ODOT SPR 833: Impacts of Intersection Treatments and Traffic Characteristics on Bicyclist Safety

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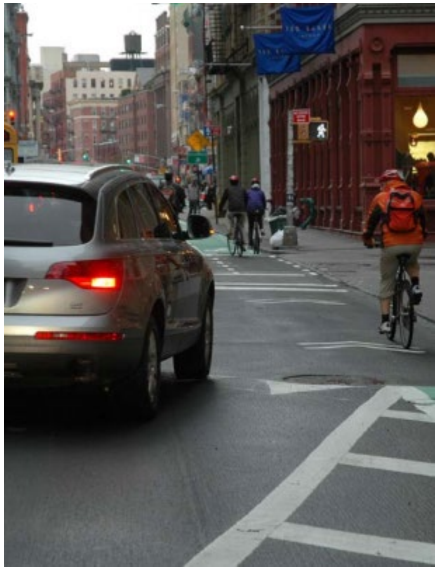
Motivation

- NTSB Report (NTSB, 2019) identified improving roadway infrastructure for bicyclists (including at intersections) as one of three primary bicyclist safety issues
  - From 2014-2016, 37% of bicyclist fatalities and 64% of injuries occurred at intersections
- Oregon 2014-2018 crash data reporting: 4,398 pedalcycle-related crashes resulting in 4,483 injuries and 45 fatalities.
  - PDO crashes likely underreported
  - Lack of data to develop robust crash modification factors
  - Surrogate safety measures (e.g. conflicts) may be used to provide data-driven guidance on intersection treatment performance

Objectives

- Determine which factors affect the frequency and severity of bicycle vehicle-conflicts and other surrogate safety measures at:
  - Bike Boxes
  - Mixing zones
  - Bicycle signals
- Provide data-driven guidance as to the efficacy of certain intersection treatments in mitigating vehicle-bicycle conflicts
- Develop guidance to practitioners to assist in countermeasure selection



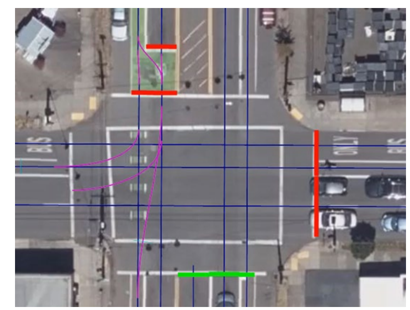
Source: MASSDot Separated Bike Lane Planning & Design Guide

Overall Methods

Data collected using three methods:

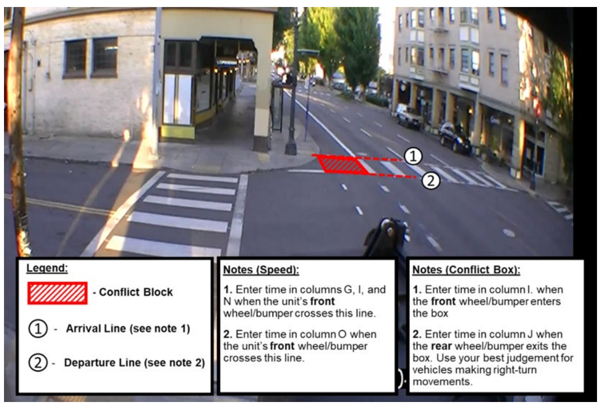
- Field-collected data at twelve study sites
  - Conflicts and volumes extracted from video
  - Statistical modeling to examine factors affecting conflict frequency and severity

- Microsimulation modeling
  - Modeled all twelve study sites using existing geometry and volumes
  - Conflicts extracted using SSAM and sensitivity analyses conducted



- Bicycling simulator experiment
  - 40 participants traversed the three treatments under varying scenarios
  - Assessed impacts on lateral position, velocity, visual attention, stress, and self-reported comfort

Field-Collected Data Analysis and Results



Field Data Analysis and Results

Summary of Video Data Collection Sites and Dates

Site ID	Treatment	Road 1	Road 2	Data Collection Date (7am-7pm)	Cameras
1	Bike Box	Broadway (SB)	Hoyt	8/27/2020	SS+QC
2	Bike Box	7th Ave (SB)	Madison St.	9/1/2020	SS+QC
3	Bike Box	Gladstone (WB)	Cesar E. Chavez	8/11/2020	SS
4	Mixing Zone	Multnomah (EB)	9th Ave	8/6/2020	SS
5	Mixing Zone	Multnomah (EB)	16th Ave	8/11/2020	SS
6	Mixing Zone	Multnomah (WB)	Grand Ave	8/18/20	SS
7	Bicycle Signal	N Broadway (WB)	N Williams	8/13/2020	SS+QC
8	Bicycle Signal	Rosa Parks (EB)	Greely Ave	8/27/2020	SS+QC
9	Bicycle Signal	Halsey (EB)	102nd Ave	8/6/2020	SS
10	Control	SE 7th Ave (NB)	SE Clay Ave	9/1/2020	SS+QC
11	Control	Weidler (EB)	9th Ave	8/13/2020	SS
12	Control	Burnside (EB)	8th Ave	8/18/2020	SS+QC
Note: SS = Streets Simplified camera, QC = Quality Counts LLC camera					

Field Data Analysis and Results

- Road User Volumes:

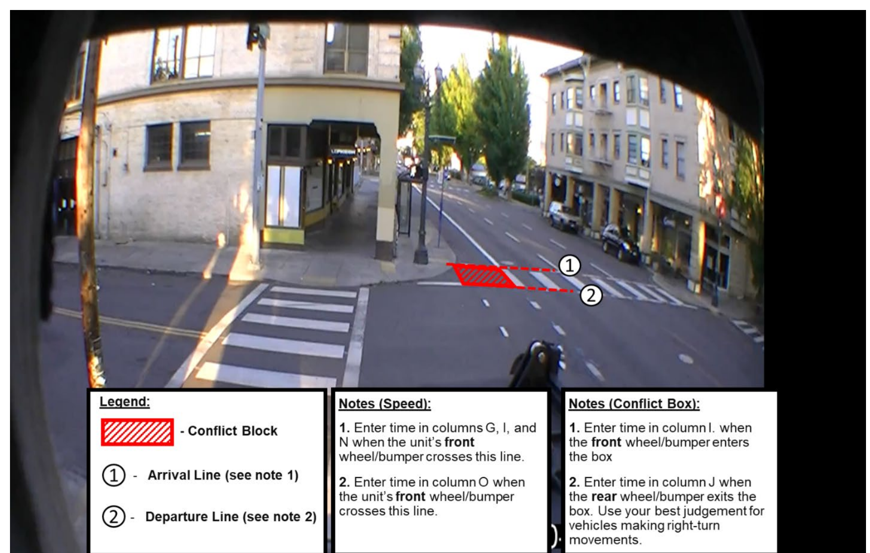
Summary of Average Hourly Volumes at Study Approaches

Site ID	Treatment	Avg. Hourly Bike Volumes				Avg. Hourly Vehicle Volumes				Avg. Hourly Parallel Pedestrian Volumes
		Left	Thru	Right	Total	Left	Thru	Right	Total	
1	Bike Box	0.1	21.5	4.5	26.1	5.2	374.0	53.5	432.7	24.7
2	Bike Box	0.0	9.0	10.0	19.0	0.0	248.3	37.9	286.2	4.2
3	Bike Box	0.0	9.2	0.0	9.2	5.1	24.8	8.3	38.2	15.0
4	Mixing Zone	0.4	7.3	0.4	8.1	12.4	50.6	32.1	95.1	25.1
5	Mixing Zone	2.3	12.0	0.0	14.3	74.0	92.8	3.4	170.2	9.9
6	Mixing Zone	0.2	11.5	0.3	12.0	0.0	64.8	58.7	123.5	11.9
7	Bicycle Signal	0.0	16.6	3.7	20.3	0.0	684.3	786.3	1470.6	4.8
8	Bicycle Signal	0.2	13.5	1.2	14.9	9.2	157.3	271.8	438.3	7.0
9	Bicycle Signal	0.1	1.2	0.1	1.4	129.3	564.3	135.5	829.1	15.2
10	Control	0.2	5.0	0.3	5.5	17.6	119.8	2.6	140.0	5.5
11	Control	0.3	12.1	0.8	13.2	37.3	838.2	57.6	933.1	17.6
12	Control	0.1	6.4	0.8	7.3	15.8	544.3	24.2	584.3	31.6

Field Data Analysis and Results

- Conflict/PET and speed extraction:

Candidate Event [1=B, 2=MV]	Time Stamp Arrival [hh:mm:ss.00]	Time Stamp Departure [hh:mm:ss.00]	First Unit to Arrive (1=Bike, 2=MV)	PET Value [s]	Elapsed Time For Speed Measurement [s]	This Column Converts Column I to a Number for Speed Calc	Speed [fps]	Speed [mph]
1	11:11:15.16	11:11:16.01	1		0:00:00.85	0.85	12.76	8.70
2	11:11:17.09	11:11:18.16		0:00:01.08	0:00:01.07	1.07	10.14	6.91
1	12:34:40.29	12:34:42.16	1		0:00:01.87	1.87	5.80	3.96
2	12:34:56.21	12:34:58.05		0:00:14.05	0:00:01.84	1.84	5.90	4.02
1	12:41:50.28	12:41:51.16	1		0:00:00.88	0.88	12.33	8.41
2	12:41:54.20	12:41:55.16		0:00:03.04	0:00:00.96	0.96	11.30	7.71
2	13:33:35.14	13:33:36.08	2		0:00:00.94	0.94	11.54	7.87
2	13:33:40.09	13:33:41.00		0:00:08.03	0:00:00.91	0.91	11.92	8.13
1	13:33:44.11	13:33:45.00		0:00:03.11	0:00:00.89	0.89	12.19	8.31
1	14:12:17.16	14:12:18.00	1		0:00:00.84	0.84	12.92	8.81
2	14:12:19.11	14:12:20.21		0:00:01.11	0:00:01.10	1.10	9.86	6.73
1	14:44:04.01	14:44:05.10	1		0:00:01.09	1.09	9.95	6.79
1	14:44:05.29	14:44:07.02		0:00:03.12	0:00:01.73	1.73	6.27	4.28
2	14:44:08.22	14:44:09.25		0:00:01.20	0:00:01.03	1.03	10.53	7.18



Field Data Analysis and Results

Summary of Observed Bicycle-Vehicle Conflicts

Site ID	Treatment	Avg. Hourly Right Turn Veh Volume	Avg. Hourly Through Bike Volume	No. of High Severity Conflicts (PET ≤ 1.5 sec)	No. of Medium Severity Conflicts (PET >1.5-3 sec)	No. of Low Severity Conflicts (PET >3-5 sec)	Total No. of Conflicts (PET ≤ 5 sec)
1	Bike Box	53.5	21.5	24	30	8	62
2	Bike Box	37.9	9.0	8	2	0	10
3	Bike Box	8.3	9.2	8	4	1	13
4	Mixing Zone	32.1	7.3	5	2	1	8
5	Mixing Zone	3.4	12	0	1	1	2
6	Mixing Zone	58.7	11.5	10	7	3	20
7*	Bicycle Signal	786.3	16.6	0	0	0	0
8*	Bicycle Signal	271.8	13.5	0	0	0	0
9*	Bicycle Signal	135.5	1.2	0	0	0	0
10	Control	2.6	5.0	0	0	0	0
11	Control	57.6	12.1	8	15	4	27
12	Control	24.2	6.4	8	4	1	13

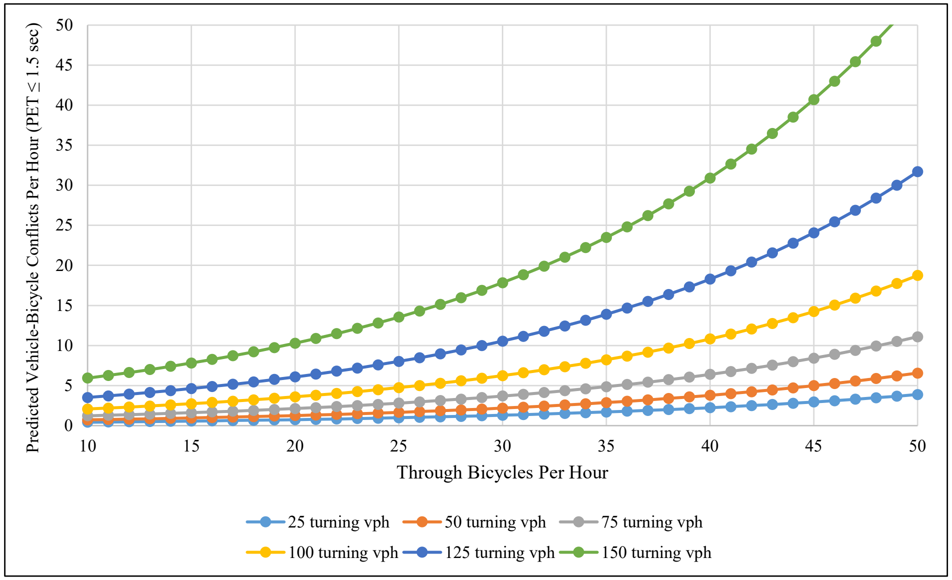
*These bicycle signal locations were expected to have very few if any conflicts since vehicle and bike movements are time-separated. These numbers do not include conflicts in which road users (vehicles or bikes) violated a signal.

Field Data Analysis and Results

- Poisson and Negative Binomial (NB) models developed using hourly conflicts and volumes.
  - Appropriate given discrete, non-negative nature of conflict count data
- Results very similar, but Poisson models showed slightly better fit

Results of Poisson Model for Conflict Frequency Across All Sites

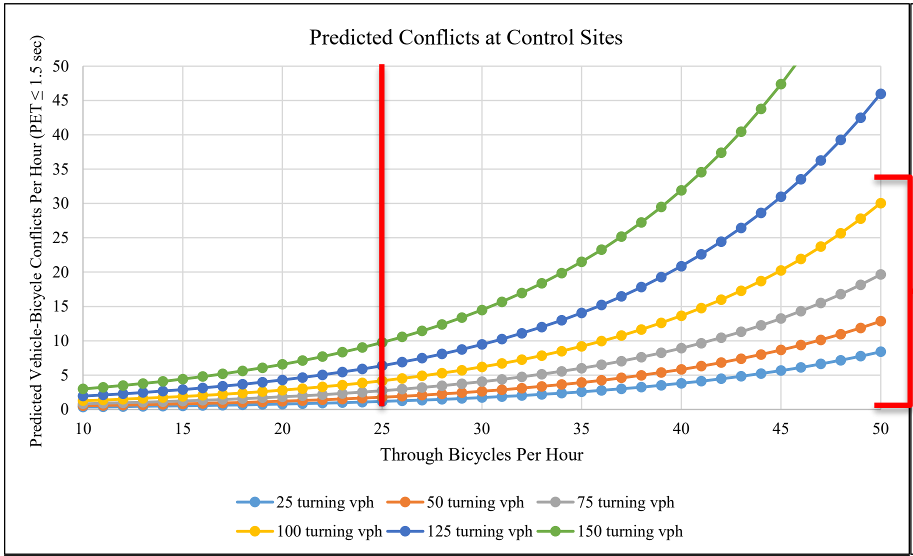
Parameter	Estimate (β)	Std. Error	P-Value
Intercept	-1.919	0.311	<0.001
Through Bike Volume	0.055	0.014	<0.001
Turning Veh Volume	0.021	0.005	<0.001

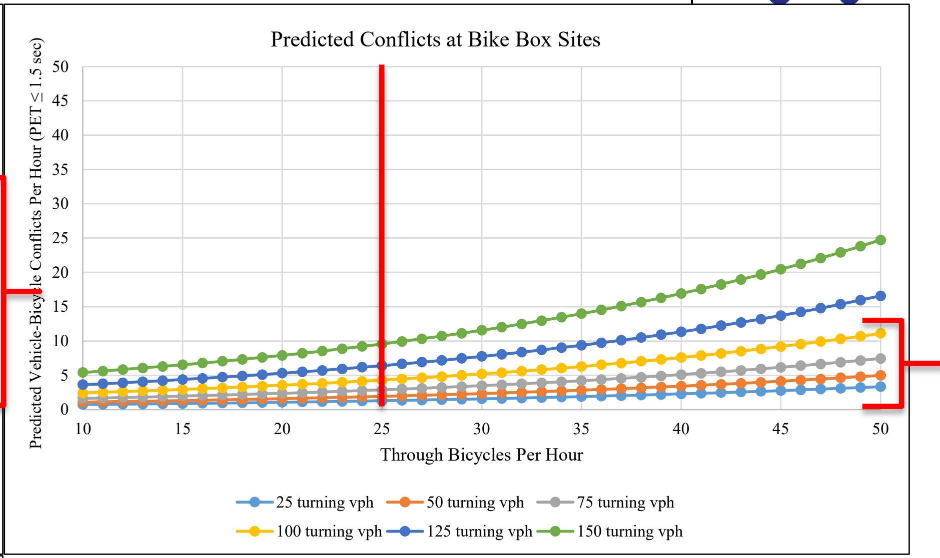


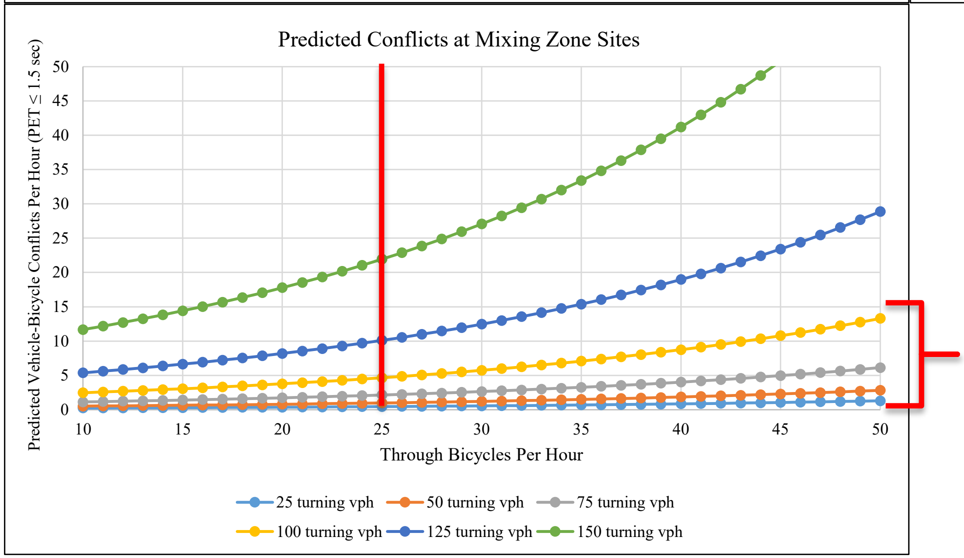
- Conflicts increase substantially when turning vehicle volume > 100vph
- Generally in line with previous research and existing guidance

Field Data Analysis and Results

Predicted Hourly Conflict Frequency for A) Control Sites, B) Bike Box Sites, and C) Mixing Zone Sites







- Conflict frequencies similar when there are ≤ 75 turning vph and ≤ 25 though bikes per hour
- At higher through bike volumes, bike boxes and mixing zones show fewer predicted conflicts
- When turning vph > 100, bike boxes have lowest predicted conflicts

Field Data Analysis and Results

Results of Poisson Models for Conflict Frequency by Site Type Considering Pedestrian Volumes

Parameter	Estimate (β)	Std. Error	P-Value
Control Site Model			
Intercept	-3.972	1.159	0.001
Bike Through Volume	0.068	0.043	0.112
Turning Veh Volume	0.021	0.012	0.081
Parallel Pedestrian Volume	0.068	0.027	0.011
Bike Box Model			
Intercept	-1.195	0.437	0.006
Bike Through Volume	0.034	0.018	0.067
Turning Veh Volume	0.013	0.009	0.147
Parallel Pedestrian Volume	0.017	0.019	0.359
Mixing Zone Model			
Intercept	-2.770	1.055	0.009
Bike Through Volume	0.044	0.049	0.361
Turning Veh Volume	0.031	0.010	0.002
Parallel Pedestrian Volume	0.008	0.028	0.776

- Parallel pedestrian volumes associated with increased conflicts at control sites
- Not a significant predictor at bike boxes or mixing zones

Field Data Analysis and Results

Summary of Bicycle-Vehicle Conflicts by Severity and Site Type

Site Type	Mean Conflict PET (s)	High Severity Conflicts (PET ≤ 1.5 sec)		Medium Severity Conflicts (PET >1.5-3 sec)		Low Severity Conflicts (PET >3-5 sec)		Total Conflicts (PET ≤ 5 sec)	
		Freq.	Percent	Freq.	Percent	Freq.	Percent	Freq.	Percent
Control	1.97	16	40.0%	19	47.5%	5	12.5%	40	100.0%
Bike Box	1.87	40	47.1%	36	42.4%	9	10.6%	85	100.0%
Mixing zone	2.22	15	50.0%	10	33.3%	5	16.7%	30	100.0%
Total Combined	1.96	71	45.8%	65	41.9%	19	12.3%	155	100.0%

Summary of Average Conflict Speed and Unit Arrival by Site Type

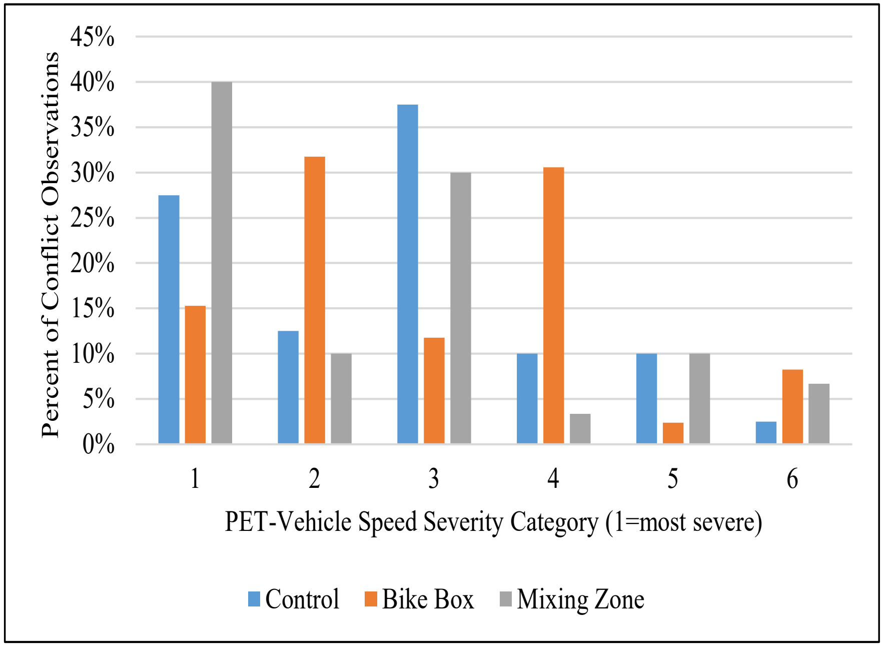
Treatment	Average Conflict Vehicle Speed (mph)	Percent of Conflicts with Bike Arriving First	Percent of Conflicts with Vehicle Arriving First
Control	8.5	72.5%	27.5%
Bike Box	6.9	77.6%	22.4%
Mixing zone	15.1	53.3%	46.7%

Field Data Analysis and Results

Percent of Conflicts Categorized by PET-Vehicle Speed Severity by Site Type

Treatment Type	PET-Veh Speed Severity Category (1=most severe)					
	1	2	3	4	5	6
	PET ≤ 1.5 sec, High Vehicle Speed	PET ≤ 1.5 sec, Low Vehicle Speed	PET > 1.5-3 sec, High Vehicle Speed	PET > 1.5-3 sec, Low Vehicle Speed	PET > 3-5 sec, High Vehicle Speed	PET > 3-5 sec, Low Vehicle Speed
Control	11 (27.5%)	5 (12.5%)	15 (37.5%)	4 (10.8%)	4 (10.0%)	1 (2.5%)
Bike Box	13 (15.3%)	27 (31.8%)	10 (11.8%)	26 (30.6%)	2 (2.4%)	7 (8.2%)
Mixing Zone	12 (40.0%)	3 (10.0%)	9 (30.0%)	1 (3.3%)	3 (10.0%)	2 (6.7%)

Note: values in table represent: frequency (percentage) in each category

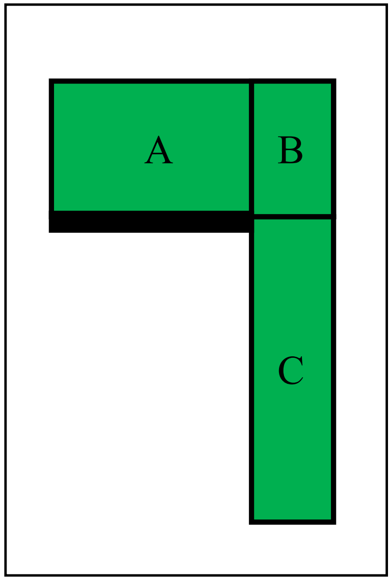


- Novel method to categorize conflict severity
- Considers PET categories and vehicle speed
  - Veh speed < 8mph = ‘low speed’
  - Veh speed ≥ 8mph = ‘high speed
- Bike boxes exhibited the lowest percentage of the most severe conflict category

Field Data Analysis and Results

Summary of Signal Indication at Arrival and Bicyclist Stopping Position at Bike Box Sites

Signal Indication on Bicyclist Arrival and Stopping Position (if applicable)	Frequency	Percent	Average PET (s)
Arrived on Green	61	71.8	1.88
Arrived on Red	24	28.2	1.86
Stopped in Position A	0	0	N/A
Stopped in Position B	20	83.3	1.97
Stopped in Position C	4	16.7	1.27



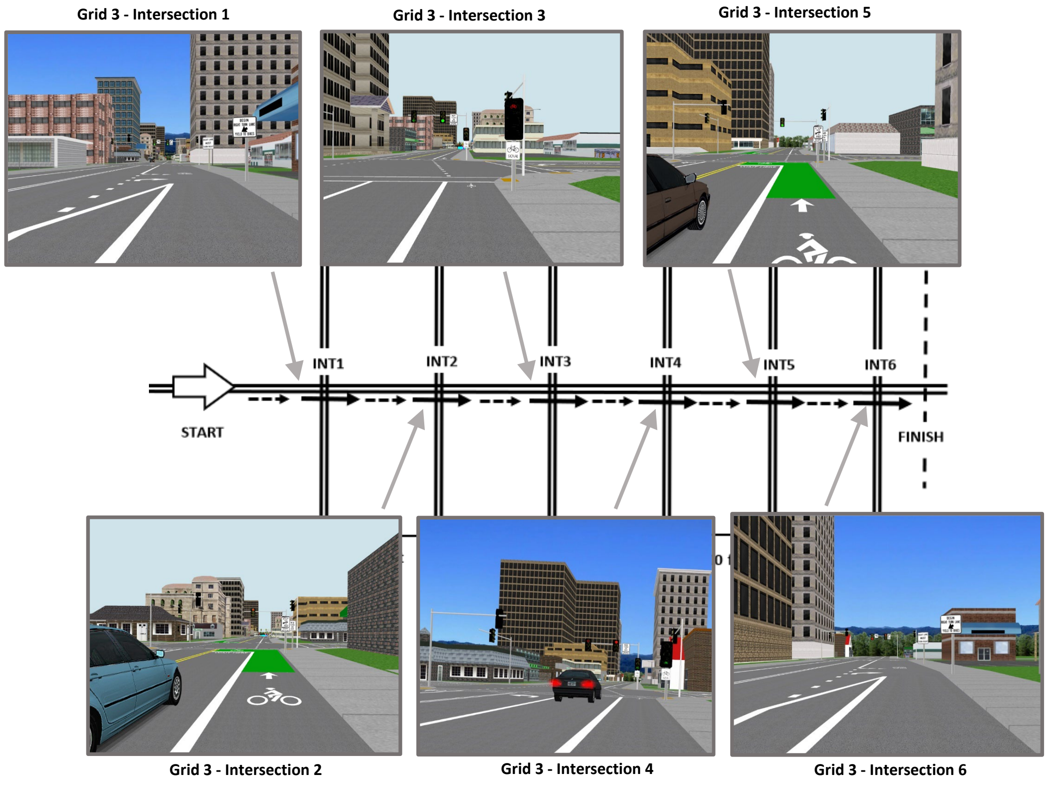
- No conflict-involved bicyclists had stopped in the 'A' area of bike box
- It is possible that stopping in the 'A' area (in front of the lead vehicle) may help prevent conflicts, though that inference cannot be verified with this data set.

Field Data Analysis and Results

Key takeaways from field data analysis include:

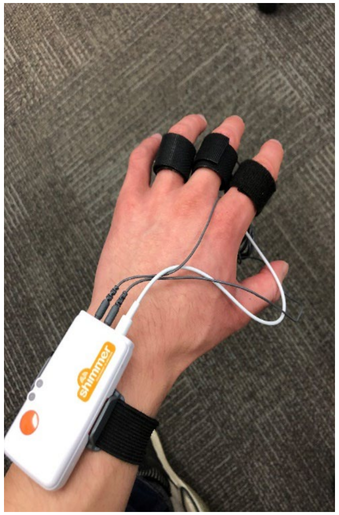
- Under low turning vehicle and bike volumes, predicted conflict frequency was similar for all three site types (bike boxes, mixing zones, and control sites)
- Under conditions with more than 25 through bikes per hour, the predicted conflict frequency at control sites were higher than those at bike boxes or mixing zones
  - This finding indicated that both bike boxes and mixing zones provide a benefit compared to control sites when through bike volumes are greater than 25 per hour, but the bike box may be a better option if turning vehicle volumes are greater than 100 per hour.
- Increased pedestrian volumes were associated with increased conflict frequency at control sites, but not at bike box or mixing zone sites
- Conflicts occurring at mixing zones had a higher vehicle speed, and were more likely have the bicyclist arrive first to the conflict point
- Bike box locations exhibited the lowest percentage of conflicts in the most severe category (low PET, high speed)

Bicycling Simulator Experiment



Bicycling Simulator Data Collection

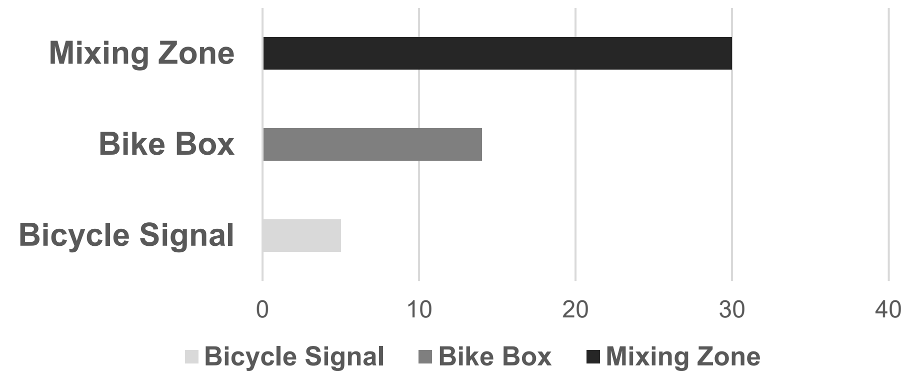
- Data collected from 40 participants
  - 23 Female – 17 Male
- Data collection techniques
  - Survey Questionnaire
  - Sim Observer
    - Lateral Position
    - Average Velocity
  - Eye Tracking
    - Visual Attention
  - Galvanic Skin Response



GSR (top) and Eye-tracking (bottom) device

Bike Sim Data Analysis and Results: ***Survey Questionnaire***

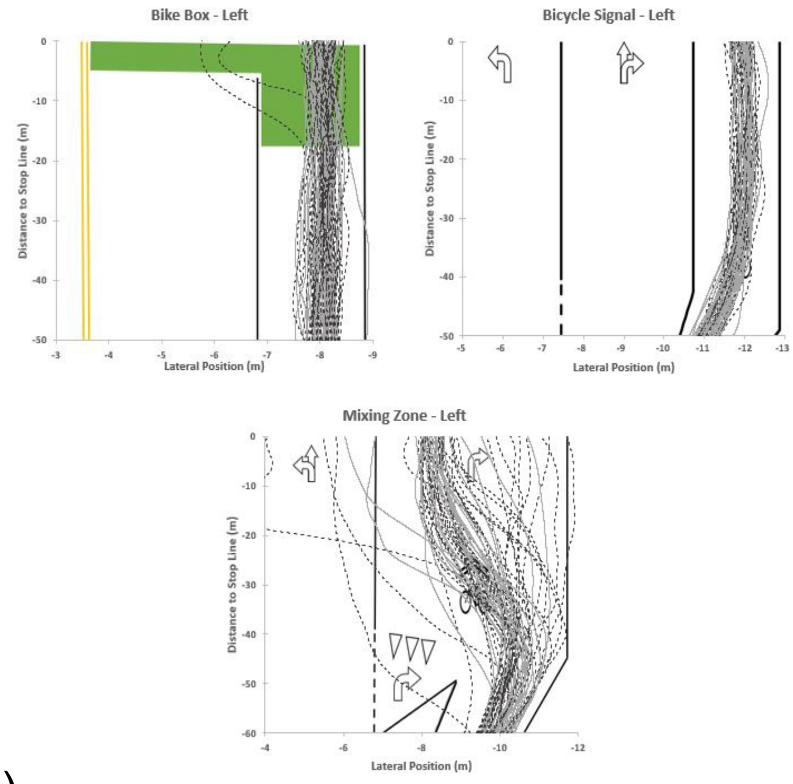
- Participant biking experience and biking frequency was well distributed
- 90% of participants have not seen at least one treatment
  - Indicates the potential for promotion and education of newer designs
- 69% were uncomfortable approaching an unfamiliar design
- Mixing zone shown to create the most discomfort



Participant number that indicated discomfort traversing treatment types

Bike Sim Data Analysis and Results: *Lateral Position*

- Assessed positioning as offset from center of lane
  - Recommended by the Society of Automotive Engineers (SAE) Standards
  - Lateral offset between rider's center of gravity and lane center
- Mixing zone proved most unpredictable
  - Scattered lane position
  - Average offset from lane center= 1.02m (left)
- Position in bike box and bicycle signals were clustered around lane center
  - Bike box average offset= 0.24m (left)
  - Bicycle signal average offset= 0.17m (left)



Lateral position through treatment types

Bike Sim Data Analysis and Results: *Lateral Position*

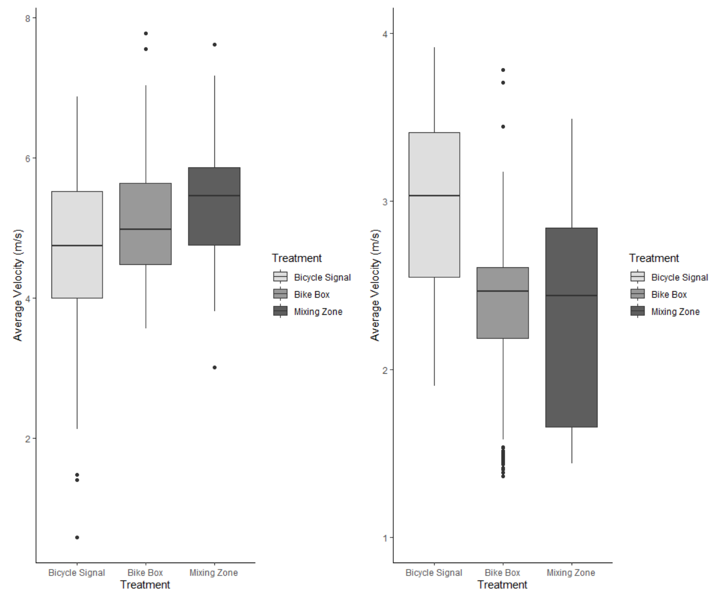
- Statistically significant result found in Repeated Measures ANOVA
  - F-stat= 26.825
  - P-value< 0.01
- Required Bonferroni pairwise comparison test
  - Statistically significant difference in offset from lane center across all treatments
  - Offset from lane center was the largest in the mixing zone

Treatment (i)	Treatment (j)	Estimate	SE	p-value	95% CI Lower	95% CI Upper
Bike Box	Mixing Zone	0.782	0.153	<0.01*	0.399	1.166
	Bicycle Signal	-0.067	0.024	0.029*	-0.128	-0.005
Mixing Zone	Bike Box	-0.782	0.153	<0.01*	-1.166	-0.399
	Bicycle Signal	-0.849	0.160	<0.01*	-1.250	-0.448
Bicycle Signal	Bike Box	0.067	0.024	0.029*	0.005	0.128
	Mixing Zone	0.849	0.160	<0.01*	0.448	1.250

Bonferroni Comparison Test Results on Position

Bike Sim Data Analysis and Results: *Average Velocity*

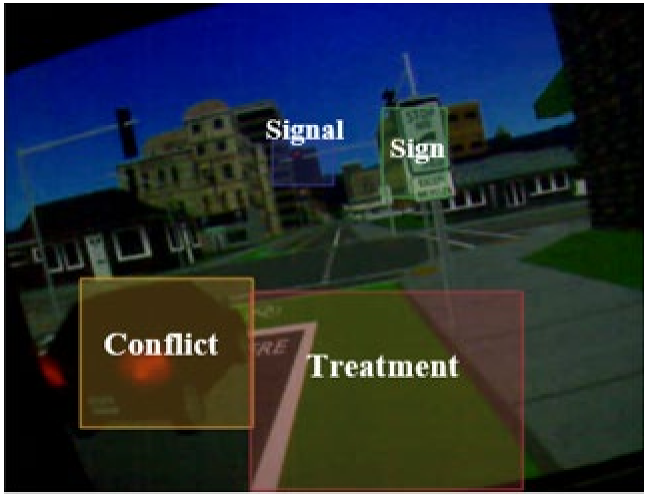
- Measured as the average velocity through the intersection
- Looked at arrivals on red and green indication separately
  - Due to the forced difference in speed dictated by the signal indication presented
- Treatment type revealed:
  - Mixing zone was associated with highest velocity when arriving on green
  - Bicycle signal was associated with highest velocity when arriving on red
- Conflict vehicle position revealed:
  - Left turning vehicle presence had lower velocity in majority of comparisons
  - Higher velocity when no conflicting vehicle was present



Average velocity boxplot in response to green (left) and red (right) indication

Bike Sim Data Analysis and Results: *Visual Attention*

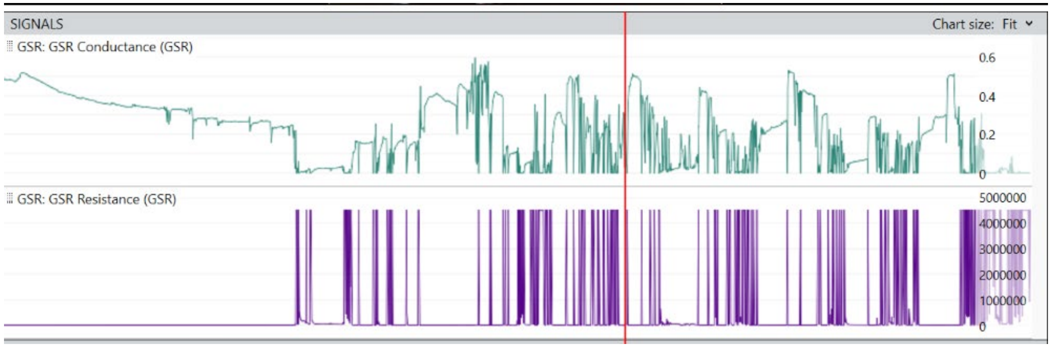
- Visual attention was used to assess conflict recognition
  - Total Fixation Duration (TFD) on conflict vehicle
- Mixing zone was associated with the largest TFD value
- Repeated Measures ANOVA test revealed a statistically significant result
  - P-value< 0.01
  - Bonferroni Pairwise Comparison test was therefore conducted
- Results of the Bonferroni test reveal:
  - All comparisons had statistical significance with comparisons across treatment type
  - Mixing zone TFD was 1.9 and 2.9 seconds more than the bike box and bicycle signal



Data reduction process for visual attention

Bike Sim Data Analysis and Results: *GSR*

- GSR was used to assess levels of stress in peaks per minute
- Results show slight variation in GSR response
  - For both treatment and conflict variables
- Stress response in bicycle signal scenarios was larger when a left-turn vehicle was present
  - May indicate that participants do not trust/understand the functionality of the treatment to remove conflicting movements
- Repeated Measures ANOVA test revealed no statistical significance
  - GSR peaks/min did not differ significantly across any variables
  - No additional testing was performed



GSR skin conductance over time for one participant

Bicycling Simulator Study Takeaways

- Bicycle Signal
  - Preferred treatment type by participants
  - Higher velocity while traversing
  - Lowest amount of conflict recognition/TFD values
  - Large fluctuations in GSR response
- Mixing Zone
  - Indicated to create the most discomfort for participants
  - Largest amount of conflict recognition/TFD values
  - Unpredictable lateral position of participants on approach
  - Slowest velocity in half of the scenarios
- Bike Box
  - Consistent middle ground between the other two treatment types
  - No extreme findings relative to the other designs
  - Provided a good balance of increased safety while promoting good riding habits

Recommendations for Practice

Recommendations for Practice

Treatment	Relative Cost of Installation	Relative Cost of Maintenance	Relative Time Frame for Application
Bike Box	Low-Med	Low-Med	Short
Mixing Zone	Low	Low	Short
Bicycle Signal	High	High	Long

<table>
<tr><th rowspan="2">Hourly Through Bicycle Volume</th><th colspan="7">Hourly Turning Vehicle Volume (vph)</th></tr>
<tr><th>25</th><th>50</th><th>75</th><th>100</th><th>125</th><th>150</th><th>>150</th></tr>
<tr><td><10</td><td colspan="3" rowspan="5">Treatment likely not required. May consider mixing zone or bike box especially if there is high parallel pedestrian volume.</td><td rowspan="5"></td><td colspan="2" rowspan="10">Consider Bike Box</td><td rowspan="11">Consider Bike Box or Bicycle Signal</td></tr>
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<tr><td>30</td><td colspan="4" rowspan="5">Consider Bike Box or Mixing Zone</td></tr>
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<tr><td>>50</td><td colspan="6">Consider Bike Box or Bicycle Signal</td></tr>
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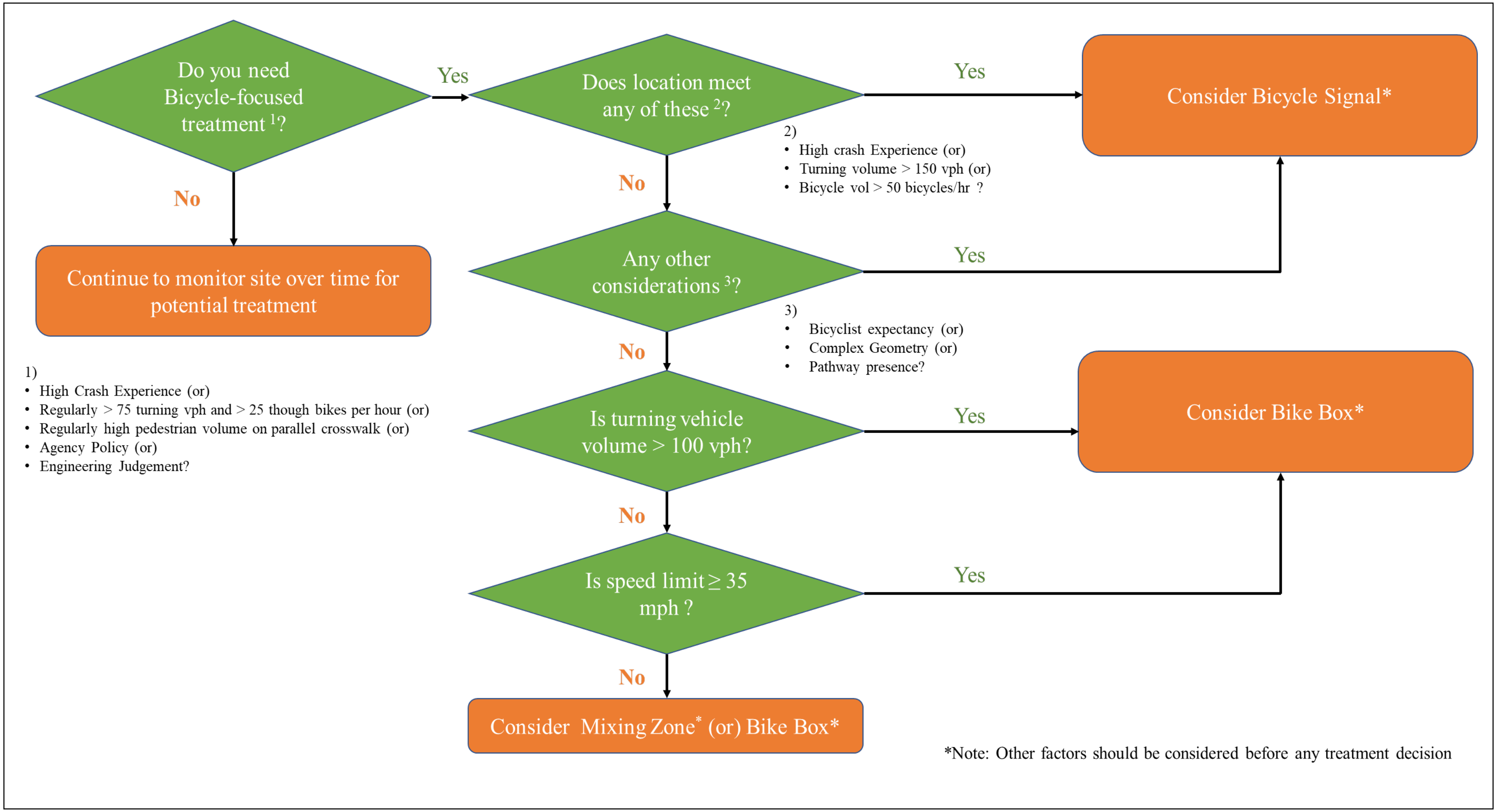
Recommendations for Practice



Recommendations for Practice

Consideration	Bike Box	Mixing Zone	Source of Guidance
Hourly Turning Vehicle Volumes and Through Bike Volumes	Generally similar predicted conflict frequency to mixing zones when turning vph < 100, but less predicted conflicts than mixing zones when turning vph > 100	Generally similar predicted conflict frequency to bike boxes when turning vph < 100, but more predicted conflicts than bike boxes when turning vph > 100	SPR833 Data Analysis
Right Side Parallel Pedestrian Volumes	Pedestrian volumes not significantly associated with conflict frequency	Pedestrian volumes not significantly associated with conflict frequency	SPR833 Data Analysis
Conflict Severity	Conflicts consistently less severe than mixing zones based on several severity measures	Conflicts consistently more severe than bike boxes based on several severity measures	SPR833 Data Analysis
Average Vehicle Speeds During Conflict	6.9 mph	15.1 mph	SPR833 Data Analysis
Bicyclist Comfort	46.7% of bicycling simulator participants felt discomfort	76.9% of bicycling simulator participants felt discomfort	SPR833 Data Analysis
Lateral Position of Bicyclists in Treatment	Rode near center of bike lane (average of 0.8 ft to the left of center of lane)	Rode more near the left edge of bike lane (average of 3.3 ft to the left of center of lane)	SPR833 Data Analysis
Bicyclist Visual Attention to Vehicle	Bicyclists give less visual attention to vehicle	Bicyclist give more visual attention to vehicle (nearly 2s more than at bike boxes)	SPR833 Data Analysis
Speed Limit	No specific guidance (apply engineering judgement)	Vehicle speeds should be 20mph or less at merge point. If speed limit is 35mph or greater, may need to provide deceleration lane	(MassDOT, 2015)
Bicycle Left Turn Volumes	May help facilitate left turns for bicyclists	Does not facilitate left turns for bicyclists	(NACTO, 2014)
Roadway Operation (one-way or two-way) and Width	Can be considered on one- or two-way streets, but may not be appropriate for wide one-way streets	Can be considered on one- or two-way streets regardless of width, but enough width for the shared bike/vehicle lane is required (9ft min)	(NACTO, 2014)

Limitations and Future Research

- Other bicycle-specific intersection treatments could be considered (e.g., protected intersections, two-stage turn queue boxes, etc.)
- Impacts of alternative phasing schemes (e.g., LBI, split LBI, bike scramble, etc.) along with compliance to bicycle signals could also be investigated.
- Field Data: Collected during COVID-19 Pandemic and likely to inherently include some small level of measurement error.

Limitations and Future Research

- Microsimulation: at the control and bike box sites, the conflict frequency outputs were excessively low and strong conclusions could not be made from these data.
  - Microsimulation modeling could be useful to investigate the operational (i.e., delay) impacts of the treatments assessed in this study and other treatments
- Bicycling Simulator:
  - Future bicycling simulator work could focus on how participant behavior changes over time to assess if the responses change as they traverse the study treatments more frequently.
  - Additional research could also be expanded to include driver and pedestrian users in the simulator experiment.

Thank You.
Questions/Discussion?

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