# Assessing the Impact of Bicycle Infrastructure Treatment Type on the Frequency of Right-Hook Conflicts Between Bicyclists and Motorized Vehicles at Signalized Intersections

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**Abstract**

Bicycle infrastructure treatments are implemented to enhance bicyclist mobility and safety. However, crashes between motorized vehicles and bicycles still occur at locations where these treatments are present, indicating the need to further investigate their safety impact. This paper aims to assess the impact of three segment-level bicycle treatments, namely: (1) conventional bike lanes, (2) protected bike lanes, and (3) sharrows (i.e., shared vehicle-bicycle traffic lanes) and two intersection-level bicycle treatments, namely (1) intersection crossing markings and (2) bike boxes, on right-hook conflicts, which is a common unsafe interaction between right-turning vehicles and through—bicycle at signalized intersections. Video data were collected from ten intersections in Boston, Cambridge, and Somerville, Massachusetts. Video recordings were processed to identify interactions between right-turning vehicles and through bicycles that corresponded to a Post Encroachment Time (PET) of less or equal to four seconds. Poisson models

were developed to relate the number of traffic conflicts with the number of right-turning vehicles, through bicycles, and the treatment type. However, the latter was not found to affect conflict frequency. Further analysis of the PET thresholds showed that there is a significant difference in the recorded PET values depending on the user sequence in the conflict area. Specifically, when a motorized vehicle was followed by a bicycle, PETs of 1 second were more frequent compared to when a bicycle was followed by a motorized vehicle. This observation suggests that different thresholds for bicycle-leading or bicycle-following PETs may be considered to account to advance conflict-based bicycle safety approaches. The outcome of this research can inform practitioners on the selection of appropriate bicycle treatments and other countermeasures for improving intersection safety for bicyclists.
*Keywords:* bicycle safety, protected bike lane, conventional bike lane, sharrows, bike box, surrogate safety measures, post encroachment time

## 1. Introduction

Increasing bicycling mode share is gaining popularity as it has been associated with environmental and multiple public health benefits, while also being an effective way to address congestion in highly crowded areas. The implementation of bicycle treatments has the potential to increase bicycle mode share by improving safety and convenience. While there is evidence that bicycle treatments improve bicyclist safety, bicycle-motorized vehicle crashes still occur at locations where treatments are present (DiGioia et al., 2017; Thomas and DeRobertis, 2013). This highlights the need to further explore the safety impacts of bicycle treatment types and provide guidance on the most appropriate treatment for different roadway environments and vehicles and bicycle demands.

Crash statistics from the United States (U.S.) suggest that a significant portion of bicycle-motorized vehicle crashes take place at urban intersections (Pedestrian and Bicycle Information Center, 2019). Furthermore, some evidence from countries around the globe like the U.S., Canada, and Germany suggests that signalized intersections are associated with a higher risk for bicyclists compared to unsignalized intersections (Strauss et al., 2015; Hurwitz et al., 2015; Liu and Marker, 2020). A common crash type between bicyclists and motorized vehicles at intersections is the "right-hook" crash (Cantisani et al., 2019; Foldberg Steffensen and Gaardbo, 2016; Hurwitz et al., 2015), where a right-turning vehicle collides with a through-going bicycle; Figure 1 illustrates this collision type. Right-hook conflicts are also very common compared to other conflicting interactions (Cantisani et al., 2019). Right-hook conflicts (and in turn, crashes) occur when right-turns are allowed during the green phase at intersections where bicyclists and motorists coexist. While both right-turning vehicles and through-bicycles are traveling as indented, their paths can cross. Given that the placement of the bicycle with respect to the motorized vehicle affects both the occurrence and severity of right-hook crashes (Warner et al., 2017; Jannat et al., 2018), it is critical to study the specifics of the interactions between bicyclists and motorists performing the aforementioned movements in the presence of bicycle treatments.

Segment-level treatments such as protected and conventional bike lanes and sharrows affect bicyclist placement with respect to motorized vehicles.

Protected and conventional bike lanes separate bicyclists from motorized vehicles. In the former case bicyclists and motorized vehicles are physically separated via various objects (e.g., bollards, parked vehicles, etc.) while in the case of conventional bike lanes pavement marking is used to indicate where bicyclists should ride. Sharrows on the other hand, allow mixed-traffic conditions and bicyclists can share the exact same road space as motorized vehicles. When protected or conventional bike lanes are implemented, bicyclists are usually on the right on motorists. Due to the physical separation that protected bike lanes offer, drivers might be driving closer to protected bike lanes compared to when driving next to conventional bike lanes. When sharrows are implemented bicycles could be found to the right or left of motorized vehicles at intersections.

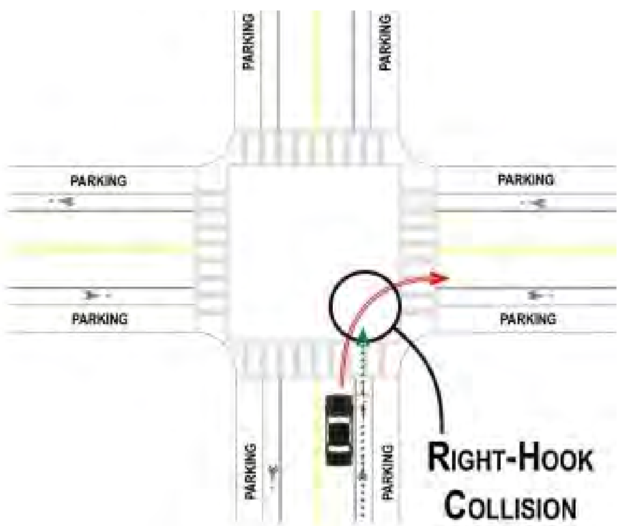



Figure 1: Right-hook collision between a bicycle and a right-turning vehicle (Adopted from Fournier et al. (2020))

In addition to segment-level treatments, it is becoming common for cities to implement intersection-level treatments, such as intersection crossing markings and bike boxes. Intersection crossing markings indicate how bicyclists should navigate through an intersection and inform drivers about the potential of a bicyclist being present within that space. Intersection crossing markings are placed in both signalized and unsignalized intersections. Bike boxes are a dedicated to bicyclists area located just upstream of signalized intersections where bicyclists can get ahead of the car queue and wait during a red signal phase (Loskorn et al., 2013; Goodman and Christopher, 2015; Federal Highway Administration, 2016). This improves bicyclist visibility and provides some level of priority to bicyclists. Various combinations of intersection- and segment-level treatments exist in the real world; for example, intersection-crossing markings can be combined with protected and conventional bike lanes. While existing research has focused on assessing the safety impact of various intersection-level treatment types, it has not assessed the safety impacts of those treatments when combined when various segment-level treatments.

This study contributes to existing literature by using field data to assess and compare the safety impact of the following bicycle treatment types at signalized intersections: (i) three segment-level treatments, namely protected bike lanes, conventional bike lanes, and sharrows, and (ii) two intersection-level treatments, namely intersection crossing markings and bike boxes. The analysis focuses on right-hook conflicts between through-going bicyclists and right-turning motorists assessed using surrogate safety metrics. The primary objective of this work is to determine whether there is correlation between the frequency of traffic conflicts and the bicycle treatment type while accounting for exposure metrics, in particularly right-turning vehicle and through-bicycle volumes. Emphasis is given on user sequence, e.g., a bicyclist followed by a motorized vehicle and vice versa, to assess whether it has an impact on the chosen threshold used to determine existence of a conflict. The following section presents literature on the safety impacts of bicycle treatments. Next, the methodological framework is presented focusing on data collection, traffic conflict definition and extraction, as well as the choice and development of the appropriate regression models. The models are presented next and the obtained insights and implications for real-world implementations are discussed. The final section includes the conclusions of this study as well as recommendations for future work.

## 2. Literature review

Bicycle treatments can be separated into segment-level (e.g., bike lanes and protected bike lanes) and intersection-level (e.g., bike box and intersection crossing markings). In North America, segment-level treatments can be broadly separated into two categories: those that separate bicyclists and motorized vehicles, e.g., conventional, buffered, and protected bike lanes, and those that do not, such as sharrows and bicycle boulevards (of City Transportation Officials, 2014). Subsection 2.1 focuses on studies that have evaluated segment-level treatments at intersections. Subsection 2.2 presents safety-related findings from studies that have focused on bike boxes and intersections crossing markings. Finally, subsection 2.3 summarizes the findings from the literature and highlights existing research gaps.

### *2.1. Segment-level treatments at intersections*

While an array of studies has assessed the safety impact of segment-level treatments, the focus of this section is to summarize studies that have evaluated the safety impact of these treatments at the intersection level, e.g., intersections where bike lanes (protected or conventional) or sharrows are present just upstream of the intersection. Table 1 summarizes the bicycle treatment types that have been studied, the type of intersection control, and the findings of studies that have assessed the impact of segment-level treatments on intersection bicycle safety. Note that findings are expressed as the outcome that was observed when such treatments were in place (i.e., reduced crash risk implies a reduction in crash risk when the noted bicycle treatment(s) was in place versus when not unless otherwise specified).

Several aspects were taken into consideration while reviewing the relevant literature; the following decisions were made regarding the inclusion or not of relevant studies. The listed studies (Table 1) are consistent in that they all account for bicycle and motorized vehicle demand as exposure terms; studies that did not account for either type of exposure (Morrison et al., 2019) were excluded. This is because recent findings on bicycle research have shown the need of incorporating both types of exposure in bicycle safety analysis (Fournier et al., 2017; Nordback et al., 2014). Additionally, studies that only considered unsignalized intersections (e.g., (Schepers et al., 2011)) were excluded as paper's focus is on signalized intersections. It is also worth noting that due to the fact that these studies were conducted in various countries, there is some inconsistency in the treatment type and configuration. European and Canadian studies consider protected and conventional bike lanes,

Table 1: Summary of research studies that have assessed the presence and/or type of segment-level bicycle treatments on intersection bicycle safety

| Study (Country) | Treatment | Traffic Control | Findings |
|---|---|---|---|
| Hamann & Peek-Asa, 2016 (U.S.) | CBL[a], Sharrows | Signalized & Unsignalized | Up to 60% reduced crash risk |
| Turner et al., 2011 (Australia, N.Zealand) | CBL configurations | Signalized | Reduced crash risk |
| Strauss et al., 2013 (Canada) | CBL, PBL[b] | Signalized | No statistically significant difference in injury risk |
| Kondo et al. 2018 (U.S.) | CBL simple and green-colored, sharrows | Signalized & Unsignalized | Treatment effectiveness depends on intersection configuration and traffic volume |
| Saad et al., 2019 (U.S.) | CBL | Signalized & Unsignalized | Reduced crash risk |
| Liu & Marker, 2020 (Germany) | CBL, PBL, | Signalized | CBL lower crash risk than PBL |
| Chen et al., 2020 (U.S.) | Not specified | Signalized & Unsignalized | Increased crash risk at minor street |
| Zangenehpour et al., 2016[1] (Canada) | PBL | Signalized | Reduced risk of right-hook conflicts |

[a] Conventional bike lane, [b] Protected bike lane

while the ones in the U.S. mostly include conventional bike lanes and sharrows, as protected bike lanes had not been widely implemented until recently. In Australia and New Zealand, there are several different configurations of conventional bike lanes (e.g., using a dotted versus a continuous line to denote the bike lane) as demonstrated in (Turner et al., 2011; Morrison et al., 2019). All studies except for one (Zangenehpour et al., 2016) used crash records to evaluate bicycle safety; Zangenehpour et al. (2016) used field data of right-hook traffic conflicts between bicyclists and motorized vehicles.

Overall, existing literature is inconclusive with respect to the impact of different treatments on bicycle safety at signalized intersections when accounting for exposure. Even though studies included test sites with different bicycle treatments the developed models only considered the presence of such treatments as a binary variable (i.e., whether a treatment was present or not) (Hamann and Peek-Asa, 2013; Saad et al., 2019; Kondo et al., 2018; Chen et al., 2020). This approach does not allow for a comparison between the different treatment types, e.g., are intersection approaches with conventional bike lanes versus with sharrows safer? From the remaining studies, i.e., those that differentiated among treatment types, one concluded that there is no difference between the presence of conventional bike lanes versus protected bike lanes (Strauss et al., 2013), while another one found that conventional bike lanes enhance safety compared to protected bike lanes (Liu and Marker, 2020). In addition to the fact that the results of the aforementioned studies do not agree, neither of them considered sharrows in their analysis. As a result, there is no comparative analysis on the safety impacts of conventional bike lanes, protected bike lanes, and sharrows.

### *2.2. Intersection-level treatments at intersections*

Several studies have assessed the impact of intersection-level treatment types on bicyclist safety by analyzing historic crash records or field data or through driver simulation experiments. The present section reviews those studies that include intersection crossing markings and/or bike boxes (see Figure 2 and Figure 3).

Bike boxes is a treatment time that is implemented only at signalized intersections (National Association of City Transportation Officials, 2014); therefore, the following studies include by default only such intersections.

Figure 2: Example of green-colored intersection crossing markings (Seattle, WA)

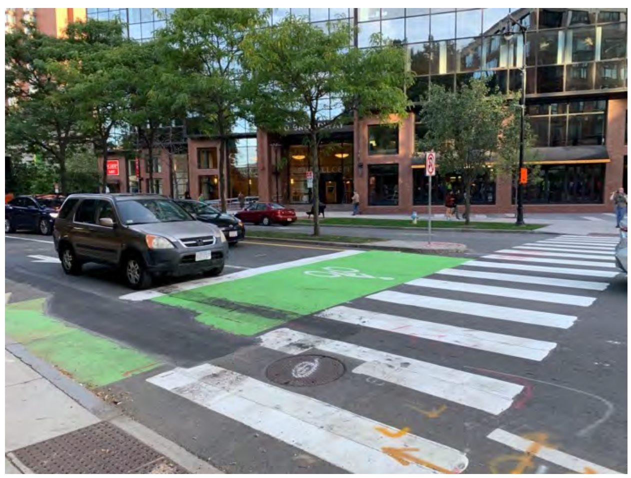


Figure 3: Example of bike box (Cambridge, MA)

Research findings related to the impact of bike boxes are conflicting. Two different studies have analyzed bicycle-motorized vehicle crash records before and after the installation of bike boxes in Portland, OR (DiGioia et al., 2017) and in New Zealand (Newman et al., 2002); in Portland, OR there was a 50% increase to the number of crashes in the after period while in New Zealand there was a reduction in the observed crashes. Increased yielding rates to bicyclists from motorists turning right and reduced conflicts (and avoidance maneuvers by bicyclists) have also been reported when bike boxes are implemented in the U.S. (Dill et al., 2012; Loskorn et al., 2013) and the United Kingdom (UK) (Allen et al., 2005; Wall et al., 2003). In one study colored pavement appeared to have a negative impact on the avoidance maneuvers compared to the white outlined bike box (Loskorn et al., 2013). Finally, a driver simulator study concluded that drivers who are also bicyclists are more likely to behave as intended when encountering a bike box (i.e., stopping behind the stop line and not encroaching on the bike box) (Fournier et al., 2020). While there is some agreement in the research findings related to the occurrence of non-crash events at intersections where bike boxes are present, it is unclear how “conflicts” and “maneuvers” are defined and detected in the aforementioned studies, therefore, limiting the ability to compare findings across different studies.

Intersection crossing markings indicate the area where bicyclists should move while crossing the intersection. Usually they connect bike lanes upstream and downstream of the intersection (National Association of City Transportation Officials, 2014) and they are placed in both signalized and unsignalized intersections. Crossings may be green colored to enhance drivers visibility.

Research on the impact of intersection crossing markings is limited compared to bike boxes. Intersection crossing markings’ impact on bicyclist safety has been evaluated in various contexts and thus, existing findings cannot be synthesized in a comprehensive and conclusive manner. A driver simulator experiment found that intersection crossing markings designed as white-dotted line markings outperformed the ones that included green-colored crossing markings in terms of increasing drivers' ability to detect bicyclists while approaching an intersection to turn right (Warner et al., 2017). A Danish study correlated the number of intersection approaches per intersection where blue-colored intersection crossing markings had been installed with crash frequency; in particular, intersections with one approach with blue-colored crossings reduces the number of intersection crashes, while more approaches with crossings increase that number (Jensen, 2008).

### *2.3. Summary of the literature*

Findings that related to the impacts of segment-level treatment on bicyclist safety at the intersection are inconclusive; the impact can be either positive or negative. Additionally, there is no study up to date assessing all three types of treatments, namely, conventional bike lanes, protected bike lanes, and sharrows. Research on bike boxes does not explicitly show whether these treatments impact crash occurrence, while in cases where non-crash events have been studied the definition of metrics used, e.g., conflict, is not clear or consistent across all studies. Finally, research that simultaneously assesses the impact of segment-level and intersection-level treatments on bicyclist safety is limited.

The great majority of the studies assessing the impact of segment-level treatments that were reviewed rely on crash records while this is the case for a significant number of the studies focusing on the safety impacts of intersection-level treatments. Crashes are rare and random events, therefore, often limiting the ability to perform statistical analysis. The fact that they are are rare events is even more apparent in bicycle safety research. Bicycle-motorized vehicle crashes tend to be underreported especially when they do not result in an injury or property damage (Stutts et al., 1990; Pucher and Dijkstra, 2000; Doom and Derweduwen, 2005; De Mol and Lammar, 2006). As a result, crash analysis might be an ineffective method in the sense that it requires many years of data to establish a representative crash frequency estimate for a site. Data availability is more limiting when a specific crash type is of interest, e.g., right-hook crashes. Consequently, alternatives to crash-based analyses have been developed; these approaches are denoted as surrogate safety methods.

Several studies have used surrogate safety methods to assess bicycle safety at intersections. One area of surrogate safety studies relies on the definition and use of objectively defined and identified safety performance metrics, known as surrogate safety indicators. Such indicators describe how close two or more road users approach in time and space, whether a collision is likely to occur and lastly, what would the injury severity of that collision be. An array of field studies has been conducted with the objective to assess the effectiveness of intersection-level bicycle treatments (Sayed et al., 2013; Madsen and Lahrmann, 2017) and control strategies such as Leading Bicycle Interval (Kothuri et al., 2018; Russo et al., 2020), as well the effect of discontinuities in the bicycle network on bicycle safety (Niaki et al., 2019). However, there is no study that differentiates on the different treatment types such as conventional and protected bike lanes and sharrows that simultaneously accounts for intersection-level treatments such as bike boxes and intersection crossing markings.

## 3. Methodology

This section first presents the experimental design in terms of site selection and video data collection. Video data processing to extract relevant interactions between through-bicyclists and right-turning motorists is explained next. Statistical models are then developed to relate the observed traffic conflicts with bicycle and motorized vehicle demand as well as with the bicycle treatment type.

### *3.1. Site selection and video data collection*

Video data were collected from ten signalized intersection approaches located in Boston (3), Cambridge (6), and Somerville (1), Massachusetts to investigate and compare the safety impact of the three segment-level and two intersection-level bicycle treatments on right-hook conflicts. Data collection took place in November and October of 2019 for the Cambridge sites and October and November 2020 for the Boston and Somerville sites. Cambridge data were recorded using a GoPro Hero7 camera mounted on a tripod while video data collection for Boston and Somerville was facilitated by cameras provided by Street Simplified, which were mounted on traffic or light poles. At each site the camera was placed to capture the studied approach and, in particular, the area containing potential crossing paths of through-bicyclists and right-turning vehicles.

Table 2 provides details on the data collection sites. The column "Period (Hours)" describes the peak period of the day for which data was collected and analyzed (total hours of data collection). The "Segment" and "Intersectio" columns contain information on the segment and intersection bicycle treatments. The extraction of traffic conflicts (i.e., column "Conflicts") is explained in the following subsection. The data collection sites are also illustrated in Figures 4-11.The bike path (whether it is on a protected or conventional bike lane or shared with motorized vehicles) is noted with a yellow arrow. The path of right-turning vehicles is noted with a red arrow. Finally, the light blue rectangular area marks where the traffic conflicts between right-turning vehicles and through-bikes might occur (i.e., where the aforementioned paths are crossing).

In Cambridge, data were collected during weekdays and specifically on Tuesdays, Wednesdays, and Thursdays of October and November 2019 during clear weather conditions (e.g., no snow or rain). For each bicycle treatment type, i.e., sharrows (one intersection), conventional (two intersections) and protected bike lanes (three intersections), data were collected approximately between 8:30-10:30 AM and 5:00-7:00 PM, resulting in a total of about four hours of data per treatment type. The selected intersections have consistency in terms of design: (1) when present conventional and protected bike lanes are located to the right of the traffic lanes, (2) there are no bicycle signals, and (3) turning right on red is not permitted. The later is important as it prohibits drivers from moving during red and enter the location where bicyclists wait to cross the intersection. Overall, a total of four intersection approaches were observed during the morning peak hours in Cambridge (one with a sharrow, two with protected bike lanes, and one with a conventional bike lane) and three during the evening peak hours (one with a sharrow, one with a conventional bike lane and one with a protected bike lane). Of the seven intersection approaches four had intersection crossing markings as their intersection-level treatment and the rest had none. The decision to select different intersection approaches for the AM and PM data collection stems from the need to ensure sufficient bicycle and car demand was present, allowing for more interactions between bicyclists and motorists to be observed. These approaches were typically not located at the same intersection as that did not always feature the same bicycle treatments; instead intersection approaches along the same main corridor were considered. The only exception was the intersection that featured sharrows as there was no other intersection in Cambridge (during the data collection period) where a sharrow was present. Lastly, due to very low bicycle demand during the AM period at Binney Street, additional data was collected from the Western Avenue and Memorial Drive intersection on a different day during the AM period.

Video recordings from Boston and Somerville sites were collected during weekdays in November 2020. Morning peak and afternoon peak periods were analyzed for the scope of this study. With respect to bike boxes, data was collected from the sites during both time periods (AM and PM) as it was not always possible to find similar sites and use one for the AM period and one for the PM period. In total, data were collected at three intersection approaches that featured conventional bike lanes upstream the intersection and one with a protected bike lane upstream the intersection. Two of the conventional bike lane sites and one of the protected bike lane ones also presented a bike box at the intersection approach and two of those were in combination with bike boxes. Finally, one intersection approach in Boston presented a combination of conventional bike lanes and a bike box at the intersection.

Table 2: Data collection sites

| Site (City) | Period (Hours) | Segment | Intersection | RT Vehicles[a] | Thru-bikes[b] | Conflicts |
|---|---|---|---|---|---|---|
| Cambridge & Springfield St (Cambridge) | AM, PM (3) | Sharrow | None | 186 | 126 | 36 |
| Binney & First St (Cambridge) | AM (2) | PBL[c] | Crossing Markings | 109 | 13 | 3 |
| Binney & Third St (Cambridge) | PM (1.5) | PBL | Crossing Markings | 79 | 36 | 10 |
| Western Ave & Memorial Dr (Cambridge) | AM (1.5) | PBL | None | 122 | 40 | 9 |
| Massachusetts Ave & Albany St (Cambridge) | PM (1.5) | CBL[d] | Crossing Markings | 162 | 241 | 43 |
| Massachusetts Ave & Sidney St (Cambridge) | AM (2) | CBL | Crossing Markings | 114 | 257 | 30 |
| Cambridge St & Sudbury St (Boston) | AM, PM (2) | CBL | Bike box | 142 | 41 | 5 |
| Massachusetts Ave & Beacon St (Boston) | AM, PM (4) | PBL | Bike box & Crossing Markings | 514 | 238 | 69 |
| Massachusetts Ave & Commonwealth Ave (Boston) | AM, PM (2) | CBL | Crossing Markings | 103 | 171 | 22 |
| Beacon St & Park St (Somerville) | AM, PM (2) | CBL | Bike box & Crossing Markings | 147 | 60 | 10 |

[a] Right-turning vehicle, [b] Through-bikes, [c] Protected bike lane, [d] Conventional bike lane

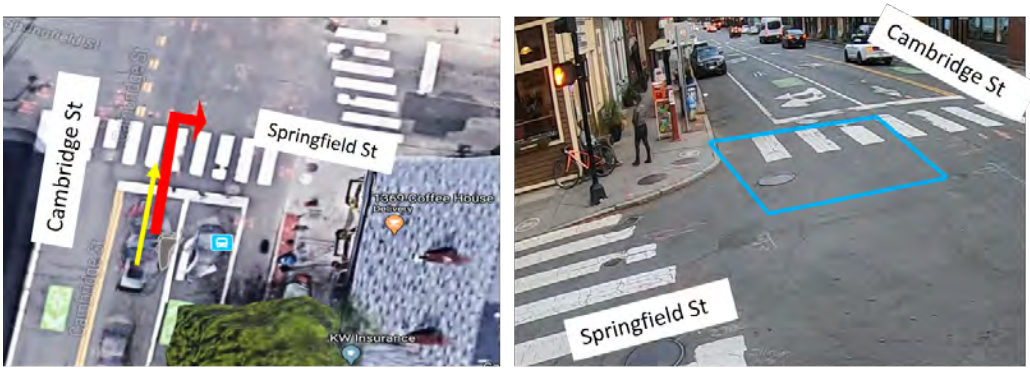
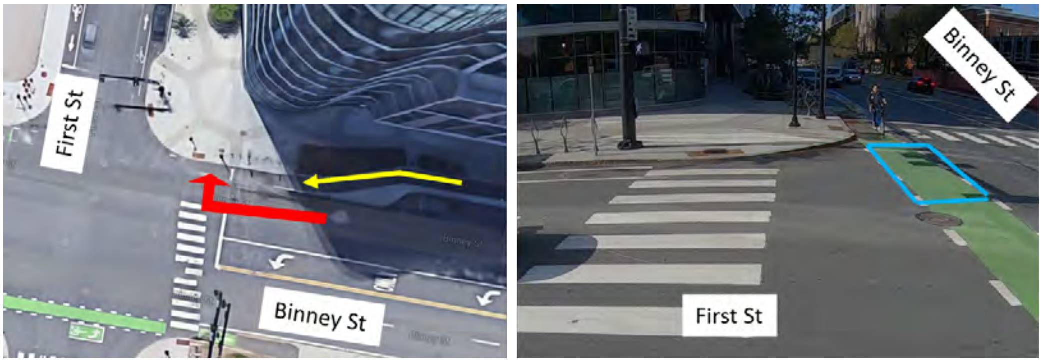



Figure 4: Cambridge Street at Springfield Street (Cambridge, MA). [Segment: sharrows; Intersection: None]

### 3.2. *Traffic conflict extraction*

Surrogate safety methods focus on the interactions between two road users, i.e., a right-turning vehicle and a through-bicycle in this case. More specifically, interactions between two road users should align with one of the following definitions in order to be considered as conflicts: "an observable situation in which two or more road users approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged" (Amundsen and Hyden, 1977), or a "situation when two road users unintentionally pass each other with a very small margin, so that the general feeling is that a collision was "near", (Laureshyn et al., 2010).

Different time-based indicators have been developed to objectively quantify the proximity aspect of two interacting users; the most commonly used ones are the Time to Collision (TTC) and the Post Encroachment Time (PET) (De Ceunynck, 2017). TTC is appropriate when users are in a collision course, meaning that one user needs to change their path or speed to avoid the collision. Essentially, TTC can be detected only when such action

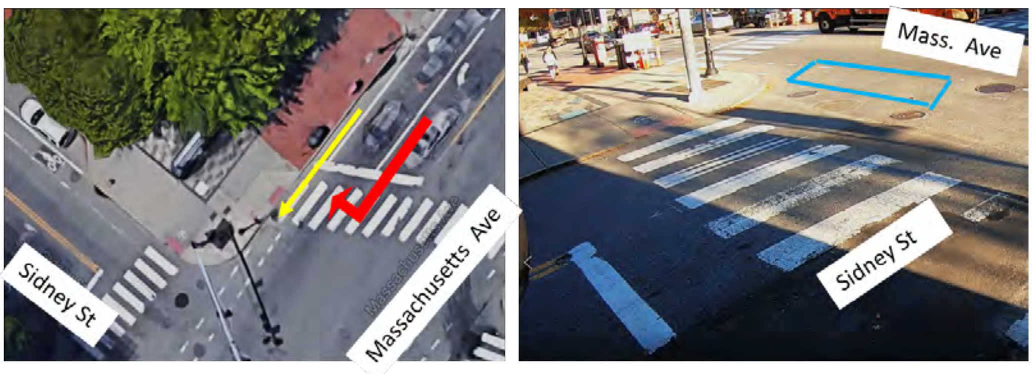



(a) Binney & First St


(b) Binney & Third St

Figure 5: Binney street (Cambridge, MA). Bicycle treatment type: protected bike lanes with green-colored intersection crossing markings


Figure 6: Western Ave at Memorial Drive (Cambridge, MA). [Segment: protected bike lanes; Intersection: None]




(a) Massachusetts Ave & Sidney St


(b) Massachusetts Ave & Albany

Figure 7: Massachusetts Avenue at... (Cambridge, MA). Segment: conventional bike lane; Intersection: crossing Markings]


Figure 8: Cambridge Street at Sudbury Street (Boston, MA). [Segment: conventional bike lane; Intersection: bike box]

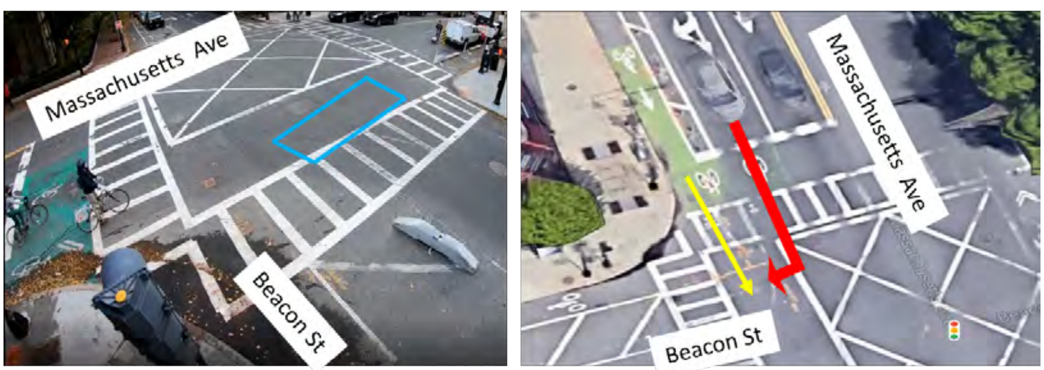



Figure 9: Massachusetts Avenue at Beacon Street (Boston, MA). [Segment: protected bike lane; Intersection: bike box and crossing markings]


Figure 10: Massachusetts Avenue at Commonwealth Avenue (Boston, MA). [Segment: conventional bike lane; Intersection: bike box and crossing markings]

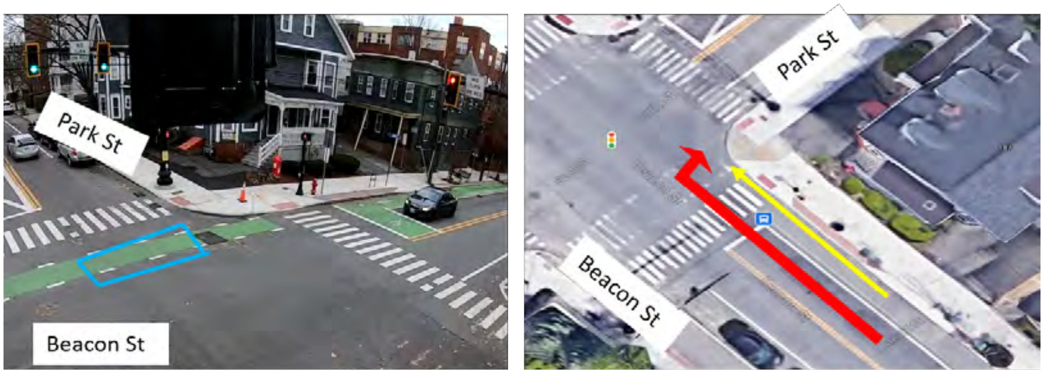



Figure 11: Beacon Street at Street (Somerville, MA). [Segment: conventional bike lane; Intersection: bike box and crossing markings (not visible on Google Maps imagery due to recent installation)]

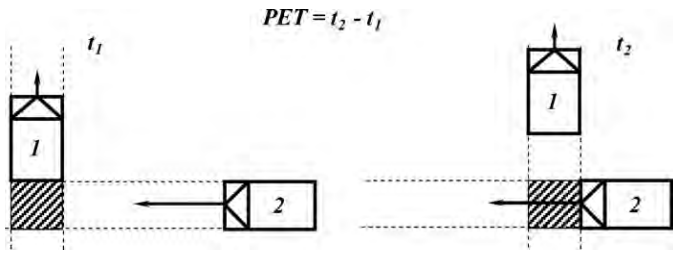



Figure 12: Post Encroachment Time graphical representation; adopted from (Allen et al., 1978)

(i.e., change in speed or path or in other words evasive maneuver) is observed and it is estimated as the time difference between the moment of the evasive maneuver until the time one of them would reach the collision point. On the other hand PET, which is defined as the time difference between the moment that the first user leaves the path of the second road user and the moment when the second user reaches the path of the first road user (Allen et al., 1978), is appropriate for cases where the user paths are crossing (or in other words, are perpendicular) by default and so a user does not aim at changing their path to avoid another one. Since in the present context of right-hook conflicts right-turning vehicles cross paths with through-going bicyclists, PET is the appropriate as it can be estimated without the existence of evasive maneuvers. Figure 12 graphically illustrates the definition of the PET indicator.

Surrogate safety methods and in particular, the time-based indicators have a proven association with traffic safety. As summarized in the review of Johnsson et al. 2018, eight studies have correlated the number of observed traffic conflicts that have been identified using the PET definition with crash occurrence. In bicycle safety research several studies have used PET to assess the impact of bicycle treatments on right-hook conflicts between bicyclists and right-turning vehicles (Zangenehpour et al., 2016; Kothuri et al., 2018; Russo et al., 2020).

The recorded videos were reviewed to manually extract the following information. A 15-minute interval was used as the time unit for the number of: (1) right-turning motorized vehicles, (2) through-bicyclists, (3) traffic conflicts, at each intersection approach. This interval was considered appropriate since it is usually used in volume studies. Smaller intervals such as 5 min. would have greater variability to the number of conflicts and recorded volumes depending on the occurrence of red phase per 5 min. As mentioned earlier, traffic conflicts are identified using the PET as the surrogate safety indicator. The number of traffic conflicts was further grouped by (a) PET value (i.e., 1, 2, 3, and 4 seconds), and (b) the road user sequence in terms of who is arriving first at the conflict area, i.e., a bicycle arrives first and is followed by a motorized vehicle or vice versa.

For each site the conflict area was defined as the area where the through-bicycle and right-turning vehicle paths were crossing. This area is illustrated with a blue rectangle in Figures 4-11. The total number of observed traffic conflicts during the data collection period were grouped per treatment type. The total number of detected traffic conflicts along with the respective volumes are shown in Table 2.

Smaller PET values indicate a closer chance of collision in the sense that users have approached each other closer in time and space. This is because a slight increase in the second user's speed (see Figure 12) would result in collision. Different time thresholds have been proposed in the literature to

(a) define which interactions are severe enough to be considered as traffic conflicts, and (b) differentiate these interactions to severe and less severe ones. Some studies suggest to only consider events with PET values lower or equal to 4 seconds (Laureshyn et al., 2017) while others analyzed events with a PET threshold of 5 seconds (Kothuri et al., 2018; Zangenehpour et al., 2016). Events reporting a PET value equal to the threshold, i.e., 4 or 5 seconds, are considered to be of mild severity. For this study, very few interactions were observed were PET was equal to 5 seconds. In addition, video analysis revealed that these interactions did not appear to be unsafe. As a result, the upper PET value used for the study was 4 seconds.

User sequence was also obtained for each PET value smaller than 4 seconds. In particular, conflicts that occurred when a bicyclist was the first user or the second user, i.e., the first or the second one to arrive at the conflict area, were counted separately. The focus on the user sequence might reveal some further information with respect to the user behavior and allow for assessing whether bicyclists and motorists have different preferences with respect to the gap they leave between themselves and the leading vehicle.

### *3.3. Model formulation*

The objective of this study is to correlate the number of conflicts per 15 minutes with the types of bicycle treatments that are present (both at the segment- and the intersection-levels), as well as the right-turning motorized vehicle and through-bicycle volume for the respective time period.

The dependent variable, i.e., the number of traffic conflicts per 15 minutes, is a positive integer and conflicts are random events. As a result, count data models, which can model discrete outcomes, are the appropriate family of models to consider (Lord and Mannering, 2010). In traffic safety literature, count data models have been used to model crash frequency data, however, more recently, they have also been used to model traffic conflicts for motorized vehicles (Essa and Sayed, 2018), between bicycles or pedestrians and motorized vehicles (Johnsson et al., 2018; Kothuri et al., 2018; Russo et al., 2020; Dill et al., 2012).

The Poisson distribution is appropriate for a set of observations where its mean and variance are approximately equal (Lord and Mannering, 2010); for the observed traffic conflicts this relation holds although variance is slightly higher than the mean (the mean and variance are 2.69 and 3.56 respectively). On the other hand, the Negative Binomial (NB) distribution is flexible, since it can represent observations where the variance exceeds the mean. Poisson, is a subcategory of NB, when the error term has zero variance. N

According to the NB distribution, the average expected number of events $\lambda_i$ (e.g., traffic conflicts) is given by the following equation:

$$\lambda_i = \exp\left(\beta X_i + \varepsilon_i\right) \tag{1}$$

where $X_i$ is a vector of explanatory variables for the $i^{th}-$observation and $\beta$ is a vector of estimable parameters. The term $\varepsilon_i$ is the error term that follows the gamma distribution with $mean = 1$ and $variance = \alpha$, where $\alpha$ is the dispersion parameter. The addition of the gamma-distributed error term allows the observations' variance to be greater than the mean; the physical meaning is that some sites experience quite higher or lower events (e.g., traffic conflicts or crashes) compared to the mean across all sites. Equation 1 represents the average expected frequency of events given by a Poisson distribution.

The NB probability distribution has the following form as determined by Long (1997):

$$P(y_i|X_i) = \frac{\Gamma(1/\alpha + y_i)}{\Gamma(1/\alpha)y_i!}(\frac{1/\alpha}{(1/\alpha) + \lambda_i})^{1/\alpha}(\frac{\lambda_i}{1/\alpha + \lambda_i})^{y_i} \tag{2}$$

where $y_i$ is the number of events (e.g., traffic conflicts) for the $i^{th}-$observation, $\Gamma(.)$ is a gamma function, and $\alpha$ is the dispersion parameter.

Finally the variance of the NB probability distribution is given by:

$$Var(y_i|X_i) = \lambda_i + \frac{\lambda_i^2}{1/\alpha} \tag{3}$$

In this study given that the mean and variance are close, both Poisson and NB distributions were considered to model traffic conflict frequency. The final selection of the distribution relies on statistical criteria; essentially, the objective is to keep the models that fit the data better. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were estimated for each model. The model that showed the lower AIC and BIC values was the one presenting a better fit for the available data. The parameters of the developed count data models were estimated by maximizing the log-likelihood function. All of the analyses were conducted by using the *statsmodel* module of the Python programming language (Seabold and Perktold, 2010).

As mentioned earlier, the recorded traffic conflicts were also categorized based on different PET values, and the road user sequence, i.e., whether a bicyclist was followed by a motorist or vice versa. Different time thresholds, e.g., PET of one versus two seconds, correspond to a higher probability of collision. These data collection would allow for a better understanding of the frequency and type of more and less severe conflicts.

## 4. Results

### *4.1. Traffic conflict model*

The first model that was estimated was the "base model" which relates the number of traffic conflicts per 15 minutes to the exposure terms, i.e., right-turning motorized vehicles and through-bicycles, and excludes any other independent variable. Note that the natural logarithm of each exposure term is used for the model instead of the actual count. This transformation allows us to model the following relationship between the dependent variable and the exposure terms: when either of the exposure terms is zero, then the dependent variable is zero as well. The traffic conflicts per 15 min are given by the following equation ( 4):

$$N_i = RT_i^{\beta_1} TB_i^{\beta_2} e^{\beta_0} \tag{4}$$

where $N$ is the number of conflicts per 15 minutes observed during the $i^{th}$ interval, $RT_i$ is the number of right-turning motorized vehicles during the $i^{th}$ interval, $TB_i$ is the number of through-bicycles observed during the same interval, and $X_4$ is the nominal variable for the bicycle treatment type.

The model as defined by Equation 4 was estimated by fitting the Poisson and NB distributions. The Poisson distribution was found to have lower AIC and BIC values ($AIC_{Poisson} = 268$ and $BIC_{Poisson} = 275$) compared to the NB one ($AIC_{NB} = 269$ and $BIC_{NB} = 279$), meaning that the Poisson

Table 3: Base model

| | Coefficient | Std error | $p-$value | Conf. Intervals (95%) |
|---|---|---|---|---|
| Intercept | -3.5922 | 0.556 | 0.000*** | [-4.682, -2.503] |
| Right-Turning Veh. | 0.9084 | 0.171 | 0.000*** | [0.573, 1.244] |
| Through-Bicyclists | 0.7057 | 0.088 | 0.000*** | [0.533, 0.879] |

*** Statistically significant 99% confidence level

distribution is more appropriate in terms of fitting. The model specifications of the Poisson model are shown in Table 3.

The base model reveals that both the number of right-turning motorized vehicles and the number of through-bicycles are significantly and positively associated with the number of conflicts at signalized intersections. These findings align with existing research on bicycle-motorized vehicle collisions at signalized intersections (Nordback et al., 2014). The developed model was assessed in terms of goodness-of-fit (GoF) using the chi-square statistical test. The GoF results revealed that the Poisson distribution fits the conflict data with a chi-square value of 38.53 and a $p$-value of 0.273.

The base model was then extended to consider the variables for the bicycle treatment presence. Specifically, the variables indicate whether a treatment is present in the studied intersection approach or not: the segment-level treatment type was treated as nominal variable with three levels (i.e., CBL, PBL, and sharrows); the variable Crossings indicates whether there are intersection crossing markings, and finally the Bike Box variable indicates whether a bike box is present. Both bike boxes and intersection crossing markings can be present at an approach. The model form (Equation 5) and specifications (Table 4) are presented below:

$$N_i = RT_i^{\beta_1} TB_i^{\beta_2} e^{\beta_0+\beta_3 CBL+\beta_4 PBL+\beta_5 Crossings+\beta_6 BikeBox} \quad (5)$$

where $N$ is the number of conflicts per 15 minutes observed during the $i^{th}$ interval, $RT_i$ is the number of right-turning motorized vehicles during the $i^{th}$ interval, $TB_is$ is the number of through-bicyclists observed during the same interval, and CBL, PBL, Crossings, and BikeBox are the variables for the various bicycle treatment types.

Table 4: Traffic conflicts model with bicycle treatment type

| | Coefficient | Std error | $p-$value | Conf. Intervals (95%) |
|---|---|---|---|---|
| Intercept | -3.0417 | 0.622 | 0.000*** | [-4.260, -1.824] |
| Right-Turning Veh. | 0.8484 | 0.224 | 0.000*** | [0.409, 1.288] |
| Through-Bicyclists | 0.6927 | 0.137 | 0.000*** | [0.424, 0.962] |
| CBL | -0.7046 | 0.371 | 0.057* | [-1.431, 0.022] |
| PBL | -0.5342 | 0.402 | 0.184 | [-1.322, 0.254] |
| Crossings | 0.3851 | 0.308 | 0.210 | [-0.218, 0.988] |
| Bike Box | -0.1313 | 0.166 | 0.429 | [-0.457 0.194] |

*,**,*** Statistically significant at the 90%, 95%, and 99% confidence level

The exposure variables (i.e., right-turning vehicles and through-bicycles) and the constant are statistically significant at the 99% confidence level. However, the treatment variables, are not statistically significant at the 95% significant level or higher. This finding suggests that the studied bicycle treatment types, at the segment or the intersection, do not affect the frequency of right-hook conflicts. However, the chi-square test results show that this model fits the Poisson distribution well ($x^2$ = 37.49, $p-$value = 0.231). The only treatment that appears to have an impact, although at the 90% confidence level is the conventional bike lane. Compared to sharrows, this segment-level bicycle treatment reduces right-hook conflicts.

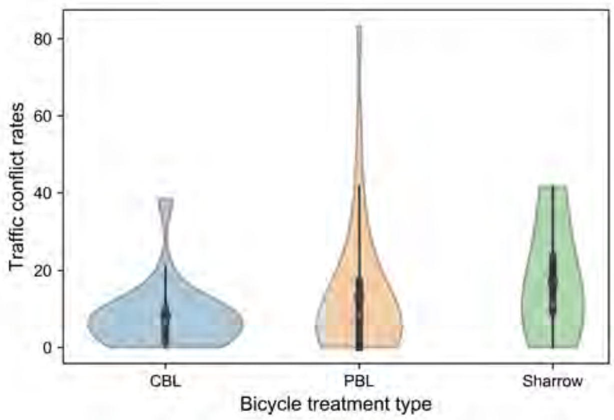



Figure 13: Conflict rates per bicycle treatment type

Conflict rates (Equation 6) were estimated for every 15 minutes interval and then, grouped by segment treatment type.

$$C_{Ri} = \frac{100 * Conflicts}{TB_i * RT_i} \tag{6}$$

where $C_{Ri}$ is the conflict rate estimated for the $i^{th}$ interval, $RT_i$ is the number of right-turning motorized vehicles during the $i^{th}$ interval, and $TB_is$ is the number of through-bicycles observed during the same interval.

Figure 13 shows three violin plots displaying the conflict rates per segment-level bicycle treatment. Violin plots summarize information in a succinct manner and show the probability density of the data at different values. These violin plots reveal that lower conflict rates are associated with intersections where conventional bike lanes are present compared to intersections with protected bike lanes and sharrows.

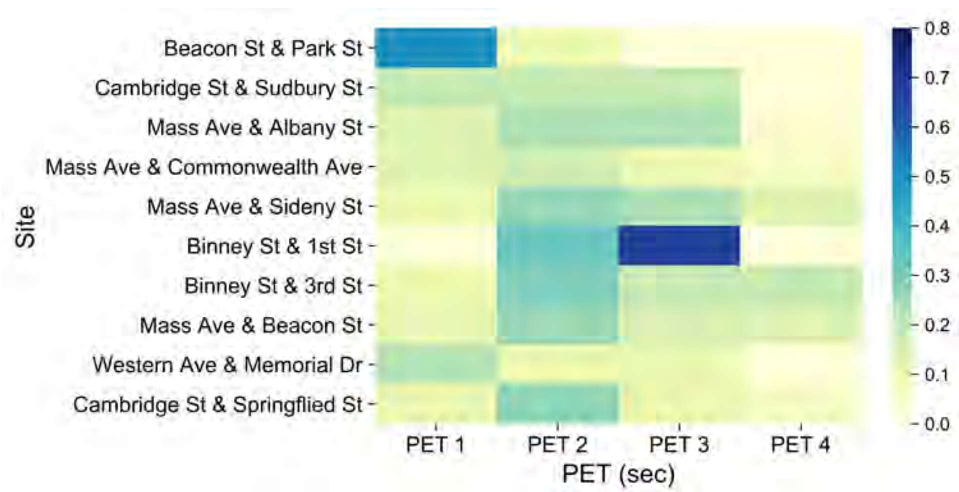
### *4.2. User sequence and PET values*

This part of the analysis examined the observed right-hook conflicts in terms of road user sequence. There are two potential user sequences: a bicyclist is user 1 and the motorist is user 2 and so, the bicycle is followed by the motorized vehicle, or the opposite. As noted earlier, while the observed conflicts were recorded, the user sequence was recorded as well. While analyzing the data it became apparent that bicyclists tend to have smaller PET values when follow motorized vehicles compared to when they are being followed.

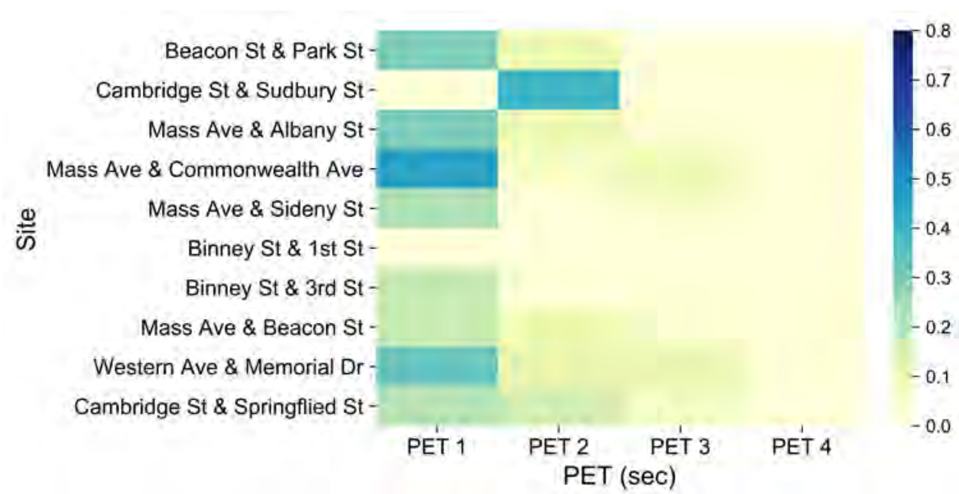
For the two different user sequences a heatmap was created to illustrate how PET values vary depending on the user sequence; see Figure 14. Each cell on the heatmap corresponds to the percentage of traffic conflicts per PET value and site over the total number of number of conflicts.

The heatmaps reveal that right-hook conflicts where a bicyclist is followed by a motorist tend to have PET values of 2 or 3 seconds, while when motorists are followed by bicyclists, PET values are more likely to be equal to 1 second. Further statistical analysis was conducted to test whether there are statistically significant differences between the occurrence of conflicts at the various PET values and the user sequence. The data per group, i.e., per PET value and per user sequence, are not normally distributed, according to the Shapiro-Wilk test (Shapiro and Wilk, 1972). Therefore, the Kruskal–Wallis test (Kruskal and Wallis, 1952) was used to assess whether the two user sequence groups per each PET value, i.e., 1, 2, and 3 seconds, are significantly different. The results of the Kruskal-Wallis test are presented in Table 5.

Findings from this analysis showed that there is a statistically significant difference between the reported PET values between the two different groups:




(a) Conflicts where a bicycle is followed by a motorized vehicle




(b) Conflicts where a motorized vehicle is followed by a bicycle

Figure 14: Heatmaps for the percentage of the number of traffic conflicts per PET value and per site over the total conflicts

Table 5: Kruskal-Wallis test results for different PET values and user sequence

| PET value (sec) | Statistic | $p-$value |
|---|---|---|
| PET = 1 | 3.871 | 0.049** |
| PET = 2 | 13.055 | 0.000*** |
| PET = 3 | 12.151 | 0.000*** |
| All PET | 5.436 | 0.020** |

** *Statistically significant at the 95% level*
*** *Statistically significant at the 99% level*

conflicts where a bicyclist was followed by a motorized vehicle or was following one. Bicyclists tend to maintain smaller distance between themselves and the vehicle in their front that is turning right, while motorists maintain a relatively larger distance. This finding could impact on the way PET is recorded.

## 5. Discussion

Overall, the bicycle treatment type does not appear to have a significant impact on the frequency of right-hook conflicts. Conventional bike lanes showed promising results for improving safety compared to sharrows, but more research is needed to conclude whether they are indeed capable of reducing the frequency of right-hook conflicts. With respect to the other treatment types, a few considerations are listed below in an effort to explain their lack of impact on reducing right-hook conflicts between bicyclists and motorists.

Intersection-level treatments, such as bike boxes and intersection crossing markings, can indeed be beneficial for improving bicyclist safety as concluded by previous studies (Dill et al., 2012; Loskorn et al., 2013; Fournier et al., 2020; Warner et al., 2017). However, their safety impact is not necessarily related to reducing right-hook conflicts and it is reasonable to infer that additional countermeasures are needed to reduce (or even eliminate) right-hook conflicts at signalized intersections. Bike boxes and intersection crossing markings should be placed at intersections to improve bicycle safety and increase driver awareness on bicyclist presence in general, however, it is critical for practitioners to understand which safety aspect they intent to improve by implementing those treatments and whether additional signage or other control devices are needed to enhance the safety impact of such treatments specifically on reducing right-hook crashes.

Another reason that explains why the particular treatments at the segment and the intersection levels are not strongly impacting right-hook conflicts is bicyclist behavior when going through the intersection. Anecdotally, bicyclists often chose to wait in front of motorized vehicles and particularly right after the crosswalk (regardless the presence of intersection treatments), ensuring that they would be the first to proceed through the intersection once the light turned green, thus, eliminating any potential conflicts. This was observed at sites with and without bike boxes and/or intersection crossing markings. Bicyclists crossing the intersection during the red signal indication was also a relatively common phenomenon. The presence of bicycle signals would be beneficial for bicyclists in terms of safety and convenience.

Finally, in the studied sites there are also considerable pedestrian volumes due to the fact that all sites were located in the downtown areas. More pedestrians and bicyclists improve safety for pedestrians and bicyclists, creating the "safety-in-numbers" effect (Jacobsen, 2015) something also observed (but not recorded) during the video data analysis. Motorized vehicles turning right yield to pedestrians and during those moments bicyclists can also proceed through the intersection without interacting with the motorized vehicles. Right-turning motorized vehicles are stopped ahead of the segment-level treatments or bike boxes during this time, which in turn reduces the potential for right-hook conflicts. The “Yield to Bicycles” sign that is placed in most of the studied intersections, might also have a strong impact on driver situational awareness and consequently, driver behavior. A driving simulator study found that the presence of “Yield to Bicycles” signs attracted drivers' glances (Warner et al., 2017). An increase in the time drivers spent looking at their right mirror before making a right turn was also observed in the presence of such signs (Warner et al., 2017).

In addition to evaluating the safety impact of bicycle treatment types on right-hook conflict occurrence at signalized intersection, the analysis also centered on the different PET values reported for the two user sequence types. PET values for conflicts that involve bicyclists followed by motorized vehicles are lower compared to the opposite user sequence and it was found that this different is statistically significant for all the PET intervals (1, 2, 3, and 4 seconds). It seems that bicyclists feel safer while the conflicting vehicle is in their front and so they do not consider it important to for example slow down so that they can increase their distance from the right-turning vehicle. This finding could motivate research on the appropriate thresholds to classify the detected conflicts as more or less severe.

## 6. Conclusions

This study aimed to assess the safety impact of five bicycle treatments at signalized intersections focusing in particular, on right-hook conflicts between right-turning motorized vehicles and through-going bicycles. Poisson regression was used to model the observed traffic conflicts while additional analysis focused on the impact of user sequence, i.e., a bicyclist arrives first at the conflict are and is followed by a motorized vehicle or vice versa, in relation to the PET values.

The developed model found a strong positive association between the observed number of conflicts and the exposure terms, i.e., right-turning vehicles and through-bicycles, but did not find a statistically significant relationship between the conflicts and the bicycle treatment type; conventional bike lanes appear to improve safety for bicyclists however, this finding was significant at the 90% confidence level.

The observations collected through the video recordings also concluded that lower PET values correspond to cases where a motorized vehicle is followed by a bicycle. This suggests that bicyclists tend to maintain a smaller distance from the motorized vehicle in their front and potentially, different PET thresholds should be defined for this user sequence in an effort to capture the potential severity of a conflict. Intuitively, it is riskier when a motorized vehicle maintains a small distance from the leading bicycle compared to the opposite.

Possible limitations of this study is the relatively small number of sites hours of the overall data collection effort; across the different sites 22 hours of data were analyzed. However, an effort was made to ensure consistency, e.g., data collection took place only on weekdays of October and November, during the peak hours of the day and during clear weather conditions. Another limitation is the lack of considering the presence and impact of control devices. For example, this study did not include signal timing considerations such as phasing sequence and signal timings or the presence of signage that could be affecting bicyclist and motorist behavior. Bicyclist and motorist behavior could also be affected by the level of familiarity with certain treatments, some of which are fairly new in the study area.

Overall, existing literature on surrogate safety techniques and specifically on traffic conflict studies using indicators such PET or TTC, is inconclusive regarding the amount of data is needed to accurately assess safety using such metrics. But even with this uncertainty, data collection used for surrogate safety studies is more easily acquired and more informative compared to crash record datasets; video data collection provides data for traffic conflict analysis but also allows us to study other factors, e.g., user compliance with the bicycle treatment and intersection control.

Future research should focus on several aspects to better understand the crash mechanism behind right-hook crashes by studying right-hook conflicts. First, the occurrence of traffic conflicts should be studied in relation to user compliance, i.e., given the lack of bicycle signals bicyclists tend to cross the intersection during red, which potentially eliminates the potential of conflicts. The presence of other intersection treatments, e.g., protected intersections, that are specifically placed to protected bicyclists from right-turning vehicles (Deliali et al., 2020) should also be evaluated using surrogate safety methods. It is also important to consider sites where intersection treatments in addition to bicycle signals are present and develop recommendations to guide their implementation based on bicycle and vehicle demand levels and intersection geometric characteristics; there is some research on this field but it is again limited in terms of the studied treatment types and control strategies (Kothuri et al., 2018; Russo et al., 2020). Finally, future research should focus on the user sequence when assessing conflicts between bicycles and motorized vehicles, leading to recommendations on the appropriate thresholds needed to determine safe and unsafe interactions between motorists and bicyclists.


## Acknowledgements

This research was partially funded by the University of Massachusetts Dissertation Fieldwork Grant, awarded in June 2019. This study was also supported the Massachusetts Department of Transportation Research Program with funding from the Federal Highway Administration State Planning and Research funds.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