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Effectiveness of Innovative Pavement Markings in Facilitating Safe Bicycle Travel

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16. Abstract:

Bicycle accommodations are an increasingly important component of the transportation system, and research has provided growing evidence that cities with higher bicycling (and walking) rates have better road safety records. In an effort to facilitate bicycle travel through intersections, newer traffic control devices have been applied, including the bicycle box, a space for bicycles to stop on a red signal ahead of the motor vehicle stop bar, and the two-stage turn box, a space where turning bicyclists can wait before making the second stage of a two-stage turn.

This study evaluated the effects of two bike boxes and two turn boxes installed in 2014 at an intersection in Charlottesville, Virginia. Videos collected during 3 days before the changes (non-consecutive over a 1-month period) and 5 days after the changes (non-consecutive in the fall and spring seasons) provided volume counts and tallies of traffic infractions and conflict events such as near misses. Data were prepared in order to pair the "before" and "after" periods, resulting in eight 12-hour sets of observations starting at 7:30 a.m., each with 48 time intervals of 15 minutes. Because the data were not normally distributed, the Wilcoxon signed-rank test was employed to compare the before and after periods. To take advantage of the paired structure of the data (i.e., before and after), a matched-pair or related-sample version of the test was performed.

After the main analysis, a subset of data (1 hour in the morning and 1 hour in the afternoon for three before and three after count dates) was re-reviewed by one researcher in order to address concerns about inter-rater reliability from the initial data reduction. Several methods were used to compare this re-reviewed dataset to the original review results.

Results were mixed. Among other findings, the following results were statistically and practically significant:

- The two bike boxes were used properly/improperly by 46%/40% and 24%/10% of approaching bicyclists on the respective leg of the intersection.
- The two turn boxes had high levels of improper (but not necessarily unsafe) use, at 57% to 100% of approaching bicyclists.
- Uncategorized bicyclist traffic infractions on one approach decreased by 43% after the changes but increased by 80% on another approach.
- Prohibited direct left turns increased 200% for motorists (from 0.1% to 0.4% of approaching motorists) and 290% for bicyclists (from 13.3% to 51.3% of approaching bicyclists).

The study recommends that the Virginia Department of Transportation (1) create or improve education materials related to bike boxes and turn boxes and (2) evaluate the feasibility of submitting requests for interim approval for bicycle boxes and two-stage bicycle turn boxes.

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FINAL REPORT

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In Cooperation with the U.S. Department of Transportation
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INTRODUCTION

The share of Virginians bicycling to work approximately doubled from 2006 to 2016 (U.S. Census Bureau, 2016). Bicycle accommodations are an increasingly important component of the transportation system, and research has provided growing evidence that cities with higher walking and bicycling rates have better road safety records (Marshall and Garrick, 2011); i.e., there might be safety in numbers (Murphy et al., 2017). However, while overall traffic fatalities in the United States steadily declined from 2004 through 2013, bicycle fatalities increased (U.S. Government Accountability Office, 2015).

Transportation agencies have deployed new types of infrastructure in an attempt to facilitate or increase bicycle travel and improve its safety (Pucher et al., 2010). Two types of pavement markings that are relatively new in the United States are the bike box, a space for bicycles to stop ahead of the motor vehicle stop bar at the intersection approach, and the two-stage turn box, a space where turning bicyclists can wait before completing the second stage of a two-stage turn (Monsere et al., 2014).

This study evaluated the effects of two bike boxes and two turn boxes at an intersection in a small city in Virginia where the local government wanted to facilitate bicycle travel through the intersection near a university. The topic was prioritized by the Virginia Transportation Research Council's (VTRC) Transportation Planning Research Advisory Committee in fall 2012.

Bike Boxes and Turn Boxes

Bike boxes in the United States typically span the bike lane and the adjacent general purpose lane (Hunter, 2000); may be tinted, usually green (Dill et al., 2011); and are usually fed by an ingress bike lane (Figure 1). Stated purposes of bike boxes include relieving bicyclists from breathing motor vehicle exhaust, making bicyclists more visible to motorists at the beginning of the green phrase, and allowing bicyclists to position themselves for turns and merges (Dill et al., 2011; Hamer, 1981).

Figure 1. Illustration of a Typical Bike Box. Image from *Urban Bikeway Design Guide, Second Edition*, by NACTO. Copyright © 2014 National Association of City Transportation Officials. Reproduced by permission of Island Press, Washington, D.C.

Outside the United States, different terminology is used for treatments that are functionally similar to bike boxes: New Zealand’s term is “advanced cycle lanes” (Newman, 2002), and the United Kingdom calls them “advanced stop lines” (ASLs) (Wall et al., 2003). ASLs have been described as a measure designed to increase cyclist safety by allowing cyclists to accelerate on a green signal in advance of motorized traffic (Allen et al., 2005). Conventional bike boxes in Europe are the full width of the approach lane(s), although some variations may be narrower (Atkins Services, 2005).

In a two-stage bicycle left turn, the bicyclist proceeds straight ahead to the right of through automobiles from the same approach (Stage 1) and then stops and waits for the green interval for the cross street, completing the turn by proceeding along the cross street (Stage 2) (Chen and Shao, 2014). The National Association of City Transportation Officials listed several benefits of two-stage turn boxes (Figure 2), including improving bicyclists’ ability to make left turns safely and comfortably, providing a formal queuing space, and reducing turning conflicts between bicyclists and motor vehicles (National Association of City Transportation Officials, 2014). Other terms for similar design treatments include “left-turn waiting areas” (China) (Liang et al., 2015) and “cyclist refuges” (Hamer, 1981).

Bike boxes and turn boxes are relatively common in parts of Europe but were introduced more recently in the United States. They have received increased interest in recent years because of their potential application for managing left turns from physically separated bikeways, an increasingly common facility type (Martinson and Golly, 2017). When this study began, the Federal Highway Administration (FHWA) classified bike boxes and turn boxes as experimental traffic control devices not covered by the 2009 edition of the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA, 2012). Since that time, both treatments have received interim approval status, allowing them to be installed under certain conditions (FHWA, 2016c; FHWA, 2017).

Figure 2. Photograph of a Bicyclist in a Two-Stage Left-Turn Box

Study Site

University Avenue and West Main Street comprise the primary east-west bicycle route through Charlottesville, Virginia. Signed as part of U.S. Bicycle Route 76 and Business U.S. Route 250, the corridor connects the city's downtown with the University of Virginia (hereinafter "university"). Bicycle facilities include bicycle lanes on the eastern half of the 1-mile segment and "Bikes May Use Full Lane" advisory signs on the western portion where the width is insufficient for bike lanes.

The study intersection of University Avenue and Rugby Road (Figure 3) is an important vehicular entrance to the University of Virginia, which is a major generator of bicycle trips. Rugby Road leads to student residential areas and additional academic buildings and has bike lanes north of the intersection; when used together with an off-street path and bicycle/pedestrian bridge (not shown in Figure 3), Rugby Road provides a key bicycle and pedestrian connection from the university's central grounds to the north grounds area.

Figure 3. Experiment Site and Surrounding Areas. Google Maps imagery © 2013 Commonwealth of Virginia, DigitalGlobe, USDA Farm Service Agency.

Conditions Prior to Changes

In addition to its unusual user mix dominated by college students, the intersection has unusual geometry. It is a signalized T-intersection with a side road on Rugby Road (the leg of the T) and a spur (McCormick Road) diverging from University Avenue (the cap of the T) (Figure 4). The side road that empties into the intersection, Carr's Hill Road, is a dead end service drive with low traffic volumes serving four residential and academic buildings and is stop-controlled. Prior to the changes, bicycle infrastructure included bike lanes on the leg of the T and a climbing bike lane eastbound approaching the intersection. Westbound left turns onto McCormick Road (the spur) were prohibited at the signal, diverting the movement to an unsignalized intersection 350 feet to the west. Right turns on red (RTORs) were prohibited from the leg of the T and from the spur.

The traffic signal operated with video detection for the McCormick Road approach and inductive loop detectors for the others and was equipped with pedestrian pushbuttons and pedestrian countdown signals for all crossings except the crossings of McCormick Road and Carr's Hill Road. For pedestrians crossing University Avenue, there was a leading pedestrian interval of about 4 seconds, which bicyclists had been observed to use. Because of the unusual geometry, McCormick Road and Rugby Road each had exclusive green phases, with Rugby Road's phase concurrent with the remainder of the pedestrian phase crossing University Avenue; both had "No Turn on Red" (NTOR) signs. Westbound RTORs from University Avenue onto Rugby Road were permitted. Signal phasing was protected/permissive for the eastbound left turn onto Rugby Road.

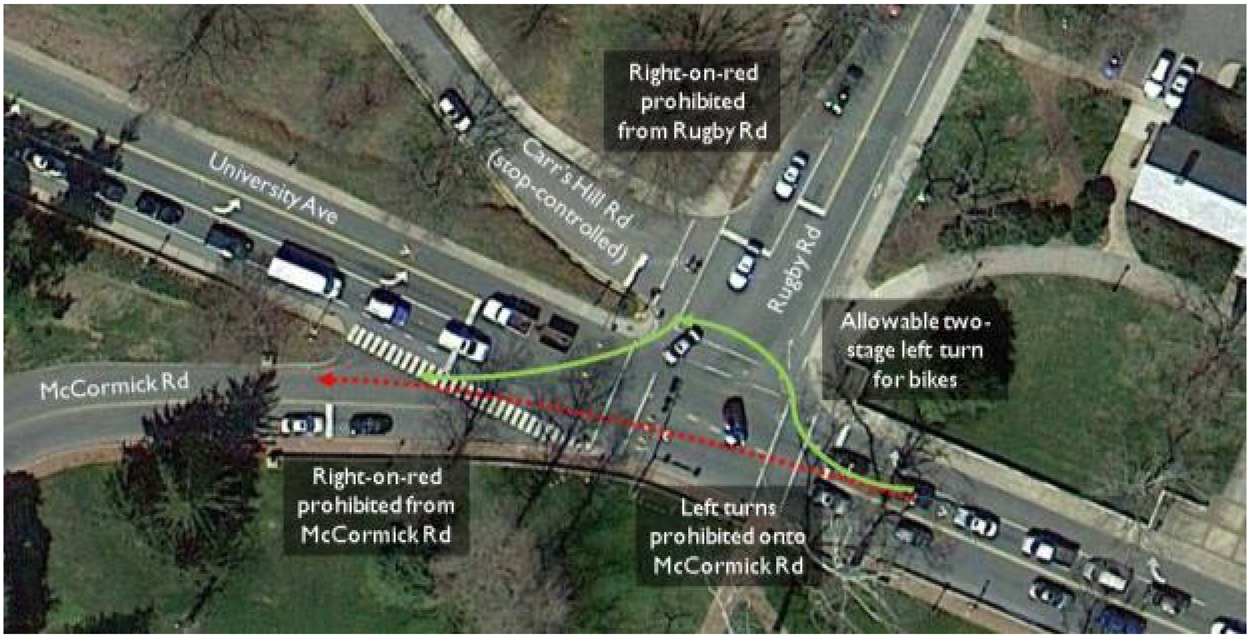

Figure 4. Intersection Aerial View Before Experiment. Google Maps imagery © 2013 Commonwealth of Virginia, DigitalGlobe, USDA Farm Service Agency.

Traffic counts from October 2012 showed that the primary bicycle movements were southbound from Rugby Road to McCormick Road in the morning and mid-day peak hours and the reverse (i.e., northbound) in the afternoon peak (W. Wuensch, unpublished data). Of bicyclists who made a turn (the primary movements were not considered turns), the westbound movement from University Avenue onto McCormick Road had the largest volume, although it was made using a variety of methods, including the illegal turn and the acceptable but unmarked two-stage turn. In the afternoon peak hour, which was the only time when significant queuing was observed, the intersection served 1,279 vehicles, 43 of which were trucks and 67 of which were bicycles, along with 465 pedestrians. Daily traffic volume estimates from 2011 (Virginia Department of Transportation [VDOT], 2012) indicated that University Avenue served about 14,000 vehicles per day, with Rugby Road at about 5,600 vehicles per day. McCormick Road, with an access control gate about ¼ mile from the intersection that was active from 7:30 a.m. to 4:30 p.m. on weekdays to prevent unauthorized through traffic, had an estimate of about 3,600 vehicles per day.

The university was planning its U-Bike bike share program but had not yet launched it or finalized its station locations.

Reasons for Changes

The westbound left-turn prohibition existed for many years because of issues including visibility, the lack of a turn lane, and a desire to limit the number of automobiles entering the campus. For bicyclists, making the legal vehicular turn using the spur of McCormick Road to the west required out-of-direction travel, an uphill climb, and waiting to turn at a location with no left-turn pocket. Bicyclists expressed a desire to improve bicycle access through the intersection, and the city's bicycle and pedestrian safety committee identified the need to improve bicycle connections between downtown and the university (A.T. Poncy, unpublished data).

With a city ordinance prohibiting bicycling on city sidewalks and the university discouraging bicycling on its pedestrian paths, there was a desire to accommodate bicycle traffic on-street by formalizing the westbound two-stage left turn maneuver that was already used by some bicyclists. The intersection did not have a history of reported bicycle crashes in the 3 years before the experiment and did not have a particularly high rate of other crashes. The primary motivation for the changes was not crash reduction, although there was a desire to keep crashes low, but rather the need to improve accommodations for bicycle travel through the intersection in order to provide a connected network of on-road bicycle facilities and shared lanes suitable for bicycling.

New Pavement Markings

In August 2014, concurrent with a street resurfacing project, bike boxes were installed westbound and southbound, and two two-stage left-turn boxes were installed eastbound and westbound (Figure 5). With these changes, eastbound and westbound bicycle left turns were facilitated using turn boxes. Westbound, the turn box was the only legal way for bicyclists to make a left turn at the intersection; eastbound, bicyclists had the option of using the turn box or making the turn from the left-turn lane.

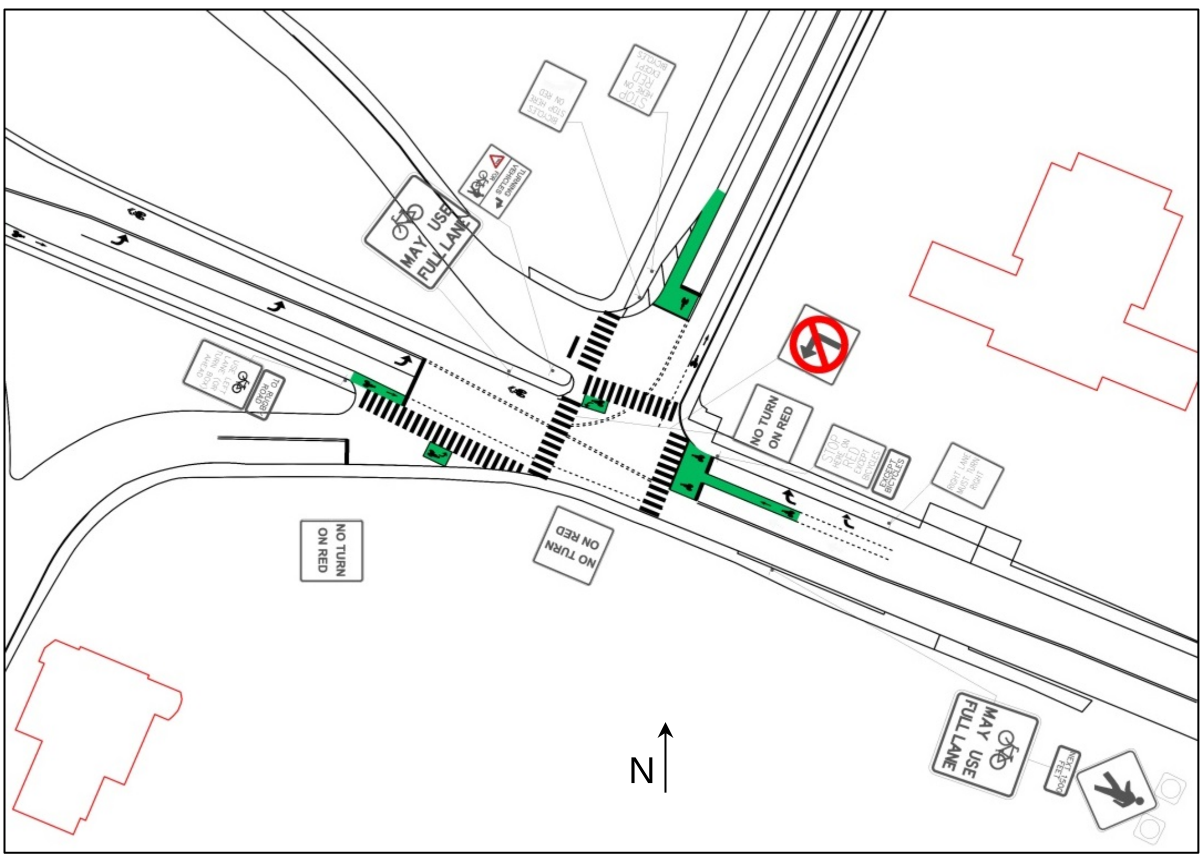

Figure 5. Intersection Improvements. Improvements as constructed included two bike boxes and two turn boxes along with striping and signage. Figure provided by the City of Charlottesville.

Other intersection changes included restriping; a new westbound ingress bike lane before the bike box; use of green-colored pavement for bike facilities; an additional westbound RTOR prohibition (required because of the bike box); and additional signs. In lieu of installing video detection so that signals would change for bicyclists waiting in the new boxes, the city changed the signal timing to a fixed-time pattern with automatic pedestrian “Walk” signals (this was part of a citywide change). The leading pedestrian interval for pedestrians crossing University Avenue was reduced to around 2 seconds when the fixed-time pattern was implemented.

PURPOSE AND SCOPE

The purpose of this study was to provide research assistance for experimental treatments to satisfy FHWA’s required experimentation process as outlined in the MUTCD (FHWA, 2012). This was accomplished through the provision of assistance to the City of Charlottesville and the documentation of lessons learned regarding how to deploy these treatments, which could be valuable to other Virginia localities seeking to accommodate bicycling.

VTRC’s role included research design, data collection and analysis, drafting of documents required under the experimentation process, and development of recommendations regarding the performance of the experimental treatments. Engineering design, public outreach efforts, and installation of experimental treatments were the responsibilities of other stakeholders (i.e., the city and the university) and were outside the scope of the study, although the researchers collaborated with stakeholders on these topics as needed. No evaluations of materials (e.g., durability of green pavement markings) were performed. The Appendix summarizes the outreach efforts.

The study addressed two questions:

1. What measurable changes occurred in bicycle traffic volumes, behavior of road users, and conflicts between road users after installation of experimental bicycle treatments?

2. What lessons can be learned as a result of this application of innovative bicycle treatments?

METHODS

The questions were addressed through the following tasks.

1. Conduct a literature review.
2. Develop a request for permission to experiment.
3. Perform a site review and collect before and after data.
4. Conduct a before-after analysis.
5. Develop recommendations.

Conducting the Literature Review

The literature review was limited to studies evaluating the performance of bike boxes and turn boxes. The initial search focused on studies of U.S. applications in relevant Transportation Research Board databases but identified relatively few and so was expanded to internet searches for English-language studies of similar treatments worldwide.

Developing the Request for Permission to Experiment

Because the pavement markings were experimental, a request for permission to experiment had to be submitted to FHWA by the City of Charlottesville, as the responsible agency. Developing the request was an iterative process involving VTRC, the city, and FHWA that included examining accepted evaluation methods for bicycle traffic control devices (Chrysler et al., 2011).

Reviewing the Site and Collecting Before and After Data

Reviewing the Site

Multiple site visits were conducted before and after the changes and during installation of the pavement markings. The purpose of these visits was to (1) document before and after conditions, (2) observe the work done by city crews during installation, (3) witness the operation of the intersection without and with the new pavement markings, and (4) meet with the data collection contractor to determine ideal camera placement.

Collecting Before and After Data

Video footage was collected to obtain automated multimodal traffic counts. Manual video reduction was performed to document the behavior of cyclists and motorists, including conflicts between road users. Three cameras were used: one on the west leg facing eastbound, one on the east leg facing westbound, and one on the stem facing southbound (Figure 6). Cameras were to be positioned in a way that video reviewers could confirm or deduce the signal phase at all times (i.e., it was necessary for cameras to capture some but not necessarily all signal faces). No data were available showing behavioral effects because of camera conspicuity; the cameras were attached to existing poles and were visible, but not overly conspicuous. A label with a contact telephone number was placed on each camera in case members of the public questioned the equipment's presence.

Processing by Miovision—which used computer recognition to classify moving objects by length as pedestrians, bicycles, cars, small trucks, and heavy trucks—provided traffic counts, but in order to classify all bicycle-related traffic interactions at the intersection, reviewers needed to watch the footage of all three cameras for the same recorded period.

Figure 6. Camera Views Obtained

In total, 96 hours of video footage was manually reviewed to collect data on bicycle-related conflicts, motorist and bicyclist illegal RTOR behavior, motorist encroachment into bike boxes, bicyclist proper and improper use of bike boxes and turn boxes (after only), and other traffic infractions (i.e., legal violations such as making illegal turns and disregarding traffic signals) by motorists and bicyclists.

Although definitive guidance did not exist on the minimum required length of short duration counts, the prevailing practice was 2 consecutive hours on a single day (FHWA, 2016d). The researchers wanted to collect more than this in order to capture full-day travel patterns on multiple non-consecutive days before and after the changes, but budget constraints prevented collection of the ideal 7 full days of data in each case. Similarly, although collecting similar data at control sites would have been ideal, the available funds were allocated to data collection at the study intersection only.

The before footage was collected on 3 non-consecutive weekdays in March and April 2014. The after footage was collected after the August 2014 installation on 5 non-consecutive weekdays in September and October 2014 and March and April 2015. The after dates were chosen to document conditions immediately after the change and after several weeks, 2 months, 7 months, and 8 months. All data collection was performed during the university's academic year on days with regular class schedules. Collection days were adjusted to capture both primary class schedule patterns: the Monday/Wednesday class schedule pattern (primarily 50-minute class periods starting at the top of each hour), and the Tuesday/Thursday pattern (primarily 75-minute class periods starting every 90 minutes).

On the first day of data collection, a 24-hour recording allowed researchers to select the best 12 hours to record for future days based on non-motorized traffic patterns (FHWA, 2016d). Although nighttime darkness can be an issue for 24-hour video-based data collection, streetlights provided sufficient nighttime illumination at this intersection. The time period of 7:30 a.m. to 7:30 p.m. was chosen based on activity levels from this initial count; that 12-hour period represented 75%, 83%, and 71% of the 24-hour bicycle, pedestrian, and automobile volumes, respectively. After the changes, another 24-hour recording allowed researchers to confirm that this 12-hour period was still usable. For the 2 days when 24 hours of video were collected, only the periods of 7:30 a.m. to 7:30 p.m. were used for analysis.

Weather conditions can affect bicycling volumes (Nosal et al., 2015). To maximize comparability of the data, five of the eight originally planned recording dates were delayed until days without substantial forecasts of rain or snow, with minimal plowed snow remaining in the roadway, and with forecast high temperatures above 50 degrees Fahrenheit. Fridays and weekends were avoided to ensure comparability with typical weekday travel levels; although Mondays were not explicitly avoided, it was inconvenient for cameras to be set up on weekends in order to record on a Monday.

Data included the following:

1. *Peak-hour volumes for motor vehicles, bicycles, and pedestrians.*

2. *Turn movement counts for motor vehicles and bicycles.*

3. *Legal violations (traffic infractions) by motorists and bicyclists, classified by the status of the traffic signal for their approach.* These included motorists/bicyclists making an illegal left turn, motorists making RTORs where prohibited, bicyclists violating a red signal indication (including with the pedestrian signal if the traffic signal was still red), bicyclists riding on the sidewalk, wrong-way bicycling, bicyclists using a bike box or turn box but not as intended, etc. To be clear, a motor vehicle or bicyclist counted in Items 1 and 2 would have been counted again here (and could have been counted in Item 4 also).

4. *Observed conflicts involving bicyclists, classified by the status of the traffic signal for their approach.* Conflicts not involving bicycles were not tallied.

5. *After only.* Bicyclist use of bike boxes and turn boxes, i.e., the number of cyclists using these pavement markings properly and improperly.

Items 1 and 2 were provided through a contractor using the Miovision traffic data collection system. Research assistants manually reviewed the video footage to create movement logs for Items 3 through 5. Each hour of video footage was reviewed independently by at least two different reviewers.

Conducting the Before-After Analysis

Because the intersection had no reported bicycle crashes for the 3 years before the changes, the scope of the before-after study did not include a crash analysis. Instead, the surrogate measure of bicycle-related conflicts was used, with conflicts coded as minor or major. Appropriate statistical tools (the matched-pairs t-test and the Wilcoxon matched-pairs signed-rank test) were used to examine changes in performance before the treatment and at intervals after the change.

Verification of Automated Volume Data

Miovision's automated algorithms used computer recognition to classify moving objects by length as pedestrians, bicycles, cars, small trucks, and heavy trucks. To check the accuracy of the automatic count, research assistants manually counted bicycles from the video collected for the first count day, and the results were compared to the automated bicycle count results.

Conflict Nomenclature

The classification of bicycle-related conflicts followed the two-tiered classification used in previous related studies (Allen et al., 2005; Atkins Services, 2005; Dill et al., 2011; Hunter, 2000) but with revised nomenclature to improve clarity. Conflicts that might have been described in other studies as "major" were termed "observed near misses" and defined as emergency/panic braking (by bicyclists) or stopping short to avoid a collision (by pedestrians)—often when both parties seemed unaware of each other until the last second. Conflicts that might have been described as "minor" in other studies were termed "forced yielding to avoid a near miss" and defined as controlled precautionary braking or change of direction, typically by the road user with the right of way and often forced by a road user without the right of way.

Although some have argued that the term "near miss" is a misnomer (i.e., what is actually occurring is a near-collision), its meaning is generally understood, and it has been used in other studies. The Near Miss Project quantified non-injury incidents involving bicyclists in the United Kingdom (Aldred and Crosweller, 2015). Examples included being blocked, close passes, vehicles crossing cyclists' paths, being driven at, and right hooks (a right-turning automobile "hooking" a bicyclist to its right). Rates were higher during the morning peak, for cyclists who traveled slower and for women. Cyclists judged most incidents as preventable if other road users had behaved differently, such as being more aware of others. The study stated that near misses, as a measure of experienced risk, comprise a missing link between perceived cycling risk and objective risk as quantified only by injury and/or death rates. A study in San Francisco found that near misses were more strongly associated with perceived traffic risk than were actual collisions (Sanders, 2015).

Conflicts and traffic infractions were classified by the status of the traffic signal controlling the approach: red, the first 5 seconds of green, and the rest of the green phase plus the yellow phase. This was done because some intersections with installations of bike boxes have experienced increases in right-hook crashes, in which a right-turning automobile collides with a through bicyclist (passing to the right of the automobile) mid-turn, during the part of the green phase after the first few seconds, i.e., when automobiles and bicyclists are moving at full speed (Hurwitz et al., 2015).

Bike box encroachment by motorists was defined as an automobile stopped on a red signal with (at least) its front wheels in the bike box or with its right wheels in the bike lane. Stopping in the bike box but not in the crosswalk was counted as only bike box encroachment; vehicles blocking both the bike box and the crosswalk were counted in the bike box encroachment category and again in the "motorist other" category to reflect the additional violation of blocking the crosswalk.

Each violation, not each violator, was counted. For instance, if a bicyclist rode on the sidewalk and went against a red signal, it was counted as two separate violations. Counts, conflicts, and traffic infractions were recorded in 15-minute bins.

Data Reduction and Observational Variability

A total of eight video reviewers received training on how to classify observations. A bicycle was defined as relying on human-generated power, although it was recognized that electric-assist bicycles have a motor. Unicycles, scooters, skateboards, roller skates, wheelchairs, or other human-powered forms of transportation were not included in the definition of a bicycle. Mopeds were to be classified as automobiles.

Two reviewers performed data reduction independently for each hour of video in order to allow for comparison to identify any influence of subjectivity. Using VLC Media Player software, reviewers were able to view videos in a rapid playback mode, stopping as needed to record behaviors. Conflicts and traffic infractions were recorded by intersection approach in 15-minute bins using Excel, resulting in a total of 788 spreadsheet tables.

There were seven combinations of reviewer pairs for the 96 hours of video analyzed, with different individuals reviewing before and after footage. Despite the training, some subjectivity remained in classifying conflicts, as did differences between reviewers in terms of what traffic infractions they noticed. Many noticeable behaviors, such as illegal right turns, motorist encroachment into bike boxes, and appropriate use of bike boxes by bicyclists, were quantifiable and objective. However, the bicycle/pedestrian and bicycle/motorist conflicts largely depended on reviewers' subjective judgment, a situation also noted by Monsere et al. (2014). In other words, if two reviewers watched the same 1-hour video and one recorded two near miss conflicts and no forced yielding conflicts but the other recorded no near miss conflicts and five forced yielding conflicts, there was a need to reconcile the two sets of observations.

After reviews were complete, a researcher reviewed all the recorded conflicts to investigate variability between reviewers. Although some subjectivity because of this final review could remain, the method was intended to address the observational variability. A one-sample paired t-test was then used to determine if the conflict observations of the two initial reviewers were different at a 95% confidence level for each 15-minute time interval. The one-sample paired t-test was used again to compare each reviewer's conflict observations for that day with the results of the researcher's review. If evidence of reviewer variability was found, the following steps were taken for analysis purposes:

1. Observations of the two reviewers for legal violations were averaged.

2. For conflicts, the average of the initial reviewers' observations was used where t-test results indicated the two reviewers' data were not significantly different. Otherwise, if one initial reviewer's observations were not different from the third reviewer's observations, those two sets of observations were averaged. If both initial reviews were different from the third review, the third review results alone were used.

Other than subjective classification of conflicts, reviewers encountered several other challenges. These are described here along with methods that were used to address them, when such methods were available.

Time Bin Classification

Sometimes it was difficult to determine which 15-minute bin to use for classification of a behavior or maneuver that occurred at more than a single instant in time. For instance, if a motorist stopped at the stop bar near the end of a 15-minute interval but then slowly encroached into a bike box, the end of the maneuver could be in the next 15-minute bin.

In those circumstances, reviewers recorded the behavior as occurring when the illegal maneuver began. For instance, in the example of motorist encroachment into the bike box, reviewers would classify the behavior into a 15-minute bin based on the time that the automobile's front wheels first encroached into the bike box.

Location Classification

Data were recorded by intersection leg, but assigning a behavior to a particular intersection leg was not always clear. For instance, if a bicyclist rode westbound on the sidewalk on the south side of University Avenue and continued on the same sidewalk onto McCormick Road, sidewalk bicycling occurred on two legs of the intersection. Under this circumstance, reviewers would record the behavior (in this case, in the "bicyclist other" category) and would classify it as occurring only on the east side of University Avenue, the leg where the behavior was first observed.

Inconsistent Camera Timestamps

There were differences in timestamps among the three cameras for some counts, which led to problems classifying behaviors into time bins. Days 1, 3, 5, and 8 had cameras synced within 30 seconds of each other, but Days 2 and 6 had discrepancies exceeding 1 minute. When timestamps did not match, if one reviewer classified events into 15-minute intervals based on Camera 1's timestamp and a second reviewer did so based on Camera 2's timestamp, the reviewers could have classified the same event into two time bins rather than into the same bin. One attempt to overcome this was by comparing results of an analysis of 15-minute bins with one of aggregated 30-minute bins.

Suboptimal Camera Views

Video cameras were not permanently installed at the intersection but rather were installed before each count and removed afterwards. This installation was inconsistent, and as a result, some counts had suboptimal viewing angles, which affected the process of manual review and classification. The following counts had limited viewing angles:

- *Day 2:* The camera installed on the east leg of University Avenue was partially obscured by condensation or dirt on the lens, and the camera installed on Rugby Road was not angled to provide a clear view of vehicles coming from the east side of University Avenue.

- *Day 4:* The camera installed on the east leg of University Avenue did not cover the full bike box on this leg.

- *Day 7:* All three cameras were aimed too low. The camera installed on Rugby Road did not cover the bike box on this leg; the cameras installed on the east and west sides of University Avenue were focused on the near side and could not show the activity on other legs. Traffic signals were not visible.

Unusual Conditions

One instance of unusual traffic conditions was encountered. During Day 4, around 8:30 a.m., normal traffic operations were interrupted when construction equipment struck a gas line within a block of the study intersection. Buses were rerouted for 30 to 40 minutes, and one leg of the intersection was closed to traffic for about 5 minutes.

Camera failures also affected two count dates. During Day 6, Camera 3 recorded only until 6 p.m., so footage existed from only two cameras for the last 90 minutes of this count. During Day 8, all cameras cut off 15 minutes early, so no data were available for the 7:15 to 7:30 p.m. time interval.

Data Preparation

Data recorded in Excel files were merged and converted, by SPSS codes developed for this study, into data suitable for statistical analysis, resulting in a single file with 77 variables containing raw data values, called X-variables (Table 1). Two versions of some X-variables were created to distinguish two reviewers having independently recorded data from the same video; these were later averaged. In order to answer questions regarding before-after changes, 33 research question variables, called Q-variables, were created based on the 77 X-variables (Table 2).

Table 1. X-Variable Descriptions

Variable		Description	
Turning Movement Counts (Automatically Collected)			
Auto	*Bike*	*Turning Movement*	
X01	X13	Right from Rugby to Carr’s Hill	
X02	X14	Right from Rugby or Carr’s Hill to University	
X03	X15	Thru from Rugby or Carr’s Hill to McCormick	
X04	X16	Left from Rugby or Carr’s Hill to University	
X05	X17	Right from McCormick to University	
X06	X18	Thru from McCormick to Rugby or Carr’s Hill	
X07	X19	Left from McCormick to University	
X08	X20	Right from University to Rugby or Carr’s Hill	
X09	X21	Thru University WB	
X10	X22	Left from University to McCormick	
X11	X23	Thru University EB	
X12	X24	Left from University to Rugby or Carr’s Hill	
Crosswalk Volumes (Automatically Collected)			
Bike	*Ped*	*Crossing*	
X25	X30	Rugby	
X26	X31	McCormick	
X27	X32	University, east leg	
X28	X33	University, west leg	
X29	X34	Carr’s Hill	
Conflicts (Manually Tallied)			
Forced Yield	*Near Miss*	*Approach: Signal Phase*	
X35	X38	Rugby: Red	
X36	X39	Rugby: Initial Green	
X37	X40	Rugby: Rest of Green and Yellow	
X41	X42	McCormick (all signal phases)	
X43	X46	University WB: Red	
X44	X47	University WB: Initial Green	
X45	X48	University WB: Rest of Green and Yellow	
X49	X50	University EB (all signal phases)	
Legal Violations (Traffic Infractions)			
Motorists	*Bicyclists*	*Approach*	*Violation*
X51	X53	Rugby	NTOR violation
X52	X54	Rugby	Other
X55	X57	McCormick	NTOR violation
X56	X58	McCormick	Other
X59	X62	University WB	NTOR violation
X60	X63	University WB	No Left Turn violation
X61	X64	University WB	Other
X65	X66	University EB	Other

Variable	Description
Bike Boxes: Use and Misuse	
Variable	*Measure*
X67	Rugby: Auto stopped with front wheels beyond stop bar (before) or encroachment into bike box (after)
X68	Rugby: Proper bike box use (after only)
X69	Rugby: Improper bike box use or failure to use (after only)
X70	University WB: Auto stopped with front wheels beyond stop bar (before) or encroachment into bike box (after)
X71	University WB: Proper bike box use (after only)
X72	University WB: Improper bike box use or failure to use (after only)
Turn Boxes: Use and Misuse	
Variable	*Measure*
X73	Turn box on Rugby (from University to McCormick): Bike two-stage left turn (before) or proper turn box use (after)
X74	Turn box on Rugby (from University to McCormick): Improper bike use (after only)
X75	Turn box on McCormick (from University to Rugby): Encroachment by auto into turn box (after only)
X76	Turn box on McCormick (from University to Rugby): Proper bike use (after only)
X77	Turn box on McCormick (from University to Rugby): Improper bike use (after)

Auto = automobile; WB = westbound; EB = eastbound; NTOR = No Turn on Red.

Table 2. Q-Variable Descriptions

Variable	Description	Definition
Q1	Motorist NTOR compliance rate on Rugby	(X01 + X02 - X51) / (X01 + X02)
Q2	Motorist NTOR compliance rate on McCormick	(X05 – X55) / X05
Q3	Motorist NTOR compliance rate on University WB	(X08 – X59) / X08
Q4	Proper use of Rugby bike box per approaching bicyclist[a]	X68 / (X13 + X14 + X15 + X16)
Q5	Proper use of University WB bike box per approaching bicyclist[a]	X71 / (X20 + X21 + X22)
Q6	Proper use of University WB turn box per turning bicyclist[a]	X73 / X22
Q7	Proper use of University EB[c] turn box per turning bicyclist[a]	X76 / X24
Q8	Motorist encroachment rate into Rugby bike box	X67 / (X01 + X02 + X03 + X04)
Q9	Motorist encroachment rate into McCormick turn box	X75 / (X05 + X06 + X07)
Q10	Motorist encroachment rate into University WB bike box	X70 / (X08 + X09 + X10)
Q11	Rate of other bicyclist infractions/bicyclist approaching on Rugby[a]	X54 / (X13 +X14 + X15 + X16)
Q12	Rate of other bicyclist infractions/bicyclist approaching on McCormick[a]	X58 / (X17 + X18 + X19)
Q13	Rate of other bicyclist infractions/bicyclist approaching on University WB[a]	X64 / (X20 + X21 + X22)
Q14	Rate of other bicyclist infractions/bicyclist approaching on University EB[a]	X66 / (X23 + X24)
Q15	Total rate of other bicyclist infractions/intersection bicyclist	(X54 + X58 + X64 + X66) / ∑(X13 through X29)
Q16	Rate of other motorist infractions/auto approaching on Rugby	X52 / (X01 + X02 + X03 + X04)
Q17	Rate of other motorist infractions/auto approaching on McCormick	X56 / (X05 + X06 + X07)
Q18	Rate of other motorist infractions/auto approaching on University WB	X61 / (X08 + X09 + X10)
Q19	Rate of other motorist infractions/auto approaching on University EB	X65 / (X11 + X12)
Q20	Total rate of other motorist infractions/intersection auto	(X52 + X56 + X61 + X65) / ∑(X01 through X12)
Q21	Improper use rate of Rugby bike box/ approaching bicyclist[a]	X69 / (X13 +X14 + X15 + X16)
Q22	Improper use rate of University WB bike box/approaching bicyclist[a]	X72 / (X20 + X21 + X22)
Q23	Improper use rate of University WB turn box/turning bicyclist[a]	X74 / X22
Q24	Improper use rate of University EB turn box/turning bicyclist[a]	X77 / X24
Q25	Illegal motorist left turn rate from University WB onto McCormick/ approach motorist	X60 / (X08 + X09 + X10)
Q26	Illegal bicyclist left turn rate from University WB onto McCormick/approach bicyclist[a]	X63 / (X20 + X21 + X22)
Q30	Conflicts/auto	(∑(X35, X36, X37, X41, X43, X44, X45, X49) + 2 * ∑(X38, X39, X40, X42, X46, X47, X48, X50)) / ∑(X01 through X12)
Q31	Conflicts/bicycle	(∑(X35, X36, X37, X41, X43, X44, X45, X49) + 2 * ∑(X38, X39, X40, X42, X46, X47, X48, X50)) / ∑(X13 through X29)
Q32	Conflicts/sum of all road users	(∑(X35, X36, X37, X41, X43, X44, X45, X49) + 2 * ∑(X38, X39, X40, X42, X46, X47, X48, X50)) / ∑(X01 through X34)
Q33	Conflicts during "rest of green and yellow" of Rugby signal phase/sum of through bicyclists and right-turning motorists on Rugby[a]	(X37 + 2 * X40) / (X15 + X01 + X02)
Q34	Conflicts during "rest of green and yellow" of Rugby signal phase/ sum of through bicyclists and right-turning motorists on University WB[a]	(X45 + 2 * X48) / (X21 + X08)
Q35	Conflicts during "rest of green and yellow" of Rugby signal phase/ approach bicyclist and motorist on Rugby	(X37 + 2 * X40) / (X15 + X16 + X01 + X02 + X03)

Q36	Conflicts during "rest of green and yellow" Rugby signal phase/ approach bicyclist and motorist on University WB	(X45 + 2 * X48) / (X21 + X22 + X08 + X09)

NTOR = No Turn on Red; WB = westbound; EB = eastbound

[a] Bicyclists who crossed as pedestrians, i.e., in crosswalks rather than in the road, are excluded.

First, aggregating for the before and after periods separately was performed for each X-variable. Second, Q-variables were created by defining specific questions to be examined in terms of a combination of the 77 X-variables. Third, three additional datasets were generated from the prepared dataset by aggregating by 30-minute interval and taking log-transformations of the 15- and 30-minute intervals, resulting in a total of four datasets for analysis: (1) 15-minute dataset, (2) 30-minute dataset, (3) 15-minute log-transformed dataset, and (4) 30-minute log-transformed dataset. The log-transformed Q-variables were created and analyzed because some of the variables with skewed distributions appeared to follow the normal distribution after the transformation. The appropriate statistical test to apply depends on the distributional shape of the variable; e.g., when a variable follows a normal distribution, the t-test is an appropriate hypothesis test. It should be noted that a small value (i.e., 0.01) was added to each variable before the log-transformation to prevent the error that results from an attempted calculation of the log of zero (an undefined value).

Statistical Analysis

Descriptive statistics were calculated, and scatter plots and histograms were created to get a sense of the data and to propose appropriate statistical techniques for analysis. To test statistically for changes after the installation of the bike boxes, two hypothesis tests were selected: the matched-pairs t-test and the Wilcoxon matched-pairs signed-rank test. The t-test is appropriate for a variable showing a normal distribution, and the Wilcoxon signed-rank test is appropriate for a variable showing a skewed distribution (as well as for a variable showing a normal distribution). Both are to test the following hypotheses:

> H_0: Central tendency of the difference between the before and after periods in Q-variable = 0
>
> H1: Central tendency of the difference between the before and after periods in Q-variable $\neq 0$

The measure of central tendency is a mean for a t-test and a median for a Wilcoxon test. If a test result rejects H_0, the before and after periods are different in the corresponding Q-variable. If not, there is not enough evidence to conclude that the before and after periods are different.

Paired versions of the two tests, the matched-pairs t-test and Wilcoxon matched-pairs signed-rank test, were employed to leverage the data structure in terms of data collection interval (e.g., 15-minute interval). Specifically, all the data were collected for the same 12 hours from 7:30 a.m. to 7:30 p.m. and recorded by 15-minute interval. Thus, data for a given 15-minute interval (e.g., 7:30 a.m. to 7:45 a.m.) before the installation correspond to data for the same 15-minute interval after the installation. In other words, the before and after data are "paired" or "matched" by the interval. This is also true for the 30-minute data created by aggregating two consecutive 15-minute intervals.

A matched-pairs test is most often used for a before-after comparison of the same entity (e.g., person or site) and increases the statistical power to detect a change or difference between the two comparing groups and/or to reduce the effects of confounding variables. An example of a confounding variable in this study would be the time of day influencing behaviors of all road users—that is, behaviors of bicyclists and/or motorists at the intersection during morning hours (when most road users are likely trying to get to class or work on time) would possibly be different from those in the afternoon and evening hours. If this is true, the time of day would be a confounding variable, potentially compromising test results unless its effects are statistically mitigated. By comparing the data by the same time interval, such a confounding effect can be removed or substantially mitigated.

Re-Review Methods

After the main analysis, a subset of data was re-reviewed by one researcher in order to address, via expert review, continued concerns about inter-rater reliability from the initial data reduction. For the 3 before days and 3 of the 5 after days, 1 hour in the morning (9:15 to 10:15 a.m.) and 1 hour in the afternoon (4:45 to 5:45 p.m.) were re-reviewed, focusing on 33 variables of interest. The two after counts that were excluded (Days 4 and 7) had different weather conditions than the other counts and/or suboptimal camera angles. The times were chosen because they were 1-hour periods with bicycle volumes of at least 40.

Several methods were used to compare this re-reviewed dataset to the original review results. A confusion matrix required transforming the data from quantitative to categorical (yes/no) because of the need to have symmetrical matrices. That is, zeros became “no” and nonzero values became “yes.” Any variables with more than 80% zero/“no” were discarded / not used; in effect, those events were so rare that this method could not analyze them. A correlation analysis produced R-values that were low, medium, or high. A t-test based on the difference between the original review results and the re-reviewed dataset determined whether the difference in means was statistically nonzero, meaning that the two datasets were different. A Bland-Altman plot was produced to examine differences and averages for qualitative data agreement, with regression performed following the plot to investigate the degree of data agreement. Finally, Cohen’s kappa for inter-rater reliability was calculated. These methods were applied on video review X-variables, and a different combination of the methods was employed on each variable based on the characteristics of the variable.

Q-variables that involved X-variables with the re-reviewed dataset that were relatively comparable to the original review results were deemed more conclusive than Q-variables involving other X-variables.

Assessment of Potential for Right-Hook Crashes

A bike box with an ingress bike lane that is to the right of a shared through/right general purpose lane can set up the possibility of right hooks occurring, especially after the initial green startup of the approach signal. In such cases, bicyclists moving at a relatively high speed can overtake right-turning cars and trucks on the right without drivers seeing them, with a turning automobile hooking a bicyclist.

The Rugby Road approach has a slight downhill grade, which is the condition seen in other locations with a combination of bike boxes and right-hook crashes. The University Avenue westbound approach also features a bike box, but its ingress bike lane is to the left of a dedicated general purpose right-turn lane. Therefore, an assessment of the potential for right-hook crashes was obtained by comparing conflicts during the “rest of green and yellow” part of the approach signal phase on these two approaches (Q33 through Q36 from Table 2).

For each approach, observed conflicts (manually tallied) were divided by the sum of the approach’s through bicyclists and right-turning motorists (from automatic counts) to estimate a conflict rate. For this type of conflict, the denominator estimates total exposure, which is represented by the sum of turning vehicles that would cross the intended path of the cyclist and through bicyclists (Monsere et al., 2014). Bicyclists crossing as pedestrians were not included.

Developing Recommendations

Semi-annual progress reports were developed and provided to FHWA and stakeholders for the duration of the study. Recommendations regarding the performance of the experimental treatments were developed based on the researchers’ understanding of the data analysis as informed by the literature, along with feedback from the study’s technical review panel.

RESULTS AND DISCUSSION

Literature Review

A full literature review was not included in the scope of the study, but an overview of the literature related to bike boxes and turn boxes is included here.

Bike Boxes

Table 3 summarizes key findings from relevant literature on bike boxes. Nine previous studies, including four from the United States, were found that examined the effects of bike boxes. They presented the effects on cars and cyclists of the marking of ASLs at 7 intersections in Christchurch, New Zealand (Newman, 2002); the capacity implications of four ASLs in the United Kingdom (Wall et al., 2003); a left-side to right-side bike box installed in Eugene, Oregon (Hunter, 2000); a before-after study of 2 signalized intersections where bike boxes were installed in Austin, Texas (Loskorn et al., 2010); a before-after study of 10 signalized intersections where bike boxes were installed and 2 control intersections (Dill et al., 2011); safety effects of bike boxes at 11 intersections in Portland, Oregon (Farley, 2014); and a comparison of 6 intersections in Toronto, 2 of which had bike boxes (Casello et al., 2017).

Lindsey et al. (2017) provided a comparative literature summary for bike boxes and many other types of bicycle treatments.

Table 3. Key Findings of Relevant Literature on Bike Boxes

Citation	Region: Focus	Methods	Key Findings
Hunter, 2000	Eugene, OR: Left-side to right-side bike box	Video and oral survey	22% of bicyclists who approached in the left-side bike lane and then crossed to the right side of the street used the bike box; the rate of conflicts rose slightly, from 1.3 to 1.5 conflicts per 100 entering bicyclists
Newman, 2002	Christchurch, NZ: Advanced cycle lanes and bike boxes	Video, questionnaires, and crash data	All-vehicle and bike crash rates at the treatment locations dropped more than for the control group.
Wall et al., 2003	Guildford, U.K.: Capacity of bike boxes	Video and questionnaires	The proportion of bicyclists using bike boxes correctly ranged from 0% to 40% at 4 study sites.
Allen et al., 2005	London: Advanced stop lines	Video	38% correctly used bike boxes; 36% of cyclists experienced encroachment into bike boxes.
Atkins Services, 2005	London: Advanced stop lines	Video and questionnaires	24% correctly used bike boxes; 46% to 91% of motorists encroached into the bike boxes in 10 sites.
Loskorn et al., 2010	Austin, TX: Bike boxes	Video	15%-25% of bicyclists correctly used bike boxes; positive changes in bicyclist behavior were observed, although 1 site had an increase in the percentage of bicyclists running a red light.
Dill et al., 2011	Portland, OR: Bike boxes	Video and questionnaires	73% of bicyclists correctly used bike boxes; 26.8% of motorists encroached into the bike boxes.
Casello et al., 2017	Toronto: Left-turn behavior of cyclists at different types of intersections	Video	The presence of bike boxes increased the likelihood that left turns would be legal and consistent with intended behavior; a bike box intersection had 90% legal compliance by bicyclists and 65% facility compliance (making the turn as intended).
Farley, 2014	Portland, OR: Bike boxes	Video	The sample size of observed conflicts was insufficient to allow statistically significant conclusions.

Transport for London sponsored two studies on ASLs in London. These studies evaluated the behavior of road users at 12 intersections after the installation of ASLs and at 2 control intersections (Allen et al., 2005) and evaluated three variations of ASLs at 10 intersections and 2 control sites (Atkins Services, 2005).

Because bike crashes are relatively infrequent (Elvik and Mysen, 1999), two of the four studies that used crash data did not find significant effects of bike boxes on crashes (Allen et al., 2005; Farley, 2014). Another study found that all-vehicle and bike crash rates dropped more than those for the control groups generally, with a few exceptions (Newman, 2002).

Eight studies examined whether cyclists were using bike boxes correctly (Allen et al., 2005; Atkins Services, 2005; Casello et al., 2017; Dill et al., 2011; Hunter, 2000; Loskorn et al., 2010; Newman, 2002; Wall et al., 2003). The results were highly inconsistent, ranging from 11% to almost 100% correct. Some reasons may be differing definitions of correct or appropriate use by researchers and differing levels of public familiarity with bike box markings. Another reason may be the differing signal configurations in different situations. For instance, the intersections in one study included a bicycle signal phase (Wall et al., 2003), which was not provided in most other study sites. Further, Casello et al. (2017) found that an advanced green signal for left-turning traffic was necessary to retain benefits related to left-turn movements without vehicular conflicts.

Eight studies used video surveillance or questionnaires to evaluate the effects of bike boxes (Allen et al., 2005; Atkins Services, 2005; Casello et al., 2017; Dill et al., 2011; Farley, 2014; Hunter, 2000; Loskorn et al., 2010; Newman, 2002). One documented encroachment by motorists in the bike box area only when at least one cyclist was in the box and observed that 36% of cyclists experienced encroachment (Allen et al., 2005), and another recorded all motorist encroachments and found that 16% of motorists encroached into the reserved area (Hunter, 2000). Another found that the percentage of no encroachment or slight encroachment by motorists ranged from 9% to 57% in the study's 10 sites (Atkins Services, 2005). Dill et al. (2011) found that 26.8% of the vehicles arriving on a red signal encroached into the bike boxes. Casello et al. (2017) did not evaluate motorist encroachment but looked at bicyclists' rule compliance (legal left-turn movements) and facility compliance (left-turn movements consistent with the infrastructure).

Five studies categorized conflicts by severity level (Allen et al., 2005; Atkins Services, 2005; Dill et al., 2011; Farley, 2014; Hunter, 2000). The conflicts were usually coded as major/serious and minor, except that Atkins Services rated the conflicts as major, minor, or discomfort and Farley used an expert panel to rate conflicts as major, substantial, or minor. Four studies found that the incidence of conflicts was too low to illustrate any significant results (Allen et al., 2005; Atkins Services, 2005; Farley, 2014; Hunter, 2000), and the fifth found that conflicts dropped by 31% after the installation of the bike boxes (Dill et al., 2011).

Turn Boxes

Table 4 summarizes key findings from relevant literature on turn boxes. Several studies examined bicyclists' left-turning behavior at intersections, although no published studies were found on the safety of U.S. turn box installations. Fehr & Peers (2018) reached the same conclusion when researching the safety efficacy of various bicycle treatments; although the authors found enough studies on bike boxes to quantify the benefits of that treatment, they found none for turn boxes, which were given a low level of confidence in terms of safety efficacy.

One study examined the effects of left-turn waiting areas on bicyclist and motorist behaviors at signalized intersections in China (Liang et al., 2015). The study focused on the influence of the waiting area on bicyclists' choice of waiting location and on motor vehicles' traveling speed, but it did not evaluate the safety effect of the design. Another study presented a discrete choice model to predict the path on which bicyclists turned left at signalized intersections in Munich, Germany (Amini et al., 2016).

Chen and Shao (2014) evaluated the operational impacts of a two-stage bicycle left turn vs. a diagonal bicycle left turn (a direct left turn from a right-side bike lane) and found that the two-stage left turn could increase capacity for through automobiles but did not affect capacity for right-turning automobiles. No marked turn boxes or bike boxes were included. Furth and Wang (2015) developed a numerical method for calculating multistage pedestrian delay and two-stage left-turn delay. The model indicated that by providing bi-directional bike crossings, delay to bicyclists caused by the two-stage left turn could be reduced.

Table 4. Key Findings of Relevant Literature on Turn Boxes

Citation	Region: Focus	Methods	Key Findings
Chen and Shao, 2014	Beijing: Two-stage bicycle left turns	Video observation	Two-stage left turns could increase capacity for through automobiles but did not affect capacity for right-turning automobiles.
Furth and Wang, 2015	Boston: Pedestrian delay and two-stage left-turn delay	Delay modeling	By providing a single-stage bike crossing signal phase, delay to bicyclists caused by the two-stage left turn was reduced by 95 seconds in one example.
Liang et al., 2015	Nanjing, China: Turn boxes	Video	87.5% to 96.9% of left-turning bicyclists correctly used turn boxes.
Amini et al., 2016	Munich: Modeling of left-turning path selection	Video observation and choice modeling	A choice model was presented to predict the path on which left-turning bicyclists travel through a signalized intersection given several factors of the intersection.
J. Parks, unpublished data	San Francisco: Turn boxes	Video	The proportions of bicyclists using turn boxes to make a two-stage left turn ranged from 32% to 51% except in 1 location where only 1% used turn boxes.
Casello et al., 2017	Toronto: Left-turn behavior of cyclists at different types of intersections	Video	The presence of two-phase turn facilities increased the likelihood that left turns would be legal and consistent with intended behavior; a turn box intersection had 70% legal compliance by bicyclists and 54% facility compliance (making the turn as intended).

In San Francisco, a before-after study evaluated the proportion of bicyclists using four two-stage turn boxes along with bicyclists' signal compliance (J. Parks, unpublished data). The proportions of all left-turning bicyclists using turn boxes to make a two-stage left turn ranged from 32% to 51%, except in one intersection where the proportion was 1%. At the intersection where before-after data were available, the proportion of bicyclists making two-stage left turns dropped from 70% in the before period to 59% in the after period; 51% of all left-turning bicyclists were within or on the edge of the turn boxes. The proportion of bicyclists violating a traffic signal when making two-stage left turns ranged from 0% to 27%.

A study of six intersections in Toronto included one intersection with a two-phase left-turn box (Casello et al., 2017). The study concluded that the facility positively influenced legal and predictable behavior by bicyclists.

It appears that many U.S. cities with turn boxes have not completed studies on them. Two examples are Durango, Colorado (T. Humphrey, unpublished data), and Seattle, Washington (K. Rowe, unpublished data), both of which had several two-stage turn boxes but no before-after studies available at the time of this literature review. In 2011, the City of Canton, Ohio, proposed a two-stage turn box experiment, but no final report had been posted as of May 2018 (FHWA, 2016b).

The MUTCD stated that two-stage turn boxes at T-intersections could be implemented without experiments being conducted (FHWA, 2016a) or an interim approval being requested. One example in Ithaca, New York, provided bicyclists with space to make a jughandle turn.

Although some before-after data were available, this type of application of turn boxes at T-intersections may be instinctively more understandable than turn boxes at four-leg intersections and is not considered in this literature review.

Request for Permission to Experiment

A Request for Permission to Experiment was developed and submitted to FHWA in collaboration with the City of Charlottesville. After a process of discussion and revisions, a revised request was approved in March 2014.

Site Review and Data Collection

Site Review

Conditions prior to the changes were documented and are described in the "Introduction" section. During installation, several inconsistencies with the original design were observed. Some were errors, and others were the result of intentional field adjustments or funding limitations.

Eastbound on University Avenue approaching the intersection, an error that occurred when the conceptual drawings were converted to engineering drawings led to yellow center skip lines being placed incorrectly. This caused a perceived narrowing of the space for eastbound vehicles (16 feet for two lanes at the narrowest point). Observations suggest that this sometimes caused motorist encroachment into the eastbound dashed bike lane through the intersection.

The two-stage turn box for eastbound University Avenue was installed south of the crosswalk (Figure 7), which requires its intended users (eastbound bicyclists turning left) to cross the crosswalk. Its location may also visually connect the McCormick Road approach to the turn box, leading bicyclists approaching from McCormick Road to advance to the turn box rather than wait at the stop bar. This change was a result of the crosswalk not being adjusted as originally designed, which in turn was because of issues related to compliance with the Americans with Disabilities Act including topography, curb ramp locations, and drawbacks to pedestrians with visual impairments of an angled crosswalk alignment.

The crosswalk across McCormick Road (shown in Figure 7) did not receive pedestrian signal heads as originally intended. Their installation would have required permission from the university and possible impacts to historic resources.

Designs included narrowing of the throat of Carr's Hill Road via a curb extension. This was deferred because of issues with stormwater structures and a historic stone wall. This in turn led to an error or field adjustment when crews placed the crosswalk across Rugby Road farther south than designed, which in turn reduced the amount of space available for the adjacent bicycle turn box. The box was ultimately placed as intended in the design but required narrowing/overlapping the crosswalk slightly (Figure 8).

Figures 9 and 10 show various before-after comparisons of the intersection.

Figure 7. The Two-Stage Turn Box for Eastbound University Avenue. This was installed south of the crosswalk rather than adjacent to its ingress bike lane.

Figure 8. The Two-Stage Turn Box for Westbound University Avenue. This was installed by narrowing / slightly overlapping a crosswalk.

Before **After**

Looking northwest; westbound University Avenue bike box is in foreground.

Looking west; eastbound University Avenue turn box is in foreground.

Looking north; westbound University Avenue turn box and Rugby Road bike box are visible.

Figure 9. Before-After Comparisons of Intersection Pavement Markings

Before **After**

Looking southwest; westbound University Avenue turn box is visible.

Looking south; westbound University Avenue bike box is in foreground.

Figure 10. Before-After Comparisons of Intersection Pavement Markings

Data Collection

Dates of data collection and weather conditions are shown in Table 5. Charlottesville has a seasonal climate, with average daily high temperatures below 50 degrees Fahrenheit in the winter months and above 80 degrees in the summer months.

Table 5. Data Collection Dates and Weather Conditions

Case	Day No.	Date	Day of Week	Weather	High Temperature[a]
Before	1	March 20, 2014	Thursday	Sunny and windy	60 °F
	2	April 8, 2014	Tuesday	Sunny and windy	66 °F
	3	April 23, 2014	Wednesday	Sunny and windy	64 °F
After	4	Sept. 3, 2014	Wednesday	Hot and sunny	86 °F
	5	Sept. 23, 2014	Tuesday	Sunny	69 °F
	6	Oct. 20, 2014	Monday	Mostly sunny, windy	68 °F
	7	March 18, 2015	Wednesday	Mostly sunny, windy	56 °F
	8	April 16, 2015	Thursday	Partly sunny, minimal light rain[b]	66 °F

[a] High temperatures were obtained from a weather history website (Weather Underground, 2019) using the 22904 zip code.
[b] Day 8 had 0.02 inches of light rain in the early afternoon. No precipitation occurred on other count days.

Total Bicycle Volumes

There was some variation in total intersection hourly bike volumes among the count days (Figure 11). More bicyclists were observed on Days 4, 5, and 6 than on other count days. These were also the only counts conducted in the fall, so possible explanations for the higher volumes include generally higher bicycle traffic in the fall semester, slightly higher temperatures (see Table 5), or other factors. The university launched its U-Bike bike share program in January 2015, between Days 6 and 7.

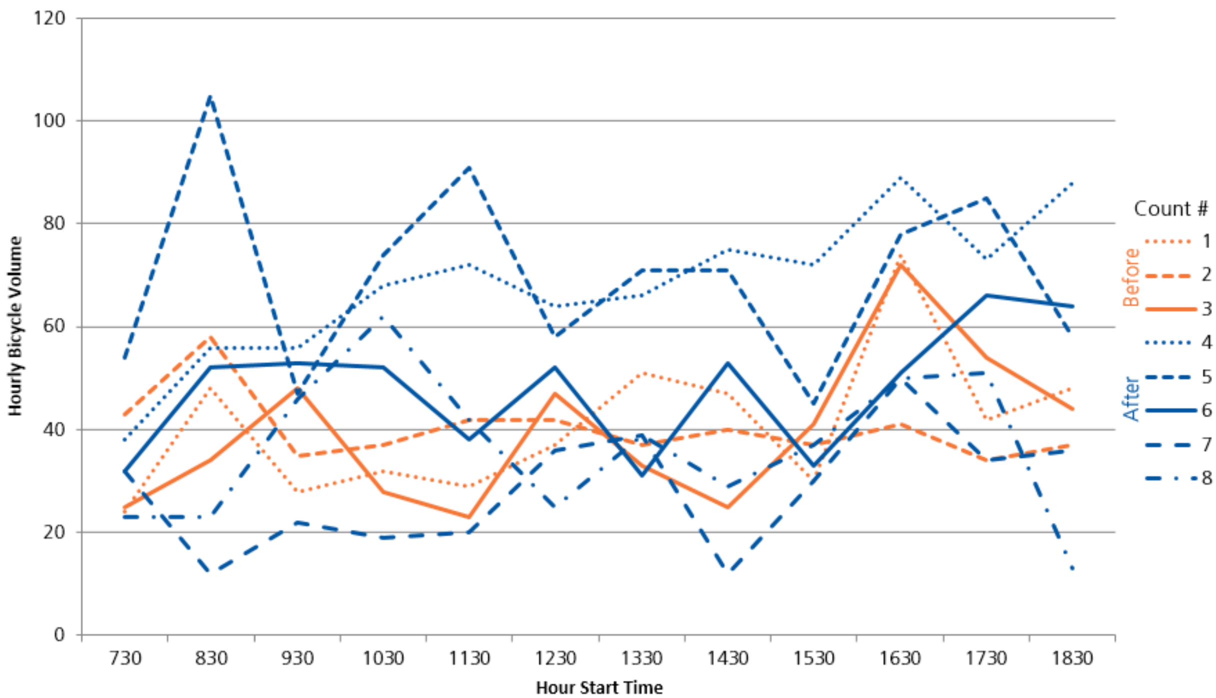

Figure 11. Hourly Bicycle Volumes by Hour Start Time for All Count Days

Legal Violations (Traffic Infractions) by Motorists and Bicyclists

Total daily observed legal violations or traffic infractions (the average of two reviewers' manual video reduction results) are presented by intersection approach leg in Figures 12 through 15 (note that scales differ for each figure). After data collection was completed, it was apparent that illegal RTORs by bicyclists had not been tallied consistently in the before counts.

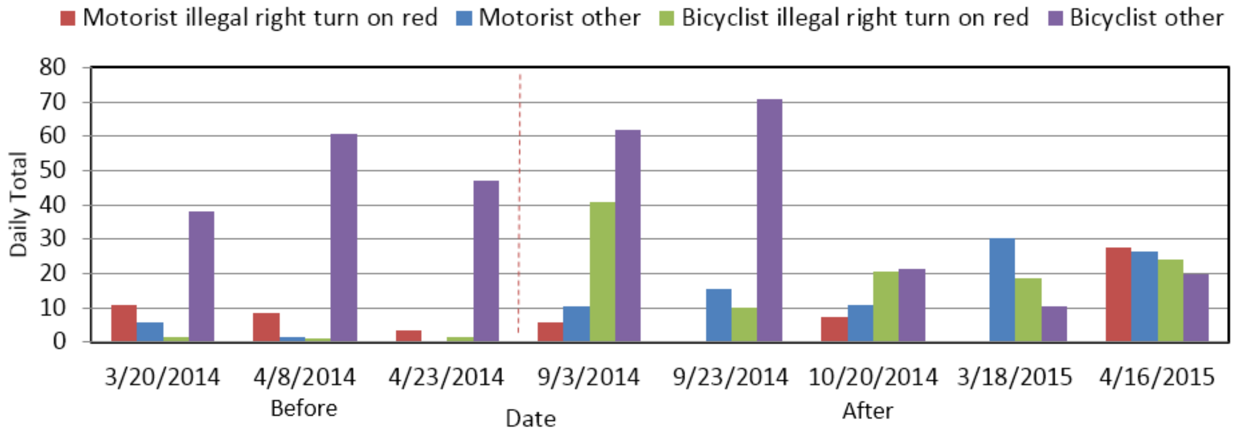

Figure 12. Legal Violations by Motorists and Bicyclists Approaching From Rugby Road

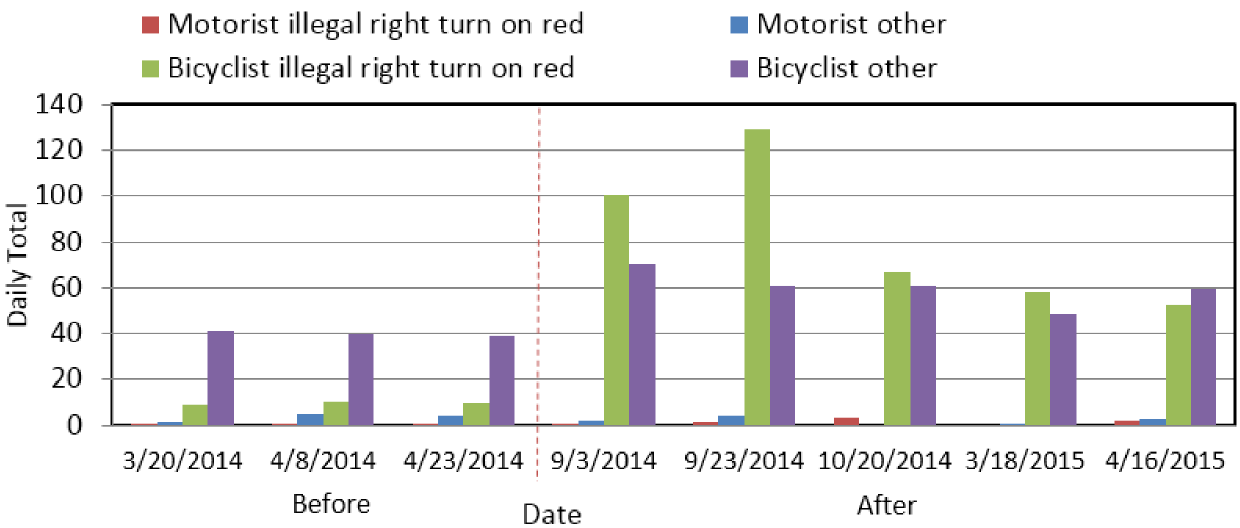

Figure 13. Legal Violations by Motorists and Bicyclists Approaching From McCormick Road

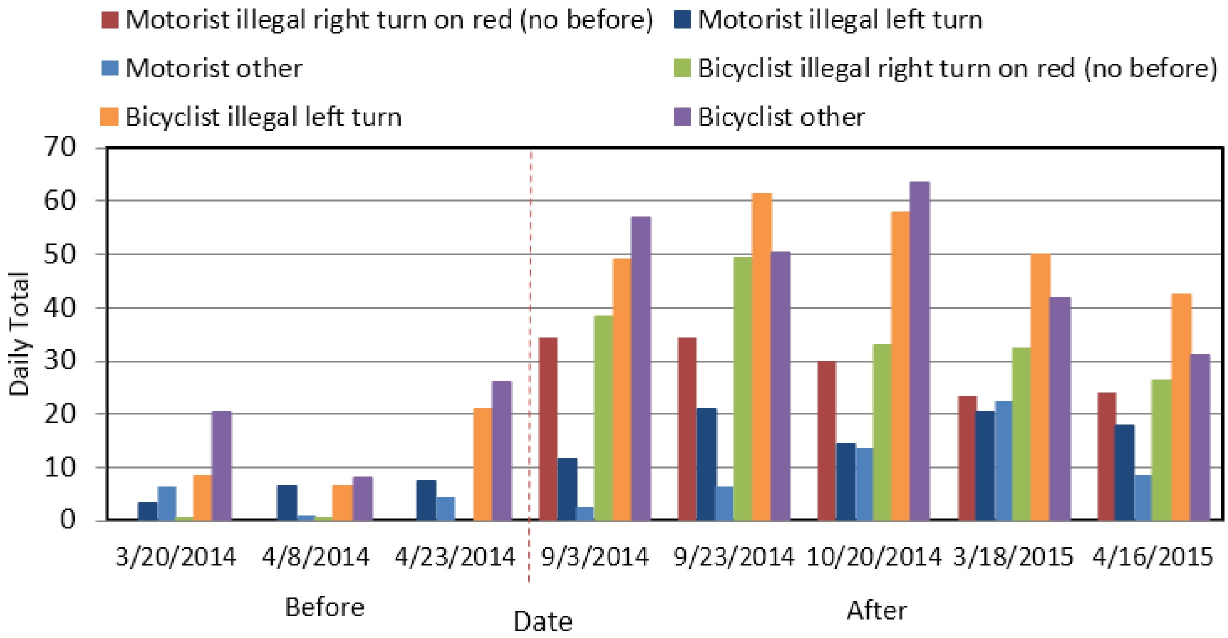

Figure 14. Legal Violations by Motorists and Bicyclists Approaching From Westbound University Avenue. A "no turn on red" prohibition was added in the after case that was not present in the before case.

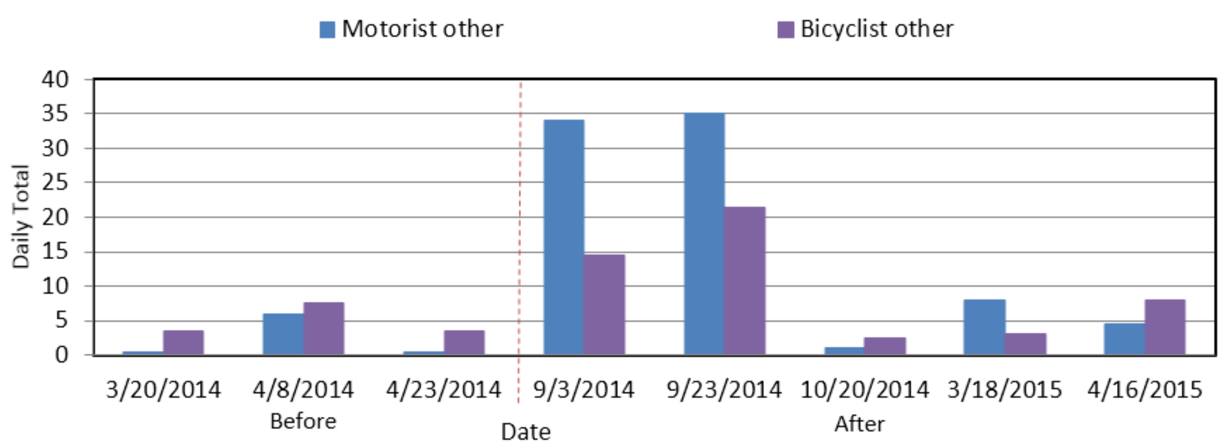

Figure 15. Legal Violations by Motorists and Bicyclists Approaching From Eastbound University Avenue

Conflicts Involving Bicyclists

Total daily observed conflicts between bicyclists and other road users are presented in Figure 16 for forced yielding events and in Figure 17 for near miss events (note that scales differ for each chart). Near miss events were infrequent, and none was observed during the three before counts and the first after count.

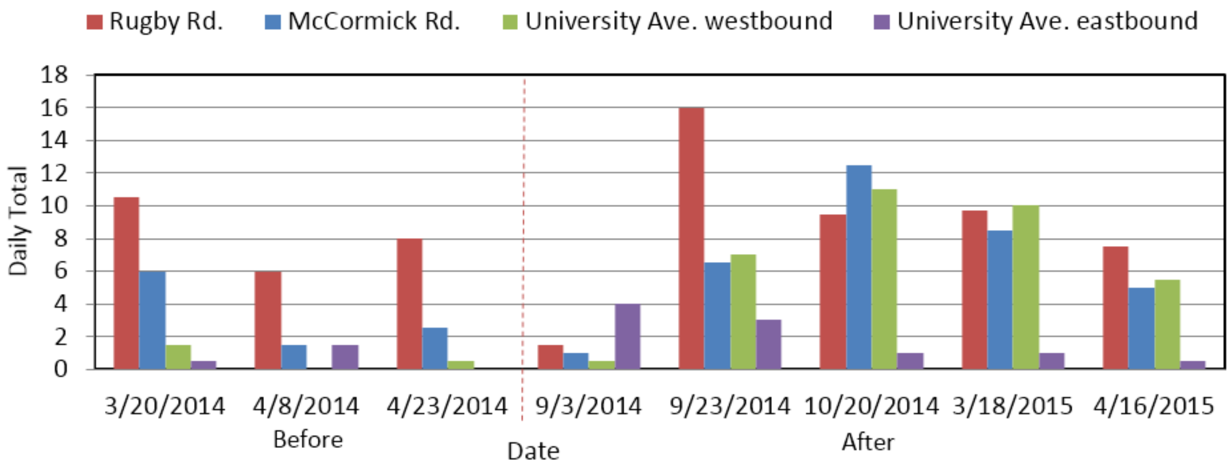

Figure 16. Observed Forced Yielding Events Involving Bicyclists

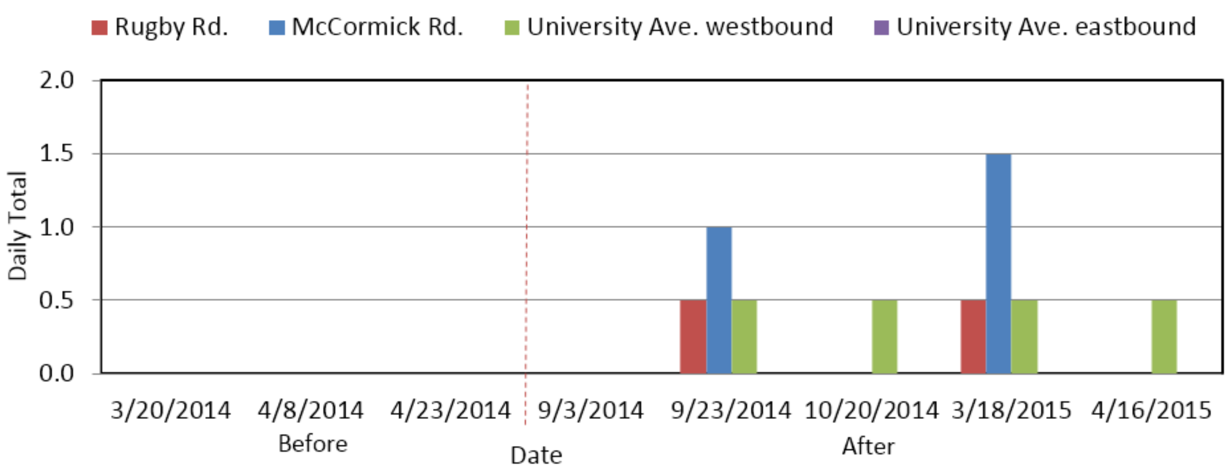

Figure 17. Observed Near Miss Events Involving Bicyclists

Bike Box and Turn Box Usage

Figures 18 and 19 show average rates of proper and improper use and daily total usage for the bike boxes after they were installed. Bike box usage rates (bars in Figures 18 and 19) represent the number of bicyclists using the markings as noted (properly or improperly, based on manual video review) divided by the total number of approaching bicyclists (from automatic counts) for each 15-minute period, averaged for each date. The daily total numbers of bicyclists using each bike box properly and improperly are also shown (lines in Figures 18 and 19).

Cumulative usage rates higher than 1.0 in Figure 19 are likely because of undercounting by the automated processing algorithms during high-volume times (see also Figure 23). Also in Figure 19, the unusually low rates of both proper and improper use for Day 7 (March 18, 2015) are at least partially explained by the camera view on Rugby Road for this count day, in which the bike box was not visible, making it difficult to perform the manual video review for many approaching bicyclists.

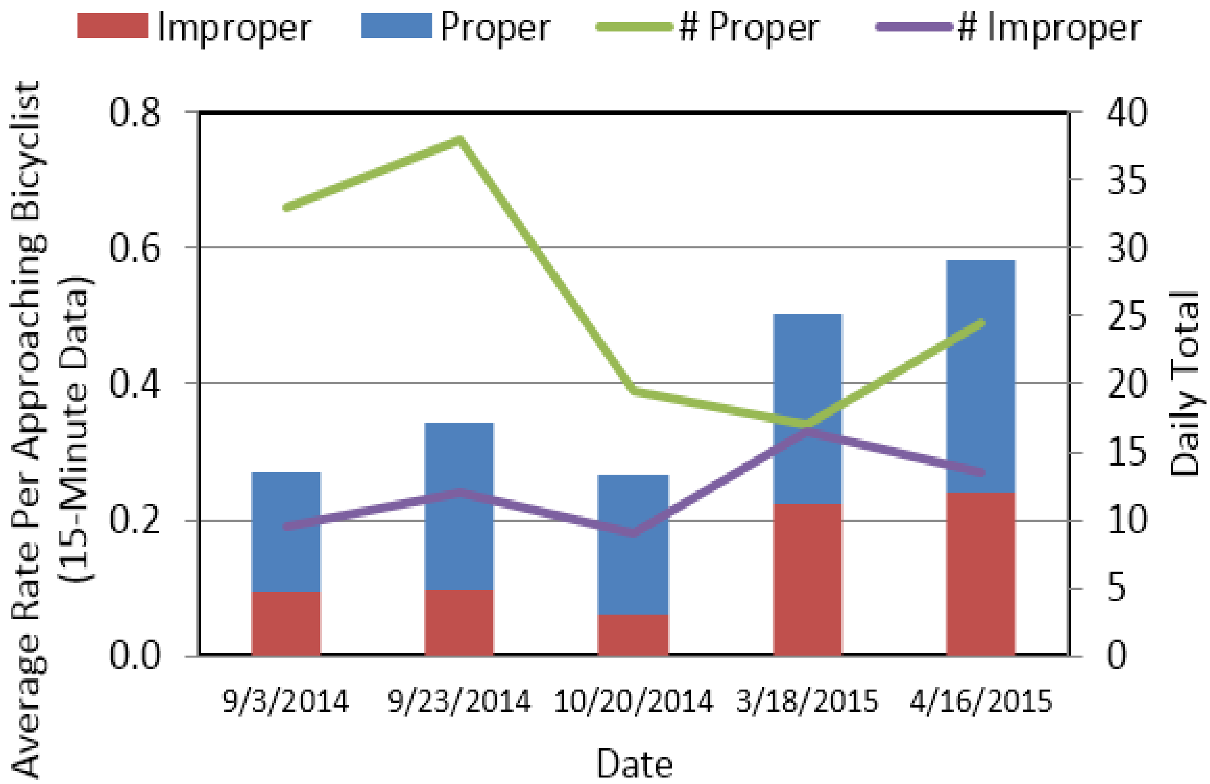

Figure 18. Bike Box Usage Rates and Counts for Westbound University Avenue

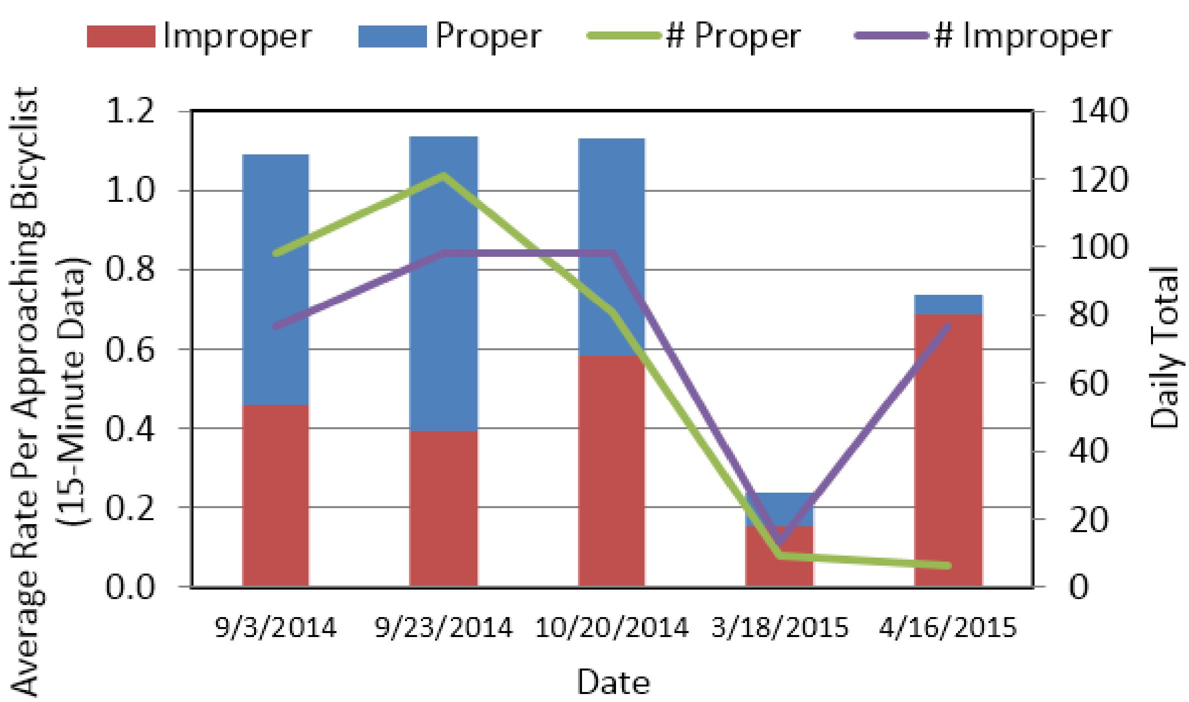

Figure 19. Bike Box Usage Rates and Counts for Rugby Road

Figures 20 and 21 show average rates of proper and improper use and daily total usage for the turn boxes after they were installed. Because turn box usage rates include bicyclists entering the boxes improperly from McCormick Road and Rugby Road as well as from the intended approaches on University Avenue, turn box usage rates (bars in Figures 20 and 21) are defined as the average number of bicyclists using the markings as noted (properly or improperly, based on manual video review) divided by the total number of bicyclists passing through the entire intersection (from automatic counts) for each 15-minute period. Thus, the rates for turn box usage in Figures 20 and 21 are not directly comparable with those for bike box usage in Figures 18 and 19. The daily total numbers of bicyclists using each turn box properly and improperly are also shown (lines in Figures 20 and 21).

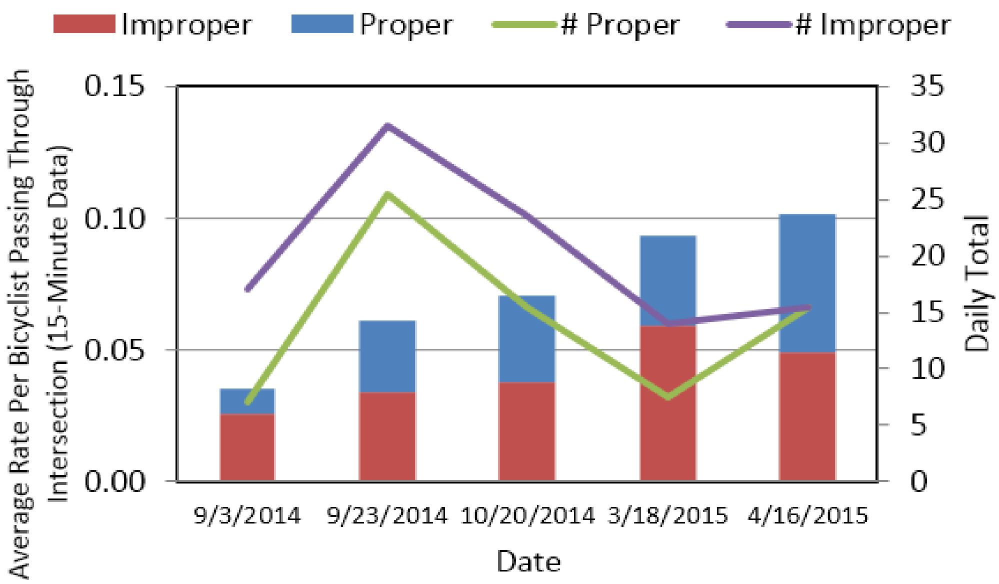

Figure 20. Turn Box Usage Rates and Counts for Westbound University Avenue

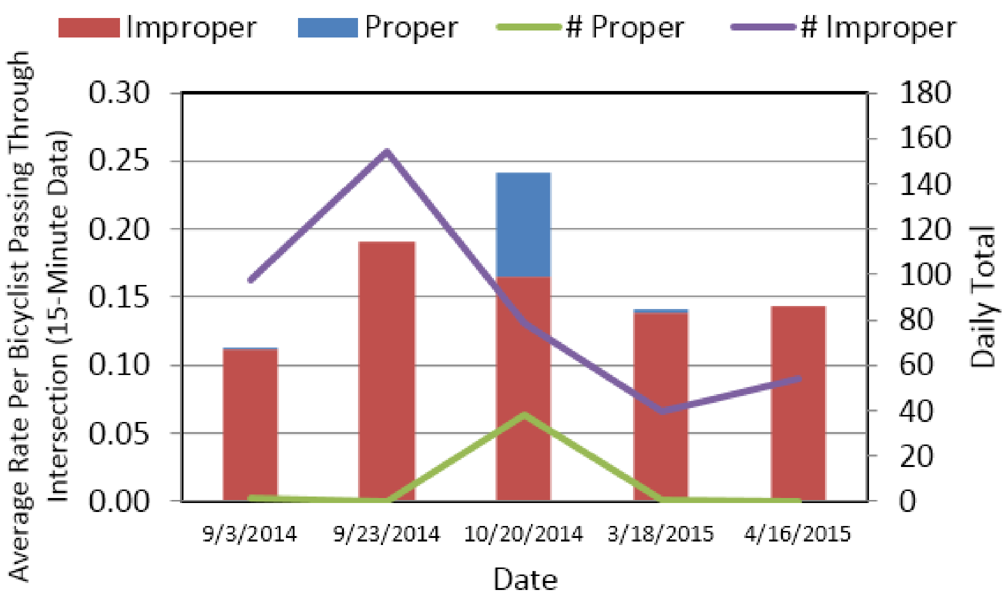

Figure 21. Turn Box Usage Rates and Counts for Eastbound University Avenue

Turn box usage rates were very different for the two turn boxes. The westbound turn box, serving the travel path into the university's central grounds from a shopping and restaurant district and downtown Charlottesville, saw fairly regular use for two-stage turns, with the substantial amounts of improper use split between bicyclists completing a two-stage turn who violated a red signal and bicyclists waiting in the box who were not completing a two-stage turn (Figure 20). The eastbound turn box, however, was used rarely for actual two-stage turns on most count days; rather, its occupants were almost exclusively bicyclists approaching from McCormick Road, who were coded as improper turn box users if they queued in the turn box (Figure 21).

Bicyclists completing a proper westbound two-stage turn were rare before the changes. As shown in Figure 22, although the daily total of proper two-stage turns for this movement remained lower than the daily total for the prohibited direct left turn by bicyclists and varied by count date, some dates after the changes had higher rates of proper westbound bicycle two-stage turns. Eastbound two-stage turns were not tallied in the before period.

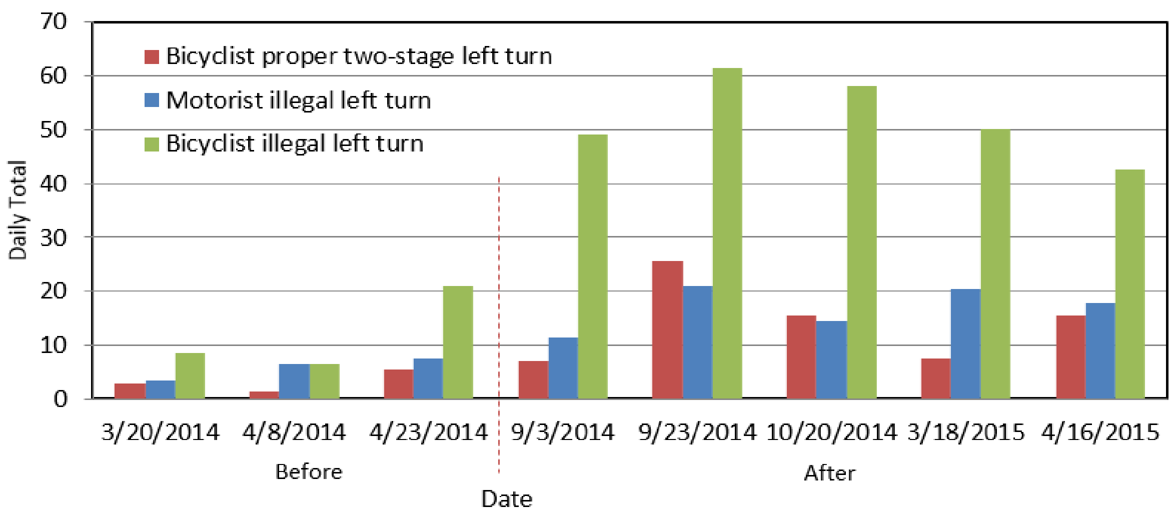

Figure 22. Proper Westbound Bike Two-Stage Left Turns and Illegal Left Turns by Motorists and Bicyclists Before and After Pavement Markings Were Installed

Data Analysis

Verification of Automated Volume Data

As a check on the accuracy of the automatic count, Day 1 video was manually reviewed and 618 bikes were tallied during the 24-hour period compared to the video-based system's automated count of 568 (Figure 23). With the manual counts taken as ground truth, the automated counts detected about 92% of bicyclists, which was an accuracy level similar to what other research has reported (e.g., Griffin et al., 2014) and was deemed acceptable for the purposes of this study.

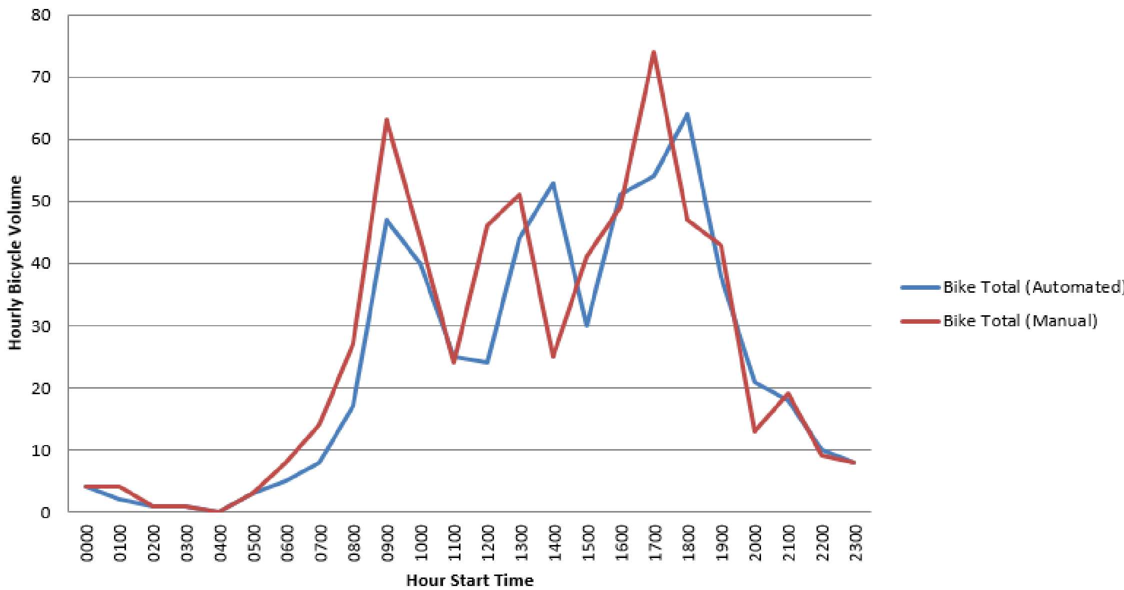

Figure 23. Automated Bike Count Compared to Manual Bike Count of First Count Date (March 20, 2014)

The results were less clear when disaggregated counts by intersection leg were examined. The manual count tallied more bikes than the automated counts on every leg but the two University Avenue legs, but the automated count data were not consistently lower or higher than the manual data. Likely causes for variations by leg include differences in the ways bicycles were classified for manual review (i.e., by approach leg) versus automated (i.e., some by approach leg and some by crosswalk). Other possible explanations for discrepancies include automated counts picking up motorized scooters, groups of bicyclists being counted inaccurately, or other classification errors in the automated and/or manual process.

Observational Variability

Statistical tests were conducted to examine the possibility that reviewers for before counts may not have been as observant as reviewers for after counts. A two-tailed t-test was conducted at the 95% confidence level. The hypotheses for the difference between two reviewers' conflict numbers are as follows: the null hypothesis (H_0) was that the difference was zero, and the alternative hypothesis (H_a) was that the difference was not zero.

$$H_0: \mu = 0$$

$$H_a: \mu \neq 0.$$

The results of the one-sample t-tests are shown in Tables 6 and 7. During many 15-minute periods, no conflicts were recorded by either reviewer; to ensure that the result would not be skewed by such records, a comparison of non-zero records only was also conducted. Although the p-value changed slightly, the result of the comparison did not change (Table 6).

A second comparison was conducted for Days 2, 6, and 8 after the first test indicated that the two reviewers' observations were different for those counts. Each reviewer's results were compared to the results of the third reviewer, who reviewed all conflicts observed by the initial reviewers (Table 7). Additional data transformations were then made as noted in the "Methods" section.

Even after undergoing training, not all video reduction technicians were consistent in classifying what they observed. This subjectivity was complicated by having several different video reduction technicians rather than one or two expert reviewers.

Table 6. Comparison Result of Conflict Observations by Two Reviewers

Day No.	All Records		Non-Zero Records	
	p-Value for the Difference	Result	p-Value for the Difference	Result
1	0.110	Not different	0.091	Not different
2	0.005	Different	0.002	Different
3	0.182	Not different	0.190	Not different
4	0.710	Not different	0.741	Not different
5	0.231	Not different	0.236	Not different
6	0.000	Different	0.000	Different
7	0.083	Not different	0.083	Not different
8	0.002	Different	0.001	Different

Table 7. Comparison Result of Conflict Observations by Two Reviewers and a Third Reviewer (Non-Zero Count)

Day No.	Between 1st and 3rd Reviewers			Between 2nd and 3rd Reviewers		
	p-Value for the Difference	Result of Hypothesis	Similarities	p-Value for the Difference	Result of Hypothesis	Similarities
2	0.018	Reject	Different	0.392	Do not reject	Same
6	0.000	Reject	Different	0.586	Do not reject	Same
8	0.009	Reject	Different	0.042	Reject	Different

Statistical Analysis

A matched-pairs t-test and a Wilcoxon matched-pairs signed-rank test were performed on each of the four datasets (i.e., 15- and 30-minute datasets and their log-transformed versions). For several Q-variables, the results indicated that the before period was different from the after period, meaning that the Q-variable or measure changed after the installation of the markings. Although the results of this analysis were statistically significant at the 95% confidence level, not all the results were practically meaningful; some Q-variables had mean and median values that were very close to zero both before and after the installation of pavement markings. Table 8 summarizes the test results that were practically meaningful.

Variables representing near miss events were weighted twice as much as those representing forced yielding events for conflict analysis purposes. Changing this weighting to 3 times as much did not change the results, likely because near miss events were relatively uncommon.

Table 8. Summary of Initial Before-After Comparisons

Variable and Description	Mean Before	Mean After	Significantly Different (p = 0.05)
Q1: No Turn on Red compliance by right-turning motorists from Rugby Rd	99.1%	99.0%	No
Q8: Motorist encroachment into crosswalk or bike box on Rugby Rd (per 100 motorists on the approach)	2.0	1.6	No
Q11: Mean rate of other traffic infractions made by bicyclists entering the intersection from Rugby Rd (or Carr's Hill Rd) (infractions per 100 bicyclists on the approach)	41.0	23.6	Yes
Q12: Mean rate of other traffic infractions made by bicyclists entering the intersection from McCormick Rd	44.8	39.3	No
Q13: Mean rate of other traffic infractions made by bicyclists entering the intersection from westbound University Ave	20.8	48.5	Yes
Q14: Mean rate of other traffic infractions made by bicyclists entering the intersection from eastbound University Avenue	16.3	29.3	Yes
Q15: Mean rate of other traffic infractions made by bicyclists in total	23.4	26.3	No
Q26: Ratio of bicyclists approaching on westbound University Ave who made the illegal (direct) left turn onto McCormick Rd	13.3	51.3	Yes
Q31: Rate of observed conflicts per bicyclist passing through the intersection	2.4	3.9	Yes

Approach-Level Bike Box Usage and Motorist Compliance with NTOR Signs

The Wilcoxon matched-pairs signed-rank test was applied to the after data to compare bicyclists' improper usage of bike boxes for the two bike boxes in the after period. A statistically significant higher proportion of bicyclists approaching from Rugby Road (40% to 45%) used the Rugby Road bike box improperly or failed to use it than the proportion of bicyclists approaching from westbound University Avenue (8% to 12%) used the bike box on westbound University Avenue improperly or failed to use it. One contributor to this difference was probably the unusual geometry of the Rugby Road approach, with the automobile stop bar and bike box set back more than 30 feet from the crosswalk and turn box (because of the presence of Carr's Hill Road; see Figures 4 and 5). Bicyclists frequently continued past the bike box (i.e., failed to use the bike box) and waited alongside pedestrians in the area near the turn box. Signal violations were a likely second contributor; bicyclists on Rugby Road often exited the bike box on a red signal, frequently during the leading pedestrian interval (i.e., improperly used the bike box). The westbound University Avenue approach has more conventional geometry and no leading pedestrian interval.

The Wilcoxon matched-pairs signed-rank test was also applied to the after data to compare NTOR compliance by motorists by approach. Results indicated that after the changes, NTOR compliance of motorists approaching on westbound University Avenue, at about 96%, was statistically lower than compliance on either of the other two approaches with NTOR signs, both of which were near 100%. Possible reasons for this difference are that (1) the westbound University Avenue approach NTOR restriction was new and the others were preexisting, and (2) the westbound University Avenue right turn is a relatively simple 90-degree movement with good sight lines but the other two had more complicated geometries (i.e., an obtuse angle for McCormick Road and a side road and visibility constraints for Rugby Road).

Re-Review Analysis

The initial results showing an increase in conflicts per bicyclist passing through the intersection prompted the partial re-review of a subset of data. The combination of methods used in the re-review supported several practically meaningful findings for specific variables of interest (Table 9). Given the uncertainties regarding observational variability, these became the statistically strongest findings of this study, although the initial results presented in Table 8 still hold some value.

Table 9. Summary of Statistically Significant Results After Re-Review

Variable	Re-Review Tests Supporting Validity	Result and Interpretation
Q4: Proper bike box use on Rugby Rd	Confusion matrix, t-test, Bland-Altman plot, regression	The Rugby Rd bike box was used properly by 46% of approaching bicyclists and improperly by 40%.
Q21: Improper bike box use on Rugby Rd	Confusion matrix, t-test, Bland-Altman plot	
Q5: Proper bike box use on westbound University Ave	Confusion matrix, t-test, Bland-Altman plot	The westbound University Ave bike box was used properly by 24% of approaching bicyclists and improperly by 10%.
Q22: Improper bike box use on westbound University Ave	Confusion matrix, t-test, Bland-Altman plot	
Q23: Improper turn box use on westbound University Ave	Confusion matrix, Bland-Altman plot	For every 10 bicyclists turning left from westbound University Ave to McCormick Rd, there were 6 to 9 bicyclists (from any approach) who used the corresponding turn box improperly.
Q24: Improper turn box use on eastbound University Ave	Confusion matrix, t-test, Bland-Altman plot, regression, Cohen's kappa	Because of low volumes of intended users (left-turning bicyclists from University to Rugby) and high volumes of improper use (primarily bicyclists coming from McCormick Rd), improper use of the eastbound turn box obscured proper use. For every 10 bicyclists turning left from eastbound University Ave to Rugby Rd, there were 90 to 107 bicyclists (from any approach) who used the corresponding turn box improperly.
Q11: Uncategorized traffic infractions by bicyclists approaching from Rugby Rd or Carr's Hill Rd (before-after)	Confusion matrix, Bland-Altman plot	Uncategorized bicyclist traffic infractions on the Rugby Rd approach decreased from 41 to 23.6 infractions per 100 approach bicyclists.
Q14: Uncategorized traffic infractions by bicyclists approaching from eastbound University Ave (before-after)	Confusion matrix, t-test, Bland-Altman plot, regression	Uncategorized bicyclist traffic infractions on the eastbound University Ave approach increased from 16.3 to 29.3 infractions per 100 approach bicyclists.
Q25: Ratio of motorists approaching on westbound University Ave who made the illegal (direct) left turn onto McCormick Rd (before-after)	Confusion matrix, Bland-Altman plot	Prohibited left turns increased from 0.1% to 0.4% of approaching motorists and from 13.3% to 51.3% of approaching bicyclists.
Q26: Ratio of bicyclists approaching on westbound University Ave who made the illegal (direct) left turn onto McCormick Rd (before-after)	Confusion matrix, Bland-Altman plot	

Potential for Right-Hook Crashes

The assessment (by way of comparing Q33 through Q36) did not indicate a clear potential for right-hook crashes (Table 10). The westbound University Avenue approach, which was striped such that right hooks should not have been likely, had higher rates of conflicts after installation of the bike boxes than the Rugby Road approach, which was striped such that right hooks may have been a concern. (To be clear, this does not necessarily suggest a higher risk of right hooks on westbound University Avenue.)

Table 10. Potential for Right-Hook Crashes

Approach	Conflicts per Potential Conflicting Road User	
	Before	After
Rugby Rd approach	0.3 per hundred	0.1 per hundred
Westbound University Ave approach	No conflicts recorded in these signal phases	0.3 per hundred

Summary

Overall, the results of this study were mixed and indicated the following:

- Rates of traffic infractions decreased for some types of infractions and for some intersection approaches but increased for others.
- Some bicyclists used the new markings properly, but some used them improperly or failed to use them.
- Conflicts between bicyclists and other road users may have increased, although these results were inconclusive.
- Near miss conflicts were rare.

Study Site Results

Bicycle Volumes

Identifying measurable changes in bicycle volumes was part of one of this study's two objectives. Although bicycle volumes were not a primary metric for this study, recent literature has continued bolstering the case for "safety in numbers." In essence, this argument is that when bicycle mode shares rise, safety outcomes improve, possibly because of heightened driver awareness. Schneider et al. (2017) compared annual pedestrian and bicyclist fatalities with trip-making estimates from the National Household Travel Survey in 46 metro areas and found that more walking and biking were associated with lower fatality rates, as were some other factors. If a causal relationship exists, then even if facility changes do not show measurable improvements in behaviors, they could lead indirectly to improved system safety if they supported an increase in bicycling.

Traffic Infractions by Bicyclists

Eastbound University Avenue Approach

The 80% increase in uncategorized bicyclist traffic infractions on the eastbound University Avenue approach (Q14) may be an artifact of relatively low bicycle volumes on that approach, along with a before infraction rate that was the lowest of the four approaches. Its after infraction rate of 29.3 infractions per 100 approaching bicyclists remained lower than the after infraction rates on the McCormick Road and westbound University Avenue approaches.

Red Signal Violations

The category of uncategorized bicyclist traffic infractions included red signal violations (red signal violations were not quantified separately). During the video reduction process, video reviewers noted that signal violations for the Rugby Road and McCormick Road approaches often occurred during a leading pedestrian interval that was provided before the green signal for the Rugby Road approach. The 43% decrease in uncategorized bicyclist traffic infractions that was seen on the Rugby Road approach (Q11) is likely to be partly attributable to decreased signal violations, which in turn could be related to bicyclists having a defined waiting area (i.e., the bike box or, although used inappropriately, the nearby turn box).

In Virginia, bicycles are classified as vehicles, so bicyclists must obey vehicular traffic signals unless otherwise instructed. Dougald (2015) found that trail users at a roadway crossing in Virginia were confused about who had the right of way; it may be the case that bicyclists at this intersection were similarly confused about whether they should use the pedestrian signals. Another possibility is that bicyclists were aware of the law but intentionally (and, arguably, rationally) disregarded the red signals in order to cross the intersection at a time with no conflicting automobile traffic. Marshall et al. (2017) found that although cyclists acknowledged having broken the law, they felt that most of the time they needed to do so in order to stay safe. This is one example where a traffic violation may not be a good surrogate for a true safety concern.

As further context for rates of traffic infractions that include signal violations, Monsere et al. (2014) found overall bicyclist compliance with traffic signals (regular and bicycle specific) to range from 67% to 98%, with lower compliance where bike volumes were relatively high or at intersections with a leading pedestrian interval. The study found that much of signal non-compliance by bicyclists occurred just before the green signal during the clearance interval for crossing traffic. A naturalistic data collection study found cyclists to be more likely to violate red signals when making right turns and less likely to do so when there was conflicting traffic (Elhenawy et al., 2016).

Additional treatments such as bicycle signals or an all-red phase with bicycle and pedestrian “scramble” (when automobiles are stopped in all directions and walking and biking movements are permitted in all directions) could reduce red signal violations—which the bike box and turn box pavement markings are not necessarily designed to overcome—while supporting proper use of the bicycle pavement markings. Other potential treatments that some cities are beginning to explore include leading bicycle intervals and split leading bicycle intervals (delaying a turn for automobiles while allowing other movements) (Kothuri et al., 2018). Improving bicyclist detection and signal actuation, such as through bicycle stencil markings and associated signs in the detection zone and detection confirmation feedback lights that illuminate to "tell" bicyclists that the traffic signal has detected their presence, could also help address signal violations, especially when the signal operation is actuated rather than fixed-time. Although Boudart et al. (2015) found a negligible effect on bicyclist signal compliance after installation of a detection confirmation feedback light, they found a statistically significant increase in the number of bicyclists positioning themselves in the signal detection area rather than using a pushbutton.

Conflicts Involving Bicyclists

The increase in total conflicts per bicyclist passing through the intersection (seen in the initial results) is concerning. One possible explanation is that the new pavement markings encouraged more aggressive bicycling, resulting in more conflicts. A second possibility is that more bicyclists used the intersection at peak times between classes when pedestrian volumes spiked, rather than bypassing it; reports from video reviewers indicated that many bicycle-pedestrian conflicts were inherent because of traffic signal phasing, especially on Rugby Road, where all automobile and bicycle traffic must turn across one of the crosswalks during the concurrent "Walk" phase (because there is no through movement that does not cross a crosswalk). If that were the case, an all-red interval with a bicycle and pedestrian scramble phase could help address it. A third possible explanation is that the new pavement markings, which reduced space for motorists on one approach (Rugby Road), led to longer automobile queues and more aggressive driver behavior. Without conducting surveys or a more detailed analysis of observed conflicts, it is not possible to state with certainty which, if any, of these explanations were contributory.

Bike Box and Turn Box Usage

By definition, traffic signal phase affects rates of both proper and improper use of bike boxes and turn boxes. A bicyclist approaching on a green signal has no opportunity to use a bike box properly; a bicyclist approaching on a red signal has no opportunity to enter a turn box properly until the signal changes to green. Differences in signal cycle times for each approach could partially explain differences in rates of proper and improper bike box use on Rugby Road and University Avenue (Figures 18 and 19). University Avenue received a longer green signal than Rugby Road, so assuming random bicycle arrival times, it is logical that the proper and improper bike box usage rates for westbound University Avenue would be lower than the corresponding rates for the Rugby Road bike box.

Improper turn box use was common in this dataset. Although not quantified separately, both turn boxes had large numbers of bicyclists from the perpendicular approach (i.e., Rugby Road or McCormick Avenue) who continued past the bike box or stop bar and waited in the turn box; these were not the intended users of the turn box. Among bicyclists who were actually making two-stage turns, common sources of improper turn box use were entering or (more frequently) leaving the turn box in violation of a red signal (including on the leading pedestrian interval).

As with traffic infractions, there exist degrees of improper facility usage that correspond to a wide range of levels of risk. Some behaviors that were classified as improper, such as bicyclists from the perpendicular approach waiting in the turn box rather than at the stop bar or in the bike box, carry relatively low risk. Others, such as stopping in a bike box on a green signal, could easily contribute to conflicts or crashes.

Comparing these results (Figures 19 through 21) with the literature (Tables 3 and 4), the rates of proper bike box use were within the ranges seen in older studies from the United Kingdom and Oregon but below the rates Dill et al. (2011) documented in Portland, Oregon. The high rates of improper turn box use suggest that this location did not see the high level of correct use found in one study from China (Liang et al., 2015) and are likely closer to what was experienced in San Francisco (J. Parks, unpublished data).

It is unclear why the prohibited direct left turn increased for both automobiles and bicycles. One possibility is that the roadway restriping to add the westbound bike lane shifted the westbound through lane about 5 feet closer to McCormick Road, which, despite the fact that the turn remained prohibited, could have made the turn slightly easier for drivers and bicyclists by providing better roadway positioning and visibility. For bicyclists, there is a chance that the added pavement markings led to inaccurate assumptions that bicyclists were permitted to make the illegal turn, although without surveys, there are no data to support this possibility. One potential solution would be for the city to allow bicyclists the option of making the prohibited vehicular left turn in addition to the two-stage turn, possibly with the use of a bike signal. The direct left turn from the bike box would assist bicyclists arriving on the red phase, just as the two-stage turn assists bicyclists arriving on green—but having both options could add confusion. If the turn box remains the only legal way of making this movement, the interim approval requires installation of a sign indicating such (FHWA, 2017).

Researchers observed that "Stop Here" signs associated with bicycle boxes generated confusion. The intent of the signs was to mark the location of the automobile stop bar and to delineate the location of the bicycle stop bar. On the Rugby Road approach, however, installation limitations related to a drainage structure and the curb line caused the two signs to appear to be next to each other at the same location.

On the westbound University Avenue approach, a single "Stop Here on Red Except Bicycles" sign was used at the automobile stop bar without a corresponding sign for bicycles. Anecdotal observations and conversations indicated that some bicyclists interpreted the sign to mean that bicyclists were not bound by the NTOR sign/restriction for this approach. For bicyclists proceeding from westbound University Avenue onto Rugby Road (and not onto Carr's Hill or into the turn box), the right turn is uncomplicated with good visibility, making such an assumption seem reasonable. If bicycle RTORs are not a concern (i.e., if a NTOR restriction is in place simply because there is a bike box but bicyclists could turn right on red safely), one option could be to explore the use of "No Turn on Red Except Bicycles" signs as were used at locations studied by Dill et al. (2011).

Potential for Right-Hook Crashes

The assessment did not indicate a clear potential for right-hook crashes, when fast-moving bicycles pass slower right-turning traffic on the right (Table 10). Rugby Road is the only intersection approach with a slight downhill grade, which is the condition that has been identified in other locations with a combination of bike boxes and right-hook crashes. In such cases, bicyclists moving at a relatively high speed can overtake right-turning cars and trucks on the right without drivers seeing them. It appears that this was not a major concern at the study intersection; the Q-variables designed to isolate conflicts that occurred after the initial startup of the green phase (Q33 through Q36) did not indicate any increase in such conflicts for the Rugby Road approach. This could be because the sharp grade break at University Avenue and the inability of cyclists on the Rugby Road approach to travel straight ahead (i.e., they must slow down somewhat to proceed "straight" onto McCormick Road because the road is not straight) keep automobile and bicycle speeds and speed differentials relatively low.

Potential Topics for Additional Study

Improvement Over Time

Improvement over time during the after condition (i.e., from Day 4 through Day 8) was not explicitly analyzed, and Figures 12 through 21 do not suggest consistent trends.

Reported Bicycle Crash

Although a crash analysis was not conducted, crash records were reviewed in 2016. One bicycle-involved injury crash was documented near the intersection while University Avenue was being resurfaced. A left-turning car coming from the unsignalized spur of McCormick Road (about 300 feet west of the signalized intersection) struck a bicyclist turning left from University Avenue onto the spur of McCormick Road. The bicyclist had the right of way, and the motorist fled the scene and was issued a summons. The legal left turn this bicyclist was making is the same turning movement that could be avoided by a bicyclist making a two-stage left turn using one of the turn boxes at the signalized intersection.

User Comprehension, Outreach, and Education

As an observational study, this effort did not examine user comprehension of the new markings. Anecdotal reports and observations suggested that the markings were useful for some bicyclists but not intuitive for many bicyclists and most other road users. Conducting surveys would be valuable in future work of this type. The University of Virginia could include questions about comprehension of these pavement markings in its regular survey of employees regarding commuting behavior and conduct similar surveys of students. Ederer et al. (2018) demonstrated a quick method of surveying bicyclists to determine their trip purpose with high response rates without requiring them to stop. This method could be adapted to ascertain whether bicyclists think they understand how to use a bike box or turn box.

Although education and outreach were outside the scope of this study, they are important implementation elements for new and novel infrastructure (Mondschein et al., 2016). Various localities have created brochures, public service messages, instructional videos, and other tools related to how to use bike boxes and turn boxes.

Lessons Learned

Pavement Marking Design Process

Engineering design was performed outside the research process, but a two-part lesson was apparent: designers (1) should involve a broad set of stakeholders early in the process and (2) should expect the design to evolve over time based on their input. In this case, those that provided substantial input other than the design engineer included city engineers and planners, the Charlottesville Bicycle and Pedestrian Advisory Committee, researchers, state department of transportation engineers, an engineering graduate student, FHWA staff, and university staff representatives. Additional input from stakeholders such as traffic signal staff, undergraduate students, and local residents could have been valuable.

Data Collection

As of the time of this study, it was possible to use automated counts to obtain a reasonably accurate depiction of automobile, bicycle, and pedestrian movements with the possible exception of movements with very low volumes. It was not possible to rely on these methods for identifying behaviors and conflicts, so manual video reduction was used. Emerging technologies blending video analytics with crowdsourcing techniques may allow future researchers to obtain information about conflicts between road users quicker and more easily without facing the issues of observational variability and inter-rater reliability that emerged in this study (Feng et al., 2014; Loewenherz et al., 2017). Other studies (e.g., Sayed et al., 2012) have used computer video monitoring to evaluate the number and severity of conflicts using the extrapolated time to collision. Such tools can produce histograms of conflicts at a variety of time to collision levels, contributing to a more objective evaluation of conflicts before and after a change.

When manual video reduction is used, developing a video review procedure and providing proper training to video reviewers are important but may not eliminate observational variability. If using a single expert video reviewer is not feasible, reducing the number of reviewers is one way to reduce observational variability.

If road user comprehension and understanding is a key metric, surveys may be a simpler and more effective method than video-based analysis of behaviors and conflicts.

Data Analysis

Future research should narrow the range of performance measures for bike boxes and turn boxes as much as possible. The large number of measures examined in this study contributed to delays in the analysis process. Also, the measures that were used evaluated various aspects of safety at the intersection but may not have fully isolated changes attributable to the bike boxes and turn boxes. For example, it was apparent that a relatively high degree of traffic violations occurred at the intersection, but many of them were not necessarily related to the new bicycle infrastructure.

CONCLUSIONS

- *Many bicyclists used the bike boxes properly. Despite the unusual geometry of this intersection, proper use of the two bike boxes on Rugby Road and westbound University Avenue was more common than improper use.* For example, proper use of the bike box on westbound University Avenue (24% of approaching bicyclists) was twice the level of improper use (10%).

- *Many bicyclists used the turn boxes improperly or failed to use them.* For the two turn boxes (intended for eastbound University Avenue to Rugby Road and westbound University Avenue to McCormick Road), rates of improper use were high. Some types of improper use were not particularly risky or unsafe. Westbound bicyclists also continued making the prohibited direct left turn; in fact, this behavior rose sharply for both bicyclists and motorists after the changes.

- *Bike boxes and turn boxes did not resolve all issues at the study site.* Rates of proper bike box use were higher than improper use rates (Table 9), indicating that the bike boxes provided space for many bicyclists to queue ahead of traffic safely and legally. Also, on one of the approaches where a bike box was added, bicyclist traffic infractions decreased (Table 9) and initial results (Table 8) showed high and unchanged levels of motorist compliance with the NTOR restriction on that approach and low rates of encroachment into the bike box. Other less positive findings suggested that bicycle pavement markings by themselves were not sufficient to address all the issues that were observed—such as red-light running by bicyclists, which may be related to the student-heavy user mix—but it should be noted that they were not necessarily expected to do so. The initial results (Table 8) indicated an increase in conflicts per bicyclist passing through the intersection.

- *Before-after results regarding traffic infractions were mixed.* Of the statistically and practically significant re-review results (Table 9), some metrics (bicyclist traffic infractions from eastbound University Avenue and prohibited motorist and bicyclist left turns from University Avenue onto McCormick Road) indicated worse conditions after the changes than before, and one (bicyclist traffic infractions from Rugby Road) indicated improved conditions. Notably, the improved conditions were for uncategorized bicyclist traffic infractions on the approach with the most significant bicycle improvements (conversion of a turn lane into a bike lane and addition of a bike box).

- *This combination of bike box designs and intersection geometry did not appear to pose a particularly high risk of right-hook crashes.* Although any situation with a bike lane to the right of conflicting motor vehicle traffic can lead to conflicts or crashes when drivers turn across a bicyclist's path, this study did not find strong evidence of this being a particularly high risk at this site, possibly because of low speed differentials caused by the intersection's unusual geometry.

- *VTRC's participation in the experimentation process allowed intersection bicycle treatments to be installed at this site 2 to 3 years earlier than would have otherwise been possible.* Bike boxes and turn boxes were experimental when these markings were installed in 2014 and received interim approval in 2016 and 2017, respectively. The City of Charlottesville required assistance with conducting the experimental process in order to install the markings under the MUTCD.

RECOMMENDATIONS

1. *VDOT's Transportation and Mobility Planning Division (TMPD) should work with VDOT's Central Office Traffic Engineering Division (COTED) to create or improve educational materials related to bike boxes and turn boxes.* Although education and outreach were outside the scope of this study, they are potentially important implementation elements alongside the addition of new bicycle infrastructure (Mondschein et al., 2016). Additional user education would be beneficial, given FHWA's interim approval of bike boxes and turn boxes along with evidence from this study that some road users may not fully understand them.

2. *VDOT's COTED should evaluate the feasibility of submitting requests for interim approval for bicycle boxes and two-stage bicycle turn boxes.* Although FHWA has issued interim approvals for both treatments, states and localities still need to request to use that interim approval status if they wish to install the devices. For each type of marking, Virginia could request use of the treatment either for VDOT and all localities—which would allow the treatment to be added to the engineering toolbox for bicycle facilities in Virginia—or for VDOT roads only.

IMPLEMENTATION AND BENEFITS

Implementation

Recommendation 1 will be implemented by TMPD's Statewide Bicycle and Pedestrian Planner and COTED's Traffic Control Devices Engineering Manager or their staff designees, who will work together to identify the appropriate educational materials to develop. In fall 2018, COTED submitted a list of suggested revisions to the Virginia Department of Motor Vehicles (DMV) for consideration in the 2019 update of the *Virginia Driver's Manual*, which the DMV oversees. These suggested revisions included graphics depicting bike boxes and basic instructions for road users. The DMV will consider these changes along with others but must work within a strict page limit for the update of the manual, scheduled to be released in summer 2019.

TMPD reviewed its website in fall 2018 and determined that additional educational information for pedestrian and bicycle facilities, including bike boxes, would be beneficial. TMPD requested implementation assistance from VTRC to add more in-depth material and graphics to the website. TMPD will update the website by summer 2019.

Other education-related implementation actions are not planned but could include creating or adapting videos and other tools and/or encouraging the Virginia Department of Education, which oversees the driver education curriculum in public and private schools, to incorporate commonly used bicycle treatments into that curriculum. One potential funding source could be DMV's transportation safety grants, which can be awarded to local governments and state agencies, among others, for purposes including public education. Efforts to develop educational materials could also be coordinated with an existing safety forum attended by COTED, DMV, and the Virginia State Police. Educational materials could also address other bicycle treatments beyond the scope of this study.

Recommendation 2 will be implemented by COTED's Traffic Control Devices Engineering Manager or designee. As noted earlier, during the study period, FHWA issued interim approval status for both bike boxes and intersection turn boxes, allowing other states and localities to request permission to implement them without the full experimentation process. A future update of the MUTCD will likely include these treatments as optional tools for facilitating bicycle travel, at which point no request for interim approval would be needed.

The rates of proper use of the bike boxes in this study, although not exceptionally high, were higher than the rates of improper bike box use. That, along with results of other bike box experiments, suggests that bike boxes might be considered as part of other intersection treatments to improve safety and bike movement under certain conditions. COTED evaluated the feasibility of a statewide request for interim approval for use of the bicycle box that would cover all local highway agencies in Virginia. This action would allow bike boxes to be added to the engineering toolbox for bicycle facilities in Virginia. COTED is deferring taking further action on this request until the need arises on a VDOT road, which may or may not occur before the update of the MUTCD. As of March 2019, the only VDOT roads with bike boxes and two-stage boxes are in Fairfax County, and VDOT's Northern Virginia District has assigned responsibility for those markings to the county.

This study's results for turn boxes, along with their track record elsewhere, were less robust than for bike boxes. In addition, there may be less of a need to add two-stage turn boxes as a tool for common application than to add bike boxes. As with bike boxes, COTED evaluated making a request for interim approval for turn boxes but is deferring action until needed for a VDOT road.

The City of Charlottesville will be responsible for modifying the study site to comply with conditions of the interim approvals. The city has expressed interest in considering similar treatments at other intersections in the future and has already received FHWA approval to use the interim approval for bike boxes.

Other potential implementation activities could include VDOT arranging, supporting, or sponsoring training or webinars on design considerations for bicycle boxes and two-stage turn boxes. During the next update of the statewide *Bicycle Policy Plan*, *Road Design Manual,* and other documents, TMPD and COTED could note and/or encourage use of one or both treatments.

Benefits

The lessons learned regarding deploying these treatments could be valuable to other localities seeking to accommodate bicycling through intersections.

The primary benefit of implementing Recommendation 1 is improved road user awareness and understanding of bike boxes and turn boxes. These treatments may become more common in the future as communities seek additional tools to achieve connected multimodal networks that facilitate bicycle travel. Improved awareness and understanding could lead to improvements in safety.

The primary benefits of implementing Recommendation 2 are facilitation of the use of the bicycle box and/or two-stage turn box in Virginia under appropriate conditions (assuming that COTED makes and receives approval for one or more requests for interim approval). As VDOT seeks to accommodate multimodal transportation needs, these treatments could help its designers provide bicycle accommodations at intersections at relatively low costs (particularly if markings are added during the repaving process). This would help with developing connected bicycle networks and improving conditions for bicyclists at intersections, which can be high-stress locations. If localities are included in the interim approval request, these benefits would extend to them also.

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Transportation is responsible for the contents of this report and makes no claims, promises, or guarantees about the accuracy, completeness, or adequacy of its contents.

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APPENDIX

OUTREACH AND EDUCATION EFFORTS

The City of Charlottesville pursued several avenues to get the word out about changes at the study intersection.

- A one-sided information sheet was sent electronically to various city and University of Virginia distribution lists. Hard copies were posted at nearby on- and off-campus locations.

- More than 500 residents and property owners along the Rugby Road corridor were mailed an information sheet about the project and how to use the new markings properly as a driver or bicyclist.

- A tri-fold brochure was posted electronically on the city's website and was made available in printed form at various events.

- Intersection approach diagrams regarding the two-stage left turn and bike boxes were posted on sign posts at the intersection.

- One thousand two-sided cards with two-stage left turn and bike box information for bicyclists and motorists were printed (Figure A1); 500 of these were distributed to partner organizations, and city and VTRC staff handed out the remainder in person to bicyclists, pedestrians, and motorists at the intersection during the first week of classes at the university after installation of the new markings.

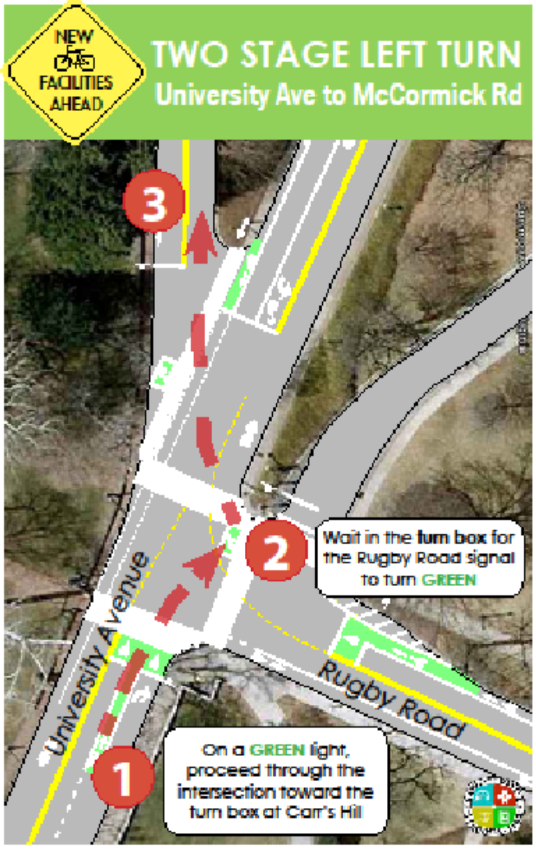
- Interior rack ads (120) were placed on city and university buses.

- Two exterior bus ads were placed on a city bus operating near the intersection.

- Public service announcements were made on local radio stations, and the city participated in two radio interviews.

- A news release was distributed that resulted in at least three news stories.

TWO STAGE LEFT TURN
University Ave to McCormick Rd



WHAT BICYCLISTS SHOULD KNOW:

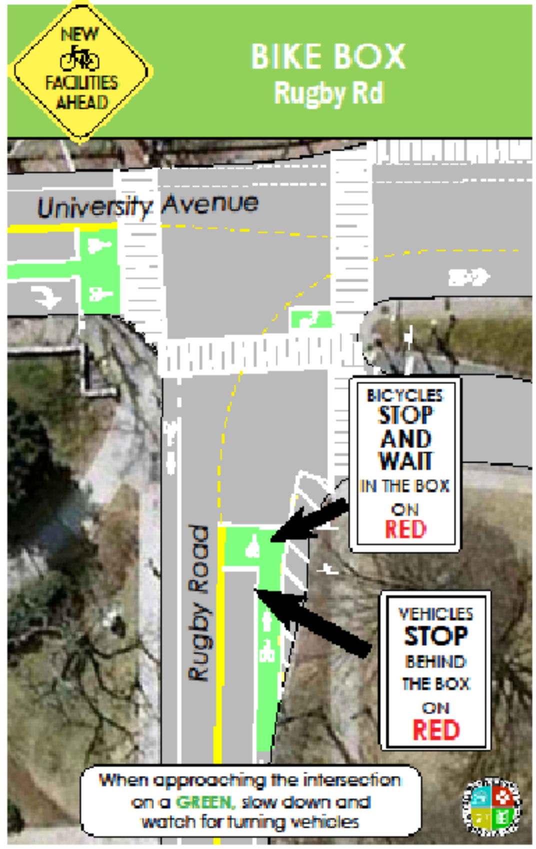
- When the light is red, enter the **bike box** using the bike lane. Once in the bike box, position yourself in the box directly in front of the right turn lane and **wait for a green light**.
- When the light is green, proceed through the intersection to the **turn box** near Carr's Hill Rd.
- Bicyclists turn their bikes and **wait for the traffic light** to change to green to complete the turn, yielding to pedestrians.

NEW PAVEMENT MARKINGS IMPROVE SAFETY FOR ALL ROAD USERS

- Increases awareness and visibility of bicyclists
- Encourages more predictable approaches to and through an intersection
- Creates safer intersection crossings – especially when drivers are turning right and bicyclists are going straight

For more information visit:
www.charlottesville.org/safestreets

BIKE BOX
Rugby Rd



WHAT BICYCLISTS SHOULD KNOW:

- When the light is red, enter the bike box along the bike lane. Once in the bike box, position yourself according to the direction you intend to travel and **wait for a green light.** (See diagram on back for more instructions to use the University Avenue bike box to make a left hand turn)
- When the light is green, proceed in advance of vehicles.
- When approaching the intersection on a green **light**, be aware of **right-turning motorists.**

WHAT DRIVERS SHOULD KNOW:

- When the signal is red, **wait behind the bike box**, keeping it clear for bicyclists.
- When the light turns green, proceed through the intersection as usual, **allowing cyclists in the box to go first.**
- When turning right on green, signal and watch for cyclists to the right.
- There will be one lane for motor vehicles approaching the Rugby Road intersection. There is no right turn lane.

For more information visit:
www.charlottesville.org/safestreets

Figure A1. Content of Two-Sided Cards. These cards were distributed to partner organizations and directly to intersection users. Figure provided by the City of Charlottesville.