DO DRIVERS MAKING A RIGHT TURN BEHAVE DIFFERENTLY BASED ON PRESENCE OF A BICYCLIST OR A BICYCLE FACILITY?

Research Paper

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INTRODUCTION

Bicycle ridership in Boston has been increasing since the beginning of the 21st century. A report published in 2014 by the League of American Bicyclists (LAB)[1] shows that the city has seen a 148% growth in bike commuters from 2000 to 2014. Even though there is an increase in the number of people commuting by bike, the numbers are still far from what they can be. A 2018 survey published by People For Bikes[2] reports that 47% of the adults in the U.S want to ride more often and 50% worry about being hit by a motor vehicle. This clearly indicates that concern for safety is a major barrier to cycling. According to the National Highway Traffic Safety Administration (NHTSA)[3], bicyclists account to 2.1% of all the traffic fatalities in 2017. More than three quarters of these fatalities happened in urban areas.

A Cyclist Safety Report[4] published in 2013 by the City of Boston consolidated the crash data obtained from multiple sources in the city. According to this report, between 2009 and 2012, bicycle collisions reported to Boston Police department (BPD) totaled 1,813 of which 91% involved a motor vehicle. However, this report failed to capture the collision characteristics and it also does not contain information on unreported crashes. Most fatalities and collisions that make it into the reports vastly under represent the actual risk of a crash as these reports do not include near-miss incidents that happen far more frequently. BikeMaps[5], a crowdsource tool that maps cycling safety observed that only 30% of the bike collision data are collected and reported. BikeMaps data also show that near-misses significantly outnumber reported collisions.

One of the most common types of crashes, the right hook, occurs at intersections between automobiles turning right and bicycles going straight (Figure 1). One of the reasons for right hooks is the ambiguity in the behavior of drivers at an intersection. Turning drivers use turn signals as they approach an intersection to convey their intent to make a turn. This behavior increases predictability and helps reduce the potential for a collision. While some drivers use signals well in advance, many use their signals when they are very close to the intersection or in some instances, not use them at all.

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[1] http://bikeleague.org/sites/default/files/Where_We_Ride_2014_data_web.pdf

[2] https://peopleforbikes.org/resources/u-s-bicycling-participation-report/

[3] https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812765

[4] http://www.cityofboston.gov/news/uploads/16776_49_15_27.pdf

[5] https://bikemaps.org

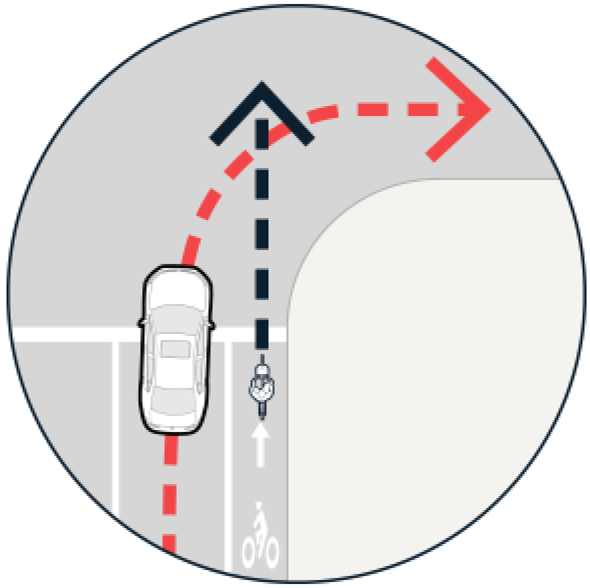

Figure 1: Example of Right Hook. Right Turning Motor Vehicle Conflicts With Bicycle Going Straight

The intent of this study is to determine whether drivers making a right turn behave more predictably by using turn signals early if the roadway has a cycle track or a bike lane, or if there is a bicyclist present nearby. This is done by conducting statistical hypothesis tests to see if there is evidence to reject hypotheses that more drivers use turn signals early when there is a higher degree of separation between bikes and motor vehicles or when there are bicyclists present on the roadway.

METHODOLOGY

The signaling behavior of drivers turning rights can be measured by counting the number of drivers that used the turn indicator before and after crossing the stopping sight distance (SSD). SSD is the distance required by vehicles to come to a complete stop. It depends on the speed, reaction time, and deceleration rate of vehicles on the roadway (1). A right turning driver crossing the SSD without braking cannot stop before reaching the conflict point with a bicyclist. If this driver does not also use a turn signal, then any bicyclist approaching the conflict point is may not be aware of the driver's intention to turn right which could lead to a crash. Therefore, drivers turning right need to signal or brake as they approach the SSD to give themselves and bicyclists a chance to avoid a right hook.

$$SSD = 1.47Vt + 1.075 * \frac{V^2}{a} \tag{1}$$

$$\begin{aligned}
&where \\
&SSD \quad = stopping\ sight\ distance, \quad ft \\
&V \quad = design\ speed, \quad mph \\
&t \quad = brake\ reaction\ time, \quad 2.5\ s \\
&a \quad = deceleration\ rate, \quad 11.4\ ft/s^2
\end{aligned}$$

The observations on right turn signal location, when repeated for intersections with different bicycle accommodations like cycletracks, bike lanes and mixed traffic conditions, indicate whether the type of bicycle facility affects signaling behavior. Similar observations in the presence or absence of a bicyclist shows if a bicyclist nearby affects driver signaling behavior.

Each right-turning driver approaching the intersection is modeled as a Bernoulli trial with two outcomes: success – signaling before SSD and failure – not signaling before SSD. The number of drivers observed to have signaled before SSD in the data follows a binomial distribution. The number of instances when vehicles signaled before SSD modeled as successes (a_i) and the number of instances when vehicles signaled after SSD (or not signaled at all) modeled as failures (b_i). The proportion (p_i) of vehicles signaling early (successes) is given in (2) where *i* represents the scenario. In this case, the tests are comparing two sample proportions and *i* takes a value of 1 or 2.

$$p_i = \frac{a_i}{n_i} \qquad \text{where } n_i = a_i + b_i \tag{2}$$

The objective is to test if the proportion of the right turning drivers signaling before SSD is higher for scenarios when a bicyclist is present or when the road has a more protected bicycle facility. Among the type of bike facilities considered in this study, cycletracks have the highest degree of protection; bike lanes have a moderate degree of separation and mixed traffic offers the least degree of protection. Each hypothesis compares the $p_i$associated with two cases. The hypothesis test formulation is shown in (3); p_1 and p_2 are the proportions of successes for two comparison cases.

$$\begin{aligned}
&H_0: p_1 - p_2 \ \geq 0 \\
&H_1: p_1 - p_2 < 0
\end{aligned} \tag{3}$$

A normal approximation to the binomial can be applied when both a_i and b_i are greater than five. The test statistic Z_0 described by (4) is a random variable that approximately follows a standard normal distribution when the null hypothesis is true ($p_1 - p_2 = 0$). It is important to note that the null hypothesis written as $H_0: p_1 - p_2 = 0$ is an acceptable alternative notation, since the alternative hypothesis dictates whether the test or one or two-tailed.

$$Z_0 = \frac{\hat{p}_1 - \hat{p}_2}{\sqrt{\hat{p} * (1 - \hat{p}) \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{4}$$

$$\begin{aligned}&where\\&\hat{p}_1\ and\ \hat{p}_2\ are\ the\ proportions\ of\ successes\ in\ the\ samples\\&\hat{p} = \frac{a_1 + a_2}{n_1 + n_2}\\&n_1\ and\ n_2\ are\ the\ sample\ sizes\end{aligned}$$

The criteria for rejecting the null hypothesis is $Z_0 < Z_\alpha$ where α represents the probability of rejecting H_0 when H_0 is true (Type I error) and Z_α is the standard normal value corresponding to α. A value of $\alpha = 0.05$ is used for this study. The other type of error in hypothesis testing is the Type II error which is failing to reject a null hypothesis when it is false. The probability of this error is denoted by β. Power of a test is represented by $(1 - \beta)$ and can be calculated using (5).

$$Power = 1 - \beta = \Phi \left[\frac{\left(Z_\alpha * \sqrt{p * (1 - p) \left(\frac{1}{n_1} + \frac{1}{n_2}\right)} + (p_1 - p_2) \right)}{\sigma_{p_1 - p_2}} \right] \tag{5}$$

$$where \qquad \sigma_{p_1 - p_2} = \sqrt{\frac{p_1(1 - p_1)}{n_1} + \frac{p_2(1 - p_2)}{n_2}}$$

A total of four tests are performed to compare the proportions and the comparison cases for each of the four tests (Table 1). The first three tests compare the proportions associated with the type of bike facility present while the fourth test compares the case when a bicyclist is present to a case when a bicyclist is absent between the turning automobile and the intersection. While designing a hypothesis test, it is important to note that the burden of proof is on the alternative hypothesis. One can only choose to reject or not to reject the null hypothesis based on the result of the test.

Table 1: Comparison Conditions in Hypothesis Tests for Difference in Proportion of Drivers Using Turn Signals Before SSD.

	Condition 1	**Condition 2**
Test 1	Cycletrack	Bike Lane
Test 2	Bike Lane	Mixed Traffic
Test 3	Cycletrack	Mixed Traffic
Test 4	Bicyclist Present	Bicyclist Absent

DATA

Data were collected at four different intersections on the Massachusetts Avenue corridor between Route 28 and Harvard Bridge in Boston (Figure 2). This corridor was chosen due to the high number of bicycle related crashes reported to BPD between 2009 and 2012. The four intersections used for data collection are where Massachusetts Avenue meets Beacon Street, Newbury Street, St Botoloph Street, and Columbus Avenue. At the time the data were collected, Massachusetts Avenue had a cycletrack (protected bike lane) on the southbound direction approaching Beacon Street, bike lanes approaching Newbury Street and Columbus Ave, and shared traffic lane (mixed traffic) at St Botoloph Street.

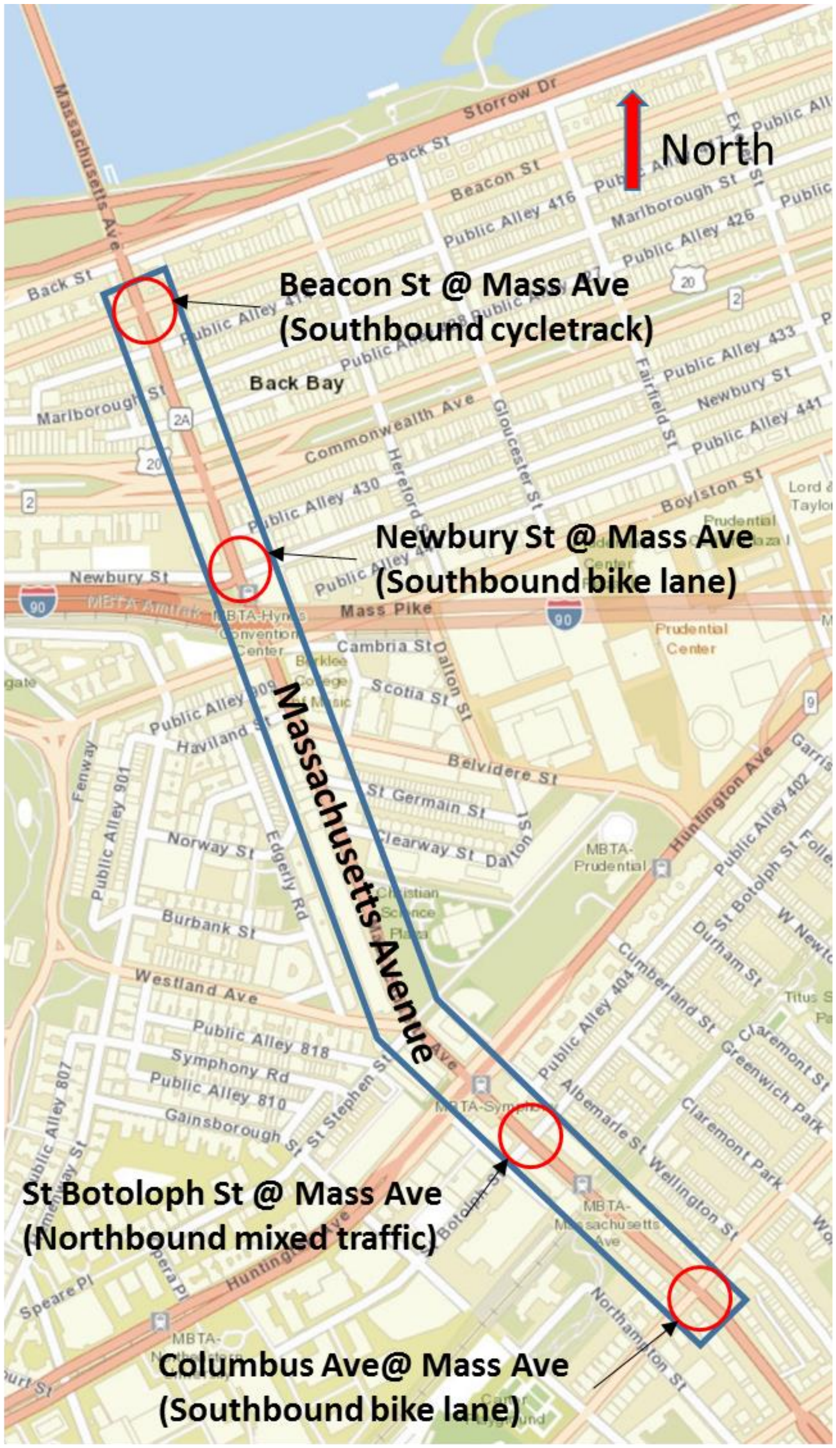

Figure 2: Analysis Corridor on Massachusetts Avenue and the Intersections at Which Data Were Collected to Study the Signaling Behavior of Right Turning Drivers.

The data were collected for right turning vehicles going northbound on Massachusetts Ave at St Botoloph Street as the northbound direction as the southbound approach had less right turning drivers. Data were collected in the southbound direction at Newbury St and Beacon St as they are one-ways going westbound and thus northbound traffic cannot turn right. At Columbus Ave, data were collected from southbound traffic on Massachusetts Ave as that approach had a larger number of vehicles turning right. Massachusetts Ave has a cycletrack at Beacon Street (Figure 3), bike lanes at Newbury St and Columbus Ave (Figures 4, 5), and bicyclist share the lane with motor vehicles at Botoloph St (Figure 6)

Figure 3: Cycletrack on Southbound Direction of Massachusetts Ave at Beacon St.

Figure 4: Bike Lane on the Southbound Direction of Massachusetts Ave at Newbury St.

Figure 5: Bike Lane on the Southbound Direction of Massachusetts Ave at Columbus Ave.

Figure 6: Mixed Traffic Marked by a Sharrow on the Northbound Direction of Massachusetts Ave at St Botoloph St.

There was no exclusive right turn lane at any of the intersections and bicycles typically use their own marked lane when present or the right most lane when no bike lane is present. For each intersection, the number of turning vehicles that used the turn indicator before and after crossing the SSD were recorded. The approach speeds were collected using a radar gun for vehicles approaching the intersection when the light had been green for some time (stale green) and vehicles approaching didn't need to slow down as they approach the intersection. This is important as the vehicles turning at the beginning of the green are usually travelling slower than the vehicles approaching the intersection on stale green and their stopping distance is not the same as the SSD calculated using the design speed. The stale green time was not a fixed value as it varied with number of vehicles in queue. In this study, the observations were recorded when the approaching vehicles no longer slowed down for vehicles in front of them. The 85^{th}

percentile speed is used as design speed which is a common practice in transportation applications. The SSDs were calculated using the design speed for each intersection approach and the formula for SSD (Table 2).

Table 2: SSD for Each Intersection and Type of Bike Facility for the Study Corridor.

Intersection	Direction	85 %ile Speed (mph)	SSD (feet)	Bike Facility
Beacon St @ Mass Ave	Southbound	33.3	230	Cycletrack
Newbury St @ Mass Ave	Southbound	29.4	190	Bike Lane
St Botoloph St @ Mass Ave	Northbound	30.3	200	Mixed Traffic
Columbus Ave @ Mass Ave	Southbound	32	215	Bike Lane

The location of the right turn signal was recorded for each intersection to obtain the number of drivers signaling before and after SSD. In addition to the location of the vehicle when turn signal was activated, it was also noted if there is a bicyclist present within the SSD either in the main travel lane or on an adjacent bike lane/cycletrack if one is present. In several instances, vehicles made a turn without using their indicators which was also noted. All the observations were taken between 3 P.M and 6 P.M on weekdays and only vehicles turning on stale green were considered.

ANALYSIS & RESULTS

The number of drivers who have signaled before SSD, after SSD, and not signaled at all by bicycle facility type and presence of bicyclist are recorded (Table 3). The percentage of drivers that signaled before the SSD (p) was within 0.1% for when a bicyclist is present (31.73%) and when a bicyclist is absent (31.63%). However, the proportion of drivers who did not signal at all is smaller by 7.89% when there is a bicyclist present. Higher proportion of drivers signaled earlier than SSD when there is a cycletrack or a bike lane than when they are in mixed traffic (Figure 7). The observations for the presence or absence of a bicyclist are the combined values for all bicycle facility types. The observations for cycletrack, bike lane, and mixed traffic include combined values from when a bicyclist is present or not. The samples indicate that a bike lane or a cycletrack induces drivers to signal earlier than mixed traffic.

Table 3: Number of Drivers Using Signals Before SSD, after SSD, or Not at all Under Different Conditions.

	Signaled before SSD	**Signaled after SSD**	**No signal at all**	**Total *(n)***
Cycletrack (combined – cyclists present or absent)	50	70	9	129
Bike Lane (combined – cyclists present or absent)	95	177	36	308
Mixed Traffic (combined – cyclists present or absent)	30	69	17	116
Bike Present (all bicycle facility types)	33	66	5	104
Bike Absent (all bicycle facility types)	142	250	57	449

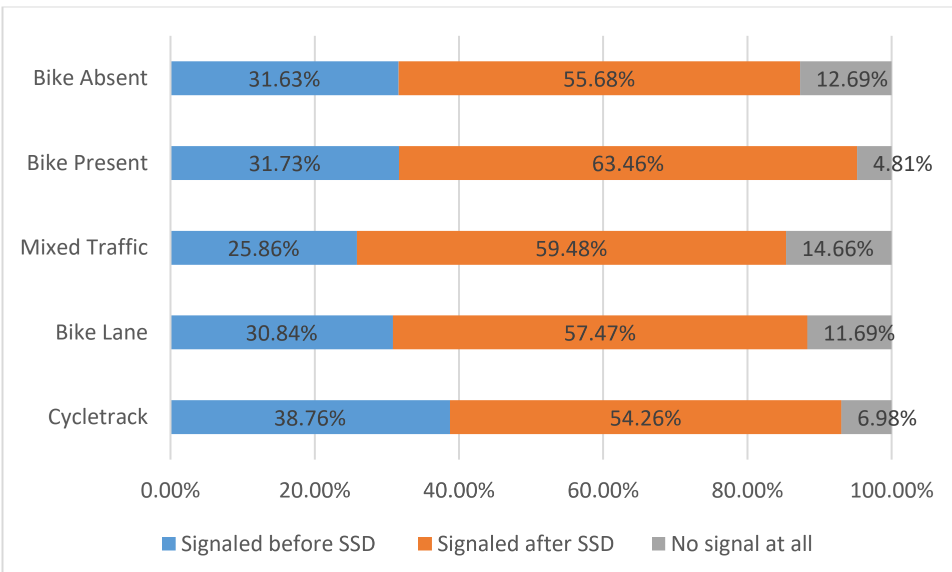

Figure 7: Proportions of Right Turn Signal Locations Under Different Conditions.

Hypothesis Tests

The difference in proportions of drivers using a turn signal before SSD is the highest in Test 3, which compares cycletrack to mixed traffic condition. When a cycle track is present, 12.9% more drives signaling before SSD than when they are in mixed traffic. There is negligible difference in the proportions of Test 4 which tests the proportions for a bicyclist being present or absent. The difference in proportions have higher values for tests comparing bicycle facilities than for the test comparing presence or absence of a bicyclist (Table 4). The sample sizes are large enough in for each test to be able to use the normal approximation for testing the difference in proportions.

Table 4: Difference in Porportions of Drivers Singalling Before SSD For the Four Test Cases.

	Condition 1	Condition 2	$p_1 - p_2$
Test 1	Cycletrack	Bike Lane	7.92%
Test 2	Bike Lane	Mixed Traffic	4.98%
Test 3	Cycletrack	Mixed Traffic	12.90%
Test 4	Bicyclist Present	Bicyclist Absent	0.10%

Based on the data, none of the four tests had evidence to reject the null hypothesis (Table 5). In other words, there is not enough evidence to suggest that vehicles do not use right turn signals earlier when there is a higher degree of separation or when there is a bicyclist present nearby. In all these cases, the probability of a Type 1 error (α) was set to 0.05. This means there is a 5% chance of rejecting the null hypothesis when it is true. The probability of Type 2 error (β) and the power of the test are also shown in Table 5.

Table 5: Results of the Hypothesis Tests. Type I and Type II Errors are Shown in addition to the Test Statistic.

	Condition 1	Condition 2	α	Z_0	Z_α	Power $= 1 - \beta$	β
Test 1	Cycletrack	Bike Lane	0.05	1.603	-1.645	0.484	0.516
Test 2	Bike Lane	Mixed Traffic	0.05	1.003	-1.645	0.255	0.745
Test 3	Cycletrack	Mixed Traffic	0.05	2.149	-1.645	0.696	0.304
Test 4	Bicyclist Present	Bicyclist Absent	0.05	0.021	-1.645	0.052	0.948

These values suggest that the case testing cycletrack vs mixed traffic has the highest power (and the smallest β) which indicates reasonable confidence that the test fails to reject the null hypothesis when it is false. The case of cycletrack vs bike lane has a $\beta = 0.516$ which is the second lowest Type 2 error probability of all the test cases. Test case 2 (bike lane vs mixed traffic) has an even higher probability of Type 2 error which makes it less powerful than the earlier two tests. In the case of whether a bicyclist is present or absent, the test does not reject the null hypothesis at a 5% significance level. This case also has $\beta = 0.948$ which means that there is a 95% probability of the test not rejecting the null hypothesis when it false. This drastically reduces the power of the test and should not be used to make a claim that vehicles signal earlier when a bicyclist is present.

The above test results place the burden of proof on the alternative hypothesis. If the null and alternative hypotheses were switched, then the burden of proof will also be switched, and the tests will look for evidence to prove that vehicles signal earlier with a higher separation and presence of a bicyclist. The switched hypothesis is formulated in (6).

$$\begin{aligned} H_0&: p_1 - p_2 \leq 0 \\ H_1&: p_1 - p_2 > 0 \end{aligned} \tag{6}$$

With this formulation of hypothesis, Test 3 (cycletrack vs mixed traffic) has sufficient evidence that drivers signal earlier next to a cycletrack than when bikes share a lane with motor vehicles, and we reject the null hypothesis at a 5% significance level. This provides a strong evidence that drivers signal early near cycletracks than when they are in mixed traffic conditions. The evidence is not strong enough to support a comparable claim in the other comparison cases.

LIMITATIONS

The main motivation of the study is to understand signaling behavior that can influence right hooks. Other factors such as bicyclist behavior, type of vehicle (e.g. car vs truck vs bus), driver familiarity, that can influence right hooks are not analyzed in this study. Bicyclist presence does not differentiate between whether there are one or more bicyclists and how visible they are to drivers. The analysis corridor did not have any exclusive right turn lanes and the analysis is only relevant to cases with a shared right turn/through lane.

The turn signal data collected show whether a driver used signal before the SSD. This is a discrete binary variable and does not have information on where exactly signals were activated. For example, on a road with and SSD of 200 feet, a driver signaling at 190 feet is different from a driver signaling at 210 feet, but it is the same as a driver signaling at 10 feet from the intersection. Using discrete data was a deliberate choice made for the purpose of improving data collection and processing efficiency. It is impossible to say how this choice might affect the results of the analysis. If a continuous variable is used, a binomial distribution cannot be used, and an appropriate continuous distribution must be used. The use of binomial distribution also assumes that each driver signals independently of other drivers. This may not always be true since the use of a signal by a driver ahead might remind the next driver to use their signal early.

CONCLUSION

Presence of a cycletrack or bike lane showed an observably higher proportion of right turning drivers signaling before the SSD compared to when bikes are travelling in mixed condition. This is especially strong with cycletrack than with a regular bike lane. While there was not enough evidence to reject the original hypothesis that drivers signal earlier with the presence of a bicyclist or a bike facility, some of the hypothesis tests have a high probability of Type 2 error. Only the case of cycletrack vs mixed traffic is the Type 2 error low. In case of whether a bicyclist is present, the Type 2 error was high enough to discount the test completely.

The test results clearly show that cycletracks are much more effective in terms or improving predictable driver behavior than other on street bike facilities, which have lower degree of separation from traffic. Presence of bicyclist did not seem to have any impact on the behavior of drivers. Based on the results of this study, it is apparent that cycletracks have the highest positive effect on right-turning driver behavior.