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COMPARING UNSAFE CYCLIST BEHAVIOR AMONG THREE URBAN TEST BEDS IN AUSTIN, TX

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Abstract: In comparison to cars, cyclists are in many ways much more exposed to the potential dangers of the road. The explicit indication of traffic signals and other devices enhance safety by clarifying how the users of the transportation system should act as operators. While past studies have evaluated control devices and their impact on cyclist behavior, experimental set-ups have been typically chosen to ensure that environmental conditions remain the same between tests. Bicycle facility treatments can be thought of as a hierarchy, ranging from no treatment to bicycle signals, raised buffers, and more. Cyclist behavior can vary depending on the type of treatment present. Additionally, the existing road environment in which the treatments are placed will also have an effect on cyclist behavior. The objective of this experiment was to observe cyclist behavior in three different urban environments with three levels of existing treatments, ranging from no treatment to bicycle lanes with raised buffers. This study aims to show how different level of bicycle facility treatment (none, medium, and high) affect cyclist behavior and overall cyclist safety. The total number of cyclists, vehicles, cyclist non-compliance, and unsafe vehicle-cyclist interactions through the intersection were obtained from video data. Unsafe passages were considered as the total occurrences of cyclist non-compliance, one-party reactions, and two-party reactions. One- and Two-party reactions are defined as when either or both a cyclist and vehicle change their path and/or speed because of a perceived danger, respectively. Regular yielding behavior was not counted as neither a one- nor two-party reaction. Non-compliance and one/two-party reactions were analyzed as types of unsafe vehicle-cyclist interactions. The aggregated data were evaluated for three different test beds in order to observe the changes in cyclist behavior and safety. Simple linear regression models were built to unveil cyclist behavior and cyclist-vehicle interactions during the 24-hours, peak versus off-peak hours, and daytime versus nighttime hours. The models were built to produce behavioral trends, not necessarily predictive equations. This experiment found that unsafe passages per cyclist decreased as vehicle lane volumes increased in low and medium bicycle stress level locations. This experiment also revealed that the higher the qualitative level facility treatment, the more likely that a linear correlation exists between the aforementioned variables in the daytime versus nighttime and peak versus off-peak hours. Finally, unsafe passages increase as the number of cyclists when there is no treatment present.

1. Introduction

One way that the rules are presented to travelers is through the explicit indication of traffic signals and other control devices. These devices exist to ensure the safety of travelers and to clearly depict how the users of the transportation system should act as operators. However, in general, the role of a cyclist on the road is not as clearly presented as the role of an motorist. In Texas, state law treats cyclists as vehicles, meaning that they are expected to follow vehicle signal indications unless otherwise stated. Although, depending on the urban environment and the perceived accident risk, cyclists may or may not follow traffic signals at the same level as their vehicle counterparts. For example, perhaps at a location with very low perceived risk (i.e., little to no traffic volume and long cycle length), a cyclist might be more inclined continue to travel through the intersection without stopping. When any user of the road (motorist or cyclist) does not follow traffic signals or laws, that user is arguably engaging in non-compliant maneuvers. By not following traffic signals or other laws, that individual's actions are no longer predictable to other users in terms of the street environment. The resulting confusion could lead to accidents and even fatalities.

There are cases in which illegal behavior by cyclists may decrease risk of an accident, such as in the case of navigating a high-speed, high-volume road. For example, a cyclist may face great danger in crossing many lanes to make a left turn when there are many fast driving vehicles present. To avoid a serious accident, a cyclist may choose to use the pedestrian crosswalk and pedestrian signal to safely cross the street. Typically, cyclists must dismount to legally cross the pedestrian crosswalk. Crossing at the crosswalk usually illegal if the cyclist does not dismount, but much safer for in terms of cyclist-vehicle interactions. Having that said, this course of action could still be deemed unsafe in terms of pedestrian-cyclist interactions. In this scenario, there is an inherent risk of seriously injuring a pedestrian when a cyclist does not dismount before using the pedestrian crosswalk.

Part of improving safety for cyclists is understanding how cyclists behave and interact with vehicles under different levels of facility treatment. Bicycle facility treatments levels can range from no bike lanes to bike lanes, bicycle signals, raised buffers, and more. The frequency of non-compliant behaviors (i.e. running red light, failing to dismount, and wrong-way riding) can vary greatly depending on the types of treatments applied to a specific environment. Past studies have largely focused on observing overall behaviors of cyclists. Most studies that have evaluated cyclist behavior through an intersection, have had experimental set-ups that have been very carefully chosen to ensure that conditions remain the same between tests. In fact, the literature lacks studies on comparative cyclist behavior that includes cyclist-vehicle interactions across different levels of treatment.

The City of Austin has initiated various undertakings to enhance bicycle facilities to improve ride quality and safety for cyclists. These efforts generally include testing and implementing new ways of making streets more bicycle friendly. The City of Austin is the only city in the state of Texas to have been awarded Gold status on the League of American Bicyclist's list of Bicycle Friendly Communities (League of American Wheelmen n.d.). Now, with the implementation of bicycle lanes, raised barriers, and bicycle signals at the end of Summer 2017, the City of Austin has stayed on the cutting-edge of bike facility improvements.

This study is a component of a two-part study on cyclist signal compliance and safety before and after the installation of bicycle signals. Non-compliant passages through intersections with both cyclists and vehicles present, which include running red lights and wrong-way bicycle riding, suggest that the addition of bike facilities, i.e. bike lanes and signals, could be helpful in increasing overall safety for cyclists. The City of Austin asked the Center for Transportation Research at The University of Texas at Austin to evaluate cyclist behavior and cyclist-vehicle interactions through selected intersections before and after bicycle signal installation. The results presented here are from the before study. This paper analyzes cyclist behavior in the three different tests beds with three levels of bicycle existing facility treatment: low, medium, and high.

In order to analyze these environments, the research team focused on answering two main questions with the first question being "what is the relationship between the number of unsafe passages per cyclist to the lane volume of vehicles?". The answer to this first question will clarify whether the increase or decrease in vehicle volume could possibly affect the number of non-compliant behaviors and unsafe cyclist-vehicle interactions at intersections. The second question asked was "how does the number of unsafe passages and the total number of cyclists change throughout different urban contexts?". Throughout much of the city, cyclists have a designated space on the road. Still, there are some locations that do not appeal to cyclists which could cause a non-uniform relationship between unsafe movements through an intersection (i.e. passage) and total number of cyclists. Environments that are considered "bicycle friendly" are chiefly intersections that have clearly painted bike lanes, raised buffers, continuous bike lanes, and lower speed limits. On the other end of the range are intersections that have little to no bicycle facilities, high speeds, and lack markings, which make it difficult for cyclists to maneuver safely and legally through intersections.

2. Literature Review

Rising numbers of bicycle-vehicle related injuries originally motivated research on improving bicycle safety. Much of the early knowledge presented by the Federal Highway Administration (FHWA) focused on overall design for cyclist safety (Howard and Burns 2001). Now there are a multitude of guides available for developing bicycle facilities, including AASHTO's Guide for the Development of Bicycle Facilities and the guides that cities and state departments of transportation (DOTs) have developed. There have been tremendous leaps in bicycle facility design, yet cyclists in the United States are eight to 30 times more likely to have a serious accident than cyclists in other countries (Pucher and Buehler 2008).

Numerous studies have evaluated bicycle design treatments and their effectiveness in reducing cyclist-motorists conflicts. Most of these study designs have been short-term, pre-, and post- evaluations. For example, Loskorn (2013) studied the effects of bicycle boxes on bicyclist and motorist behavior throughout intersections in the City of Austin. The chosen intersections that were used to conduct this experiment were Speedway and 38th St, and Shoal Creek Boulevard at Anderson Lane. This experiment used these intersections based on their similarities such as heavy bicycle traffic, medium to high traffic volume, well populated areas, and integrated bicycle lanes. This experiment normalized the data between each intersection and ignored the slight deviations in urban context. Loskorn et al. (2013) concluded that the addition of the bike boxes in each studied intersection improved overall safety for cyclists and motorists. Other studies typically evaluate vehicle-cyclist conflicts and in addition sometimes distribute surveys.

Understanding cyclist's preferences can provide insights on facility efficacy but gaining a better grasp on cyclist behavior is also imperative. Howard and Burns (2001) found that bicycle commuters adjust routes to benefit from existing bicycling facilities, implying that bicycle facility implementation in general will have good usage. Going another step further, Sener, Eluru, and Bhat (2009) underscored cyclists' preference for continuous bicycle facilities, lower traffic volume, and lower roadway speed limits. The next piece of the bicycle facility implementation puzzle is untangling how non-compliant behavior changes across different levels of bicycle facility treatment.

From adding painted bike lanes to raised buffers, the idea remains that giving cyclists a clear space on the road will reduce the number of unsafe interactions and ultimately the number of conflicts between vehicles and bicycles. Harris et al. (2013) examined the risk of injury associated with route infrastructure characteristics at different locations and found that intersections of two local streets has much lower risk of injury than intersections of two major streets. However, while this study did consider intersection configuration (i.e., traffic light with cyclist control, separated cyclist track, etc.), it did not consider relative cyclist compliance/non-compliance behavior between the different configurations. Shaw et al. (2015) described that cyclists commonly cited lack of infrastructure or poorly connecting infrastructure as reasons for rule breaking. The question regarding to what degree non-compliant maneuvers varies between different levels of bicycle infrastructure remains.

Furthering the overall understanding on compliance/non-compliance behaviors at bicycling facilities can help better shape expectations. The most dangerous hazard cyclist's face on the road are other vehicles. Adding bicycle facilities can help the road network serve as a better protector to cyclists. However, even a perfect road configuration alone will not guarantee the safety of cyclists, whose actions are directed by their own perceptions of relative safety. The aim of this study was to investigate non-compliant maneuvers performed by cyclists across three different test beds in Austin, Texas. The City of Austin has a substantial bicycling community and looking to expand bicycle facility implementation. Given the lack of research focus on comparative cycling behaviors, it is expected that this research will contribute to the general knowledge of cyclist behavior.

3. Methodology

The City of Austin provided almost 200 hours of recorded video data, in October of 2016, for the following intersections in Austin, Texas:

- 3rd Street and Brazos Street
- 3rd Street and Congress Avenue
- 3rd Street and Colorado Street
- 3rd Street and Lavaca Street
- Martin Luther King, Jr. Blvd and Rio Grande Street, and
- Airport Blvd. and Wilshire Blvd.

Team members then categorized these intersections into three different urban test beds in order to observe how non-compliant cyclist behavior and unsafe cyclist-vehicle interactions differs among the existing environments. The categories included 3rd Street Test Bed (all 3rd Street intersections), MLK and Rio Grande Test Bed, and finally Airport and Wilshire Test Bed. Each test bed has been evaluated in terms of comparative level of bicycle facility treatment, ranging from low to high (Table 1).

At the lower end of the spectrum is the 3rd Street Corridor, which has the most advanced facilities out of the three test beds. On 3rd Street, there are straight bike lanes that are protected by raised barriers. MLK and Rio Grande was considered medium in terms of comfort and stress level, having bike facilities with delineated bike lanes. However, the intersection is very wide, and the bike lanes do not follow a straight trajectory. Lastly, Airport and Wilshire was ranked at the top end of the spectrum, with no designated bike paths at a relatively high-speed, high-volume intersection.

Table 1: Test Bed Characteristics

Test Bed	Speed Limit (mph)	Bike Facility	Delineated Bike Lanes	Raised Buffers	Continuous, Straight Bike Lane	Level of Bike Facility Treatment
3rd Street	30	Yes	Yes	Yes	Yes	High
MLK & Rio Grande	30	Yes	Yes	No	No	Medium
Airport & Wilshire	45	No	n/a	n/a	n/a	Low

For each intersection, cyclists and vehicles were observed and counted using the software COUNTpro by Traffic Data, Inc. Since some videos did not capture every approach of the intersection the team evaluated approaches that were in full view, added up the vehicle volumes for only those approaches and then divided by the number of lanes whose movements could be clearly seen. Doing so led to an equivalent hourly lane volume (EHLV) number. This method assumes that the lane volumes are evenly distributed amongst each and every lane, which is not necessarily true. However, using EHLV still captures the hours that have higher traffic volumes versus the hours that have lighter traffic volumes, which was adequate for the scope of this study.

3.1. Data Reduction

While observing the videos, team members took notes of the following types of non-compliant cyclist behaviors* and unsafe cyclist-vehicle interactions**:

- One Party Reaction**
- Two Party Reaction**
- Running a red light*
- Failure to use bike lane*
- Wrong way riding (i.e., riding in the opposite bike lane) *
- Failing to dismount bicycle when using pedestrian crosswalk*

A one or two-party reaction were the names used to classify the types of interactions between a cyclist and a vehicle. A one-party reaction is a single reaction in which either the cyclist or the vehicle changes its path and/or speed in order to avoid a potential collision with the other. A one-party reaction always implies there was both a car and vehicle present. A two-party reaction is when both the cyclist and vehicle change their path and/or speed to avoid a potential collision. A change in speed and/or path could mean, for example, a car braking abruptly to let a cyclist pass or a cyclist swerving in order to avoid hitting an approaching car. The running a red-light category only included the number of cyclists committing the action and not the number of cars because the focus of the study is to understand cyclist behavior. Failure to use a bike lane was deemed a non-compliant maneuver, because for the test beds present in this particular study the bike lane is the safest place for a cyclist to ride. Riding in the opposite bike lane means that the cyclists were also riding on the wrong side of the street, another non-compliant maneuver. Lastly, using a pedestrian signal rather than a vehicle signal to cross was considered non-compliant.

3.2. Model Building

The main questions this paper aims to answer are (1) do non-compliant behaviors and unsafe cyclist-vehicle interactions through an intersection increase or decrease with changing traffic lane volume (i.e. EHLV) and (2) do non-compliant behaviors and unsafe cyclist-vehicle interactions increase or decrease with changing cyclist volume? Secondly, this paper aims to discover how the relationship between these variables changes among the three different test beds with rather different levels of bicycle facility treatment (see Table 1). Here, whenever the term unsafe passage is used, it is referring to a single movement through an intersection which directly affects the cyclists. If a vehicle did something illegal/non-compliant (i.e., car running red light) and there was no bicycle present in the intersection to have been affected by the behavior, then that behavior was not included in the counts. A simple Ordinary Least Squares (OLS) linear regression was used to reveal the relationships. All data analysis was conducted using Excel. The data was analyzed for each test bed in three different ways, which were (1) in terms of all the data collected for the test bed, (2) daytime versus nighttime hours, and (3) peak versus off-peak hours.

The first regression modeling approach was made using all of the collected data for each of the three test beds. The independent (x) variables were EHLV and Total Number of Cyclists, and the dependent variables were Unsafe Passages/Number of Cyclists and Unsafe Passages. Unsafe passages was divided by the total number of cyclists to normalize the data. The total number of unsafe passages in some cases seemed very high, but when compared to the total number of cyclists the fraction was relatively low. Normalizing helped reduce the scatter in the data points for evaluating the relationship between unsafe behavior and EHLV. The linear correlation between unsafe behavior and total number of cyclists was also estimated using all the available data for each test bed.

The second and third modeling approaches used the same independent and dependent variables, but analyzed the data in separate groups (nighttime vs. daytime and peak vs. off-peak). The daytime versus nighttime analysis gathered the data into two groups, 07:00 am to 19:00 pm and 19:00 pm to 07:00 am, respectively. The peak versus off-peak hours analysis assumed a morning peak occurring from 07:00 am to 10:00 am, an afternoon peak occurring from 16:00 pm to 20:00 pm, and all other hours were considered off-peak hours. Linear regression models were built for each condition. The regression of unsafe passages per cyclists used EHLV as the independent variables and the number of unsafe passages used the total number of cyclist for the day versus night and peak versus off-peak models. Evaluating the daytime data points separately from the nighttime data points (or peak and off-peak separately) revealed how the relationship between the independent and dependent variables changed for each condition in each of the three test beds.

4. Results

This section evaluates how the relationship between (1) unsafe passages (non-compliant behaviors and unsafe cyclist-vehicle interactions) per cyclists and EHLV and (2) unsafe passages and total number of cyclists change between the three different test beds. Among the intersections studied, two provide safe and pleasant experiences for cyclists because of the presence of bicycle infrastructure such as designated bicycle lanes, low speed limits, and other safety considerations; while the other lacks preliminary bicycle facilities. The explanation for the simple linear regression models for each of the three test beds follows. In general, the R-squares for these models are low. However, the P values are all > 0.01, meaning that there is a 99% chance each independent variable has correlation with the dependent variables. One could argue that this qualifies as certainty in an uncertain world. In this study, the R-square is of secondary importance because the goal is to explain overall behavior, not use the regression equation to make accurate predictions.

4.1. 3rd Street Test Bed

The 3rd Street test bed has the most advanced bicycle facilities and safety features out of the three test beds in this study. This 3rd Street lies within the grid-style downtown Austin network. Therefore, the transition from intersection to intersection follows an East to West linear path. Both the eastbound and westbound bicycle lanes are protected by raised barriers in this test bed and combined with the other characteristics outlined in Table 1, provides the most comfortable riding experience for cyclists out of the three sites.

Count data was analyzed as a whole and also divided into day, night, peak, and off-peak hours for the linear regression analysis. Overall, statistically significant correlation ($p < 0.01$) between (1) Unsafe Passages/Number of Cyclists and EHLV and (2) Unsafe Passages and Number of Cyclists was revealed in both the night versus day and peak versus off-peak analysis. There was less statistical significance in grouping the data as a whole.

4.1.1. Day versus Night Analysis

The linear regression model with Unsafe Passages/Number of Cyclists with EHLV as the independent variable shows a more rapid reduction of non-complaint maneuvers in the nighttime than during the daytime. The model created with only the day data is

[1] $y= -0.0008x + 0.2914$,

where $R^2 = 0.2026$, $p = 7.6e-11$ for the constant, and $p=0.0013$ for the coefficient (Figure 1). The OLS analysis revealed that the percentage of Unsafe Passages/Number of Cyclists decreases by 0.08% for every additional vehicle per hour per lane (vph/ln) during the day. For nighttime, the equation from the linear regression analysis is

[2] $y = -0.0024x + 0.4598$,

where $R^2 = 0.1621$, $p = 1.58e-11$ for the constant, and $p = 0.0050$ for the coefficient (Figure 1). This means that the percentage of Unsafe Passages/Number of Cyclists decreases by 0.24% for every additional vehicle per hour per lane during the night. Nighttime shows a more rapid reduction in percentage of unsafe passages than during the day perhaps because cyclists feel a higher sense of risk during dark hours than during day hours.

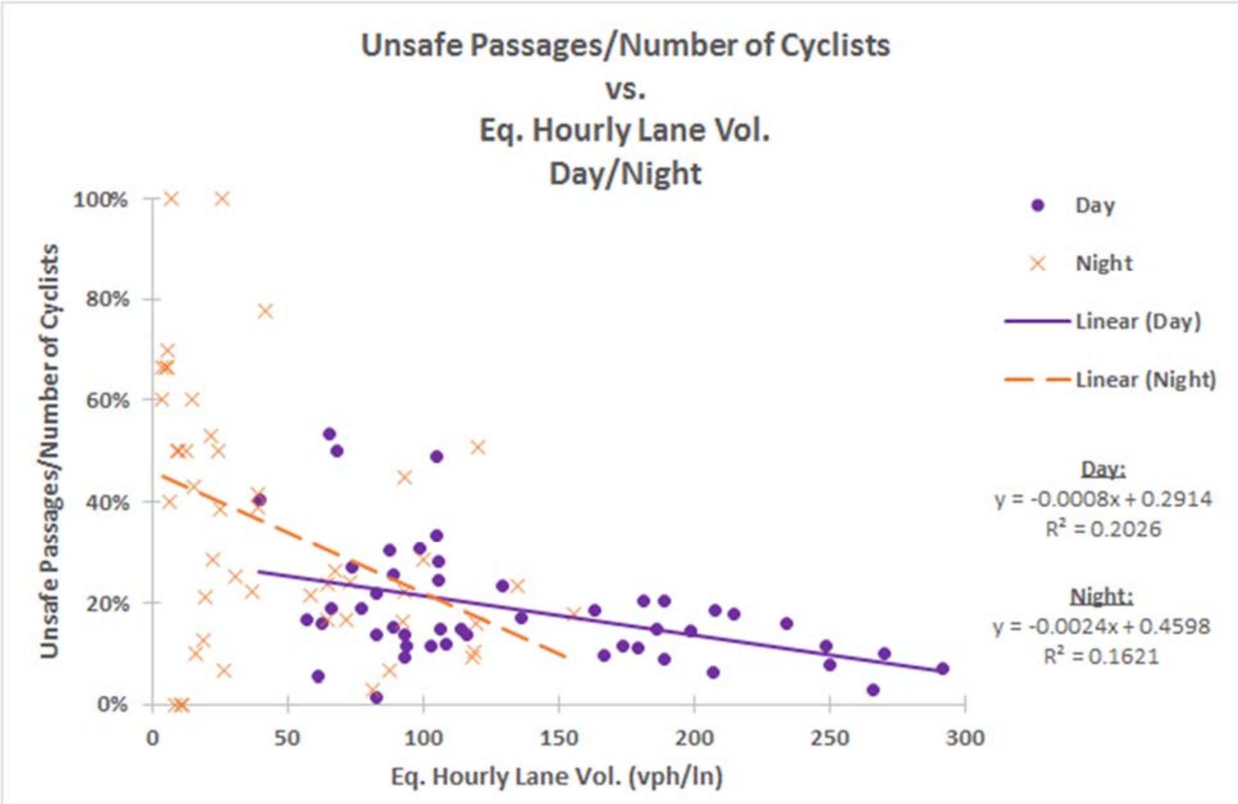

Figure 1: 3rd Street Day and Night Unsafe Passages/Number of Cyclists versus Equivalent Hours Lane Volumes.

4.1.2. Peak versus Off-Peak

The peak versus off-peak analysis revealed that Unsafe Passages/Number of Cyclists decreases more rapidly with increasing vph/ln during the off-peak than during the peak hours. During the peak hours, the equation is

[4] $y = -0.0009x + 0.3292$,

where $R^2 = 0.2441$, p = 2.11e-6 for the constant, and p =.0075 for the coefficient (Figure 2). This percentage of Unsafe Passages/Number of Cyclists decreases by 0.09% for every additional vehicle per hour per lane.

The off-peak hour equation is

[5] $y = -0.0021x + 0.4354$,

where $R^2 = 0.2277$, p = 3.05e-16 for the constant, and p = 4.44e-05 for the coefficient (Figure 2). The percentage of Unsafe Passages/ Number of Cyclists decreases by 0.21% for every additional vehicle per hour per lane. Off-peak hours show a more rapid decrease in the percent of unsafe passages than during the peak hours. The more rapid decrease could possibly occur because cyclists feel relatively more confident in crossing the intersection since there are fewer vehicles overall during off-peak hours.

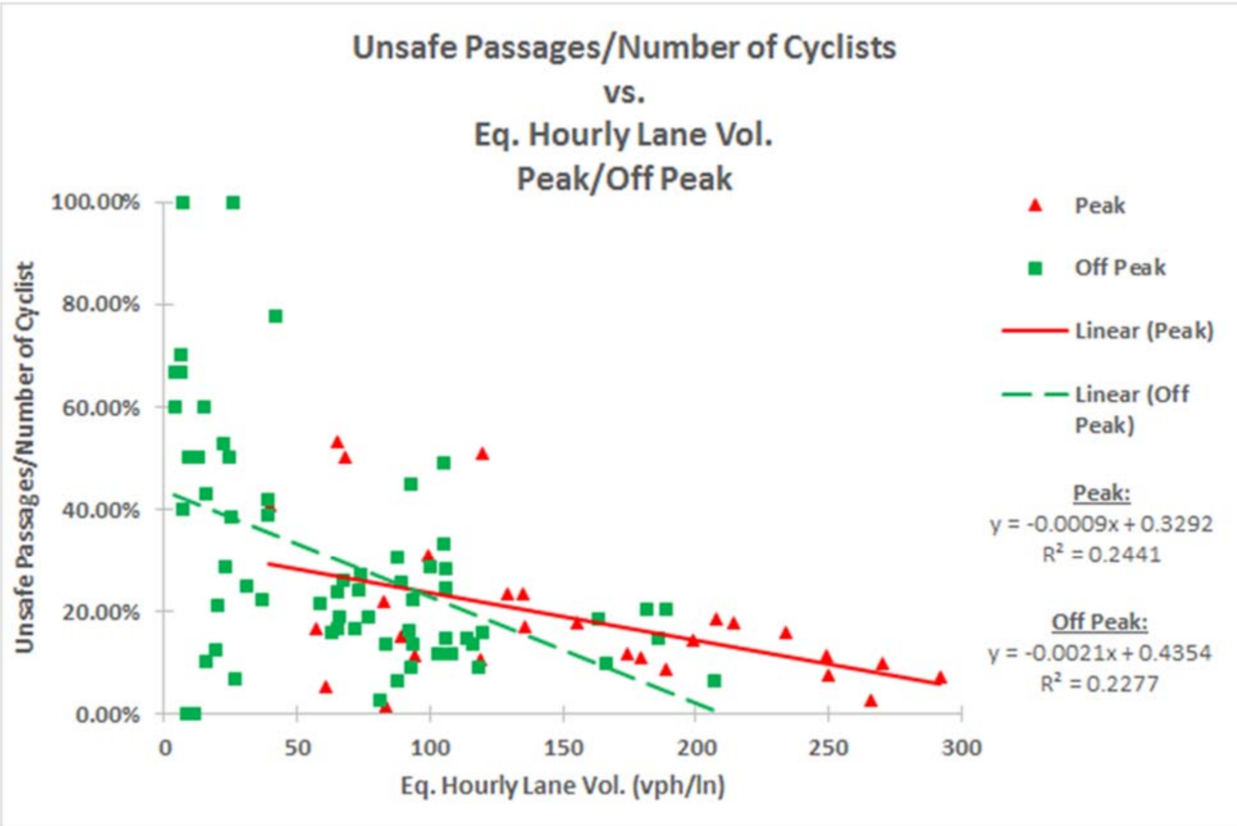

Figure 2: 3rd Street Peak and Off Peak Unsafe Passages/Number of Cyclists versus Equivalent Hours Lane Volumes.

4.2. MLK and Rio Grande Test Bed

The intersection of MLK and Rio Grande is located southwest of The University of Texas campus, slightly north of the downtown area. On the north side of MLK, Rio Grande is a one way, one-lane street with a two-way bike lane on the west side of the street. Between the bike lane and vehicle lane there is a small buffer zone. On the south side of MLK, Rio Grande is a two lane, two-way street where there is southbound shared lane marking and a small colored bike lane at the northbound intersection. This bike lane lies between two traffic lanes with no protection from vehicles. MLK also has two bicycle lanes, one on either side of the street in which the only separation between cyclists and vehicles is a continuous white line. The lack of symmetry in the design and raised buffers in this intersection causes a lesser degree of comfort for cyclists in comparison to the 3rd Street test bed.

Once again, count data was analyzed as a whole then divided into day, night, peak, and off-peak hours for the linear regression analysis. The only model that had a statistically significant correlation ($p < 0.01$) was the overall combined data of Unsafe Passages/Number of Cyclists to EHLV for all hours.

4.2.1. All Hours Analysis

The estimated model for Unsafe Passages/Number of Cyclists with EHLV as the independent variable using all the data collected for 24 hours is

[5] $y = -0.0018x + 0.5142$,

where $R^2 = 0.2511$, p = 2.54e-05 for the constant, and p=0.0126 for the coefficient (Figure 3). The p value equaled .0126, making it .26% above the 1% threshold value. This was the only model that contained a p value close to 1%. The OLS analysis revealed that the percentage of Unsafe Passages/Number of Cyclists decreases by 0.18% for every additional vehicle per hour per lane.

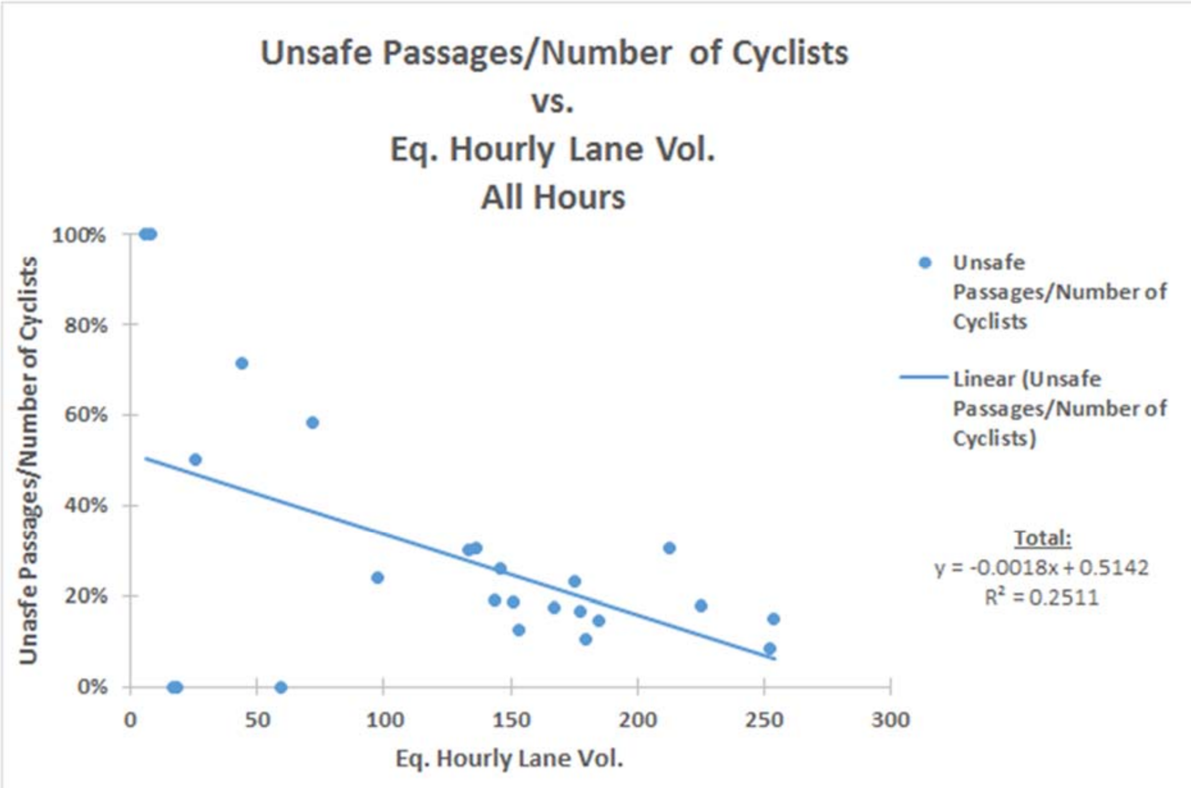

Figure 3. MLK and Rio Unsafe Passages/Number of Cyclists versus Equivalent Hours Lane Volumes.

4.3. Airport and Wilshire Test Bed

The population in the Mueller area has been growing in recent years, therefore leading to the increase of cyclists on the road. This intersection consists of higher traffic volumes, higher speeds, and completely lacks any type of bicycle facilities. The Airport and Wilshire test bed has 12 lanes of traffic that can travel through the intersection and a speed limit of 45 mph. This intersection stands as the most stressful test bed for cyclists. Most of the observed cyclists cross Airport Street through prohibited directions or try to use the pedestrian crosswalk signal to avoid conflicts with vehicles. In general, Texas state law states that a bicycle has the same rights and responsibilities as a motor vehicle (*Texas Constitution and Statutes Transportation Code Title 7. Vehicles and Traffic Subtitle C. Rules of the Road Chapter 551. Operation of Bicycles, Mopeds, and Play Vehicles* n.d.). This means that unless the cyclist dismounted and walked the bike across the pedestrian crosswalk, the action was considered an act of non-compliance.

Only daytime hours were included in the analysis for this intersection due to the poor quality of the videos. This intersection was recorded using a lower quality, temporary camera. For the nighttime hours, it was nearly impossible to see the vehicles due to the headlights shining directly at the camera and completely blending together. The count data was analyzed as a whole and divided into day, peak, and off-peak categories for the linear regression analysis. The peak hours for Airport and Wilshire model were considered from 07:00 am to 10:00 am and from 16:00 pm to 19:00 pm. There is statistically significant correlation ($p < 0.01$) between Unsafe Passages and Total Number of Cyclists in the all hour's analysis, but not in the peak versus off-peak analysis.

4.3.1. All Hours Analysis

The model for Unsafe Passages with Total Number of Cyclists as the independent variable using all of the data collected for 12 hours at Airport and Wilshire is

[6] $y= 0.9762x - 1.9271$,

where R2 = 0.9692, p = 0.0266 for the constant, and p=6.935E-09 for the coefficient (Figure 4). The p value equaled 0.0266, making it 1.66% above the 1% threshold value. This was the only model containing p values that came very close to the 1% threshold. The OLS analysis revealed that the percentage of Unsafe Passages increased by 97.62% for every additional cyclist counted in this model. Almost every cyclist that crossed through this intersection performed an illegal maneuver.

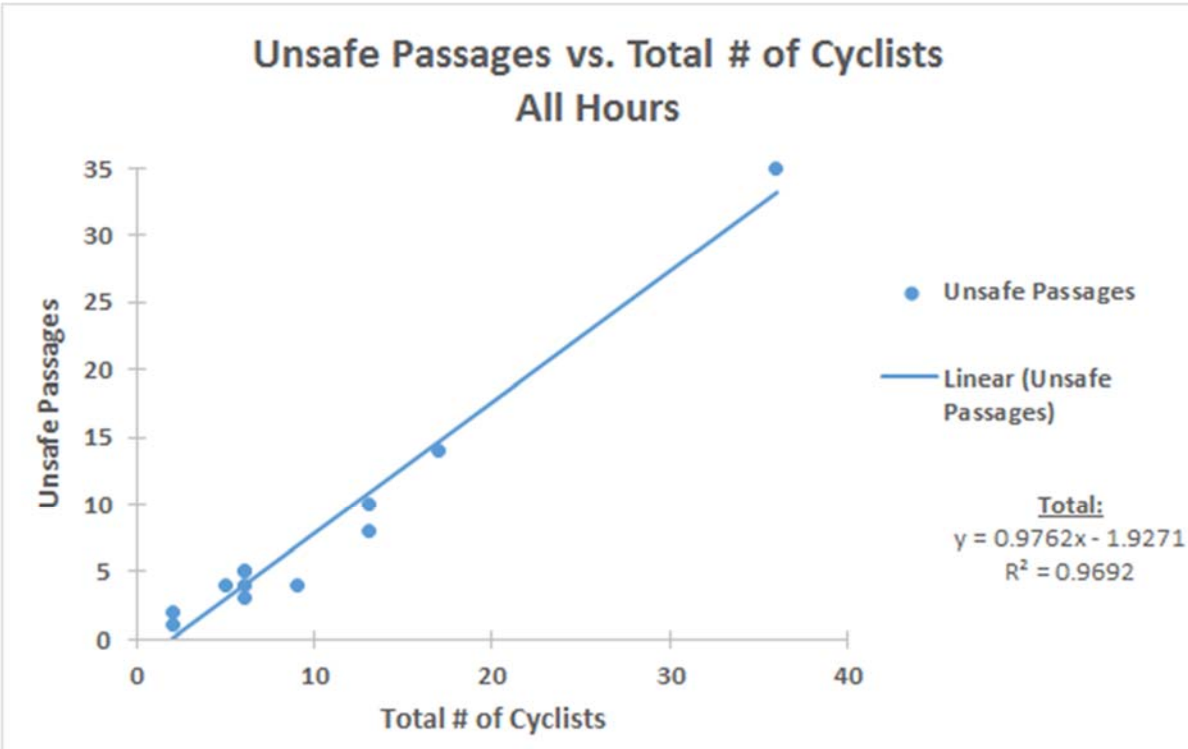

Figure 4. Airport and Wilshire Unsafe Passages versus Total Number of Cyclists.

5. Discussion

In the previous section, unsafe cyclist behavior was analyzed comparatively across three different test beds and significant correlations were recognized. This section aims to evaluate how non-compliant maneuvers varies throughout different cycling environments. Each test bed was examined to explore the different patterns in non-compliant maneuvers among intersections with varying levels of bicycle facility treatment. A discussion of the three different test beds, all containing contrasting physical characteristics follows.

5.1. 3rd Street Test Bed

Intersections along the 3rd street include Brazos, Congress, Colorado, and Lavaca Street. Along 3rd Street, there are painted bicycle lanes protected by raised barriers on both sides of the street. There are only two traffic lanes along the 3rd Street corridor and based on the video observations the traffic volume and vehicle speeds are relatively low compared to the other intersections introduced. It is worth mentioning that 3rd Street is located in the downtown area adjacent to many trip origins/destinations and is considered a popular path for cyclists. 3rd Street experiences the highest number of cyclists for almost all hours of the day (Figure 5). Additionally, it has the lowest average intersection volume (Figure 6). 3rd Street provides a very clear, separated space on the roadway for cyclists and an easy-to-follow path.

5.2. MLK and Rio Grande Test Bed

This intersection is located to the southwest of The University of Texas campus. The southbound cyclists on Rio Grande Street have been provided a shared lane marking on the vehicle traffic lane. The northbound bicycle lane on Rio Grande Street is the center lane located between two traffic lanes at the intersection in which cyclists are left exposed with no solid protection from the vehicles on either side. However, the northbound Rio Grande Street bike lane does have a green paint treatment which has been shown to make cyclists feel safer and give motorists an increased awareness that bicyclists might be present and where those bicyclists are likely to be positioned within the traveled way (United States Department of Transportation - Federal Highway Administration 2011). On the other side of the intersection, Rio Grande Street has a two-way bicycle lane along its west side that is only separated by a small buffer zone from the through traffic. MLK has two bicycle lanes, one on each side of the street going east and west delineated by a continuous white line.

While MLK and Rio Grande does offer cyclists a designated space on the roadway, in comparison to 3rd Street this intersection offers less visibility and solid protection. This a very spaced out intersection in which the bicycle paths do not follow a straight-line path on Rio Grande Street. MLK and Rio Grande had the second highest number of cyclists throughout the day and had high average automobile intersection volume (Figure 5 & 6). In fact, for the morning peak hours (7:00 to 10:00), traffic volume was higher here than at Airport and Wilshire.

5.3. Airport and Wilshire Test Bed

The last location is the intersection of Airport and Wilshire. This intersection consists of high traffic volume (Figure 6), high speed, and lacks any type of bicycle facilities. The traffic volume is significantly higher in this intersection as shown in the following charts compared to the first two locations. This intersection has a total of 12 lanes of traffic, and Airport has a speed limit of 45 mph. Based on the data collected, the total number of cyclists at this location is significantly lower (Figure 5) than the other locations but has a much higher percentage of cyclists that were involved in some type of unsafe passage. Instead of following the legal and allowed direction to make a U-turn to access the cross street or walking their bike along the pedestrian crosswalk, most of the observed cyclists crossed Airport Blvd. The cyclists went through the prohibited directions or used the pedestrian crosswalk signal to avoid conflicts with vehicles. With no other option available, the cyclists were forced to constantly perform this movement and many did so by failing to dismount.

As shown in Figures 5 and 6, the 3rd Street Test Bed has the highest cyclist volume especially during afternoon peak hours, but on average has the lowest traffic volume during peak and off-peak hours. On the other hand, the Airport and Wilshire Test Bed, which has a much higher traffic volume, higher speed limit and no bike facilities in place, has the lowest cyclist volume amongst the three studied test beds.

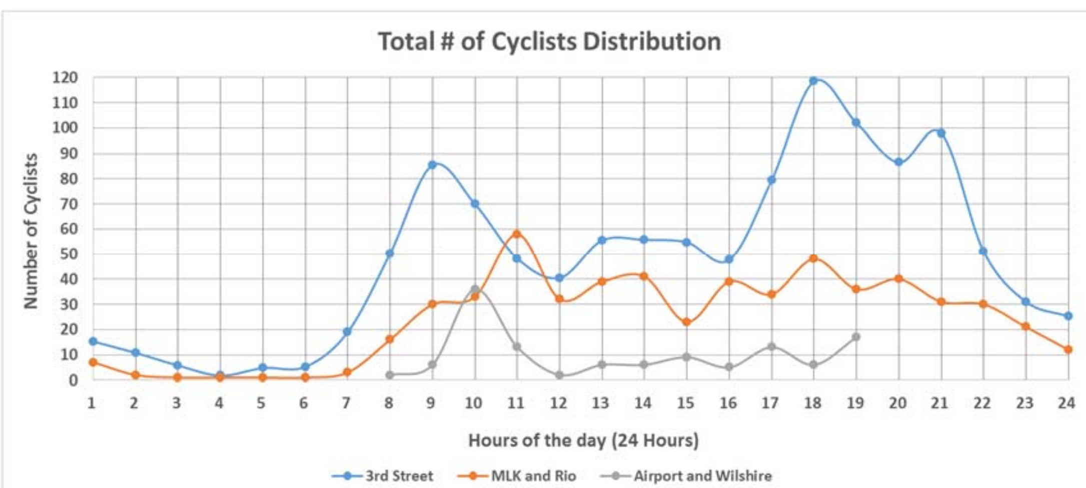

Figure 5. Total # of Cyclists Distribution over the 24-hour day, with the exception of Airport and Wilshire showing 12 hours of the day.

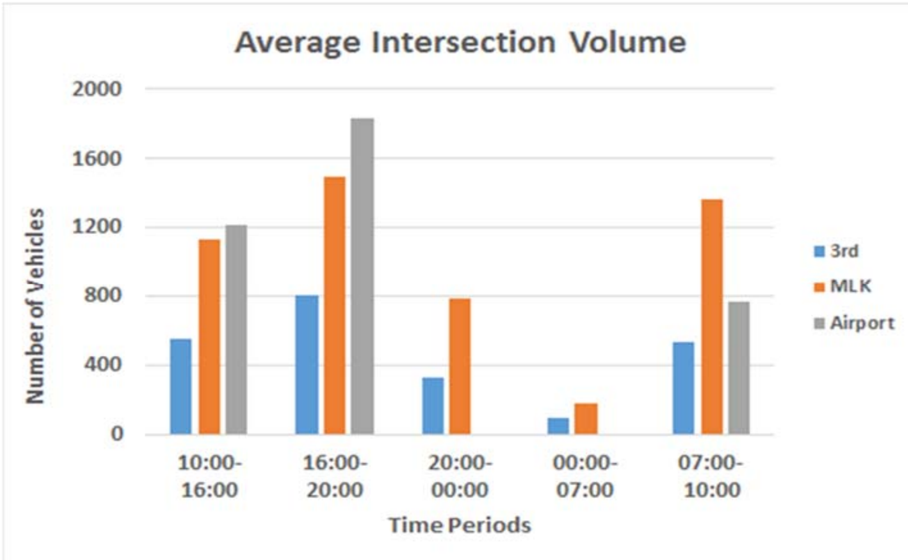

Figure 6. Average Intersection Volume for the three test beds.

5.4. Comparison of the Three Test Beds

Out of the three analyses, each test bed had a different modeling approach (all hours, day vs. night, peak vs. off-peak) that showed the strongest evidence of a linear correlation. The test bed with the lowest bicycle stress level (3rd Street) had the excellent p-values for the daytime versus nighttime analysis and the peak versus off-peak. In the middle range, MLK and Rio Grande had the best p-values for the all hours. Finally, Airport and Wilshire, the least bicycle friendly test bed, had the best p-values in the all hours modeling approach.

3rd Street has a very straight forward easy-to-follow path and showed excellent p-values for the nighttime versus daytime analysis. The analysis revealed that as EHLV increases, the number of unsafe passages/cyclists decreases in both the daytime and the nighttime hours. This finding suggests that increasing vehicle presence on the road will lower the probability of non-compliant behaviors and unsafe cyclist-vehicle interactions. However, one might expect that during the nighttime when there are fewer vehicles on the road the cyclists might behave more randomly. Some might follow the expected behavior and others might not. This was not the case with the 3rd Street test bed since the analysis shows that cyclists tend to show a very strong probability of finding the observed behavior in the nighttime and the off-peak times. The reason this behavior exists both in the daytime and the nighttime (and the peak/off-peak times) may be attributed to the fact that the cyclists have a very clear space on the road. The fact of the matter is that on 3rd Street, cyclists and vehicles follow the rules because it is easy, and it is obvious what to do at the intersections.

At MLK and Rio Grande, the all hour's analysis approach has the strongest model. The analysis shows that as EHLV increases, the number of unsafe passages/cyclists decreases overall as well. This intersection, while not as easy to maneuver as 3rd Street, still had bicycle facilities. The night versus day and the peak versus off-peak analyses did not show any statistically significant linear correlation between the dependent variables and independent variables tested. This finding was interpreted to indicate that cyclists may behave more randomly when considering these different time groups. It could also mean that some groups of cyclists mimic each other.

Airport and Wilshire also had the strongest model with the all hours' analysis approach and the highest R^2 value out of all of the models discussed. While the Airport and Wilshire Test Bed does not have a high volume of cyclists, it has a high average number of vehicles and it is a confusing intersection to cross. Even cars at this intersection cannot cross Airport Blvd. in a straight path. They must travel on Airport and make a U-turn followed by a right turn in order to cross the street. Based on the observations, most of cyclists at this location are involved in red light infringement and wrong-way riding. More than 95% of the observed cyclists crossed the Airport Street in an unsafe fashion. Most of the observed cyclists using this location were involved in more than one type of unsafe passage. Since the intersection's physical configuration does not allow a direct and safe crossing, cyclists use the pedestrian signal to cross the street or in some cases they cross the street while the light is green for the traffic perpendicular to them. Once again, the peak versus off-peak analysis did not show any statistically significant linear correlation. Cyclists during the peak hours versus the off-peak hours behaved randomly showing that there is no clear and straightforward interpretation for how to cross this intersection safely and efficiently.

6. Conclusion

Three tests beds varying in degree of overall bicycle facility treatment were selected to evaluate comparative non-compliant behaviors and unsafe cyclist-vehicle interactions, which has not been extensively documented in the literature. One test bed per chosen location was used as a representative of high, medium, or low level of bicycle facility treatment and was examined to explore the different patterns. This paper has presented largely objective data to achieve this goal. Overall, the analysis shows Unsafe Passages per Cyclists decrease as Equivalent Lane Volume increase. This behavior occurs because as the volume of cars increases throughout the intersection cyclist become more cautious to their environment due to the fact that a potential collision is more likely to occur with more motorists around.

In summary, the test beds of the 3rd Street Corridor, MLK and Rio Grande, and Airport and Wilshire have each shown their own trend of behaviors which are described below:

6.1. 3rd Street Test Bed (High level of facility treatment)

- Non-compliant and unsafe movements through an intersection are linearly correlated with vehicle volumes throughout all times of the day

During daylight and nighttime (including peak and off-peak hours) non-compliant behaviors and unsafe cyclist-vehicle interactions were linearly correlated with EHLV because cyclists have clear and straight paths. The 3rd Street corridor contains a clear and simple path for cyclists to follow, making it easy for cyclists to obey the rules of the road. The bicycle facilities offer cyclist a protected designated space on the road. This corridor has an extremely safe set-up with raised barriers, low vehicle speeds, and painted bike lanes.

6.2. MLK and Rio Grande Test Bed (Medium level of facility treatment)

- non-compliant behaviors and unsafe cyclist-vehicle interactions are linearly correlated with vehicle volumes only when analyzing an entire day as a whole

When the data was grouped into daytime, nighttime, peak, and off-peak models, the models were weak. The points were scattered, implying that cyclists behave more randomly at this medium-stress location. The fact that this intersection is wide, has a more complicated path for cyclists, and higher traffic volume means that cyclists end up making more random decisions about preforming non-compliant maneuvers that are not linearly correlated with changes in vehicle lane volumes.

6.3. Airport and Wilshire Test Bed (Low level of facility treatment)

- At a high-stress location with no bicycle facilities, non-compliant behaviors and unsafe cyclist-vehicle interactions increase as the number of cyclists increase

There was a clear correlation between these two variables with a high R2 value (97%). Nearly every cyclist that went through this intersection did so an non-compliant manor. It seems the cyclists at this intersection are much more likely to act in a noncompliant behavior due to the lack of bike facilities and the complicated intersection configuration.

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