of encroachment of passing vehicles into adjacent (motor vehicle) travel lanes to the left. It is important to determine how often vehicles encroach into adjacent travel lanes from 10-, 11-, and 12-ft travel lanes when adjacent to a bicycle lane. The number of lanes in the direction of travel should be considered in this research.
8. This research focused on analyzing the lateral position of bicyclists, passing vehicles, and parked vehicles where bike lanes were installed along midblock locations of two-lane and four-lane roadways. Future research should investigate the applicability of the results and guidelines for one-way streets, contra-flow lanes, and bike lanes at intersections and for cross sections with two-way, left-turn lanes.

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation