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CHARACTERIZATION OF BICYCLE RIDER BEHAVIOR AMONG VARIOUS STREET ENVIRONMENTS

Final Report

by

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DISCLAIMER

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EXECUTIVE SUMMARY

Since the establishment of the Bicycle Master Plan in 2009, the City of Austin has greatly expanded its bicycle network to fulfill the population's growing interest in cycling. The City of Austin has continuously advanced towards a more bicycle-friendly environment with the growth in the installation of protected bicycle lanes. However, issues with non-compliance have been recognized as improvements in bicycle facilities have been made. It is hypothesized that non-compliant behavior arises when cyclists are unclear of their role in the traffic system, and can be reduced by providing a built environment with clearer instructions.

This study was conducted to address factors that impact cyclist non-compliant behavior. This report reviews an observational study before the installation of bicycle signals to evaluate cyclist behavior in the existing local context. Observations were made throughout a 24-hour period at 11 intersection and non-compliant cyclist behavior was characterized as well as motorist-cyclist interactions. The non-compliance rate was computed as the total number of non-compliant cyclists observed at an intersection divided by the total number of cyclists observed at the intersection. Both time of day and level of traffic stress (LTS) were considered factors relevant to the studied behaviors. LTS was assigned to each intersection based on a set of criteria. The objectives of this study are to:

(1) identify whether cyclist behave differently across built environments;
(2) find the factors that impose differences in cyclist behavior; and
(3) identify the correlation between the LTS and cyclist behavior.

Though many have studied cyclist behavior and factors influencing cyclist behavior, most of these studies have focused on intrinsic factors rather than the effect of the local environment. The study found that non-compliance rate of cyclists was inversely correlated with LTS, with higher non-compliance rate at lower LTS, and intersections with LTS 1 showed significantly higher non-compliance rate (25.33%) than other LTS groups (9.96%, 8.50%, and 3.09% corresponding to LTS 2, 3, and 4 respectively). The study also pointed out that the non-compliance rate was correlated with time. During morning off-peak (0:00 to 7:00), cyclist showed significantly higher non-compliance rate (27.74%) comparing to other time periods (12.91%, 14.93%, 10.14%, and 10.87%, corresponding to morning peak, mid-day off-peak, mid-day peak, and night off-peak respectively). Lastly, it was found that cyclists do behave differently across the different urban environments.

Chapter 1. Introduction

1.1 Problem Statement

Over the period of three decades, from 1977 to 2009, the total number of trips made by bicycles has more than tripled while bike share of trips has almost doubled (1). At the same time, the share of work trips by bicycle has increased to 0.6% (1). With the gradual growth of bicycle use, infrastructure is further required to accommodate safe cycling trips. More and more attention has been directed toward improving bicycle facilities. However, in order to select the best infrastructure to achieve safety goals, there must be an understanding of cyclist behavior.

There have been various studies trying to characterize bicycle riders and bicycle networks. Dill et al. developed characterizations of bicyclists to guide a better understanding of the targeted groups (2) and Furth et al. developed criteria for “Level of Traffic Stress” to help further categorize bicycle facilities in terms of rider comfort (3). These two studies have been used to characterize bicycle networks and to set goals for network improvements.

The City of Austin serves as an example of a city that has noticed the increase in bicycle trips and the need to improve bicycle networks. Since the 2009 Austin Bicycle Master Plan was established, there has been a significant expansion in the existing bicycle network. In 2012, Austin was recognized and selected by PeopleForBikes as one of the six groundbreaker cities for the Green Lane Project, which encouraged installing protected bicycle lanes to advance bicycling (4). As more than 50% of bicyclists were categorized as “interested but concerned” (3), the City recognized that the introduction of protected bicycle lanes could satisfy the needs of these potential riders and capture more bicycling trips. However, while the growth in the bicycle rider population and the City of Austin shift toward a more bike-friendly environment poses a positive sign that a greener way of living is gradually being adopted, other issues regarding bicycle network expansion have been recognized.

Issues with non-compliance arise as bicyclists are uncertain about their roles in the traffic system. That is, as stated by law, bicyclists should be treated as cars, yet some locations allow bicyclists to legally behave as pedestrians. Confusion can result from this uncertainty in how they should behave, as pedestrians or as cars. Thus, it is essential for the built environment to provide clear instructions to all road users, including bicyclists. Yet, the question as to what improvements should be made to provide the best-built environment for bicyclists remains unanswered. By developing an understanding of how different factors in the environment impact bicyclist behavior, more tailored safety and facility recommendations can be made.

1.2 Objectives

This study aims to provide insights on this broad question. Eleven intersections across four levels of traffic stress were analyzed and bicyclists behaviors were categorized in terms of two factors, type of vehicle-cyclist interaction and cyclist non-compliance. The broad question was broken into several pieces but mainly focused on the non-compliance behavior of bicyclists. The fundamental question was "Do bicyclists behave differently in different environments?" in which the study tried to identify whether a difference in non-compliance behavior exists among the observed intersections. The second question was "If a difference exists, what are the factors that can account for the differences?" in which the study attempts to find the factors that impose differences among the studied intersections. Lastly, "If a trend exists, what is the correlation between the found factor and level of non-compliance?", in which this study attempts to identify how each factor relates to the observed bicyclists behavior.

1.3 Expected Contributions

Two contributions are expected from this study, (1) Provide an understanding to how cyclist behavior is impacted by the built environment so that appropriate actions may be taken to ensure lawful actions of cyclists; and (2) open the gate for future research with regard to cyclist behavior and the built environment, such as the effects of bicycle signals on cyclist non-compliance behavior. Though the study is designed for and conducted in Austin, Texas, the completion of this study provides a record to aid similar research in other regions.

1.4 Report Overview

The remainder of the report is organized as follows: Chapter 2 presents a series of literature reviews related to cyclist behavior and effects of bicycle facility to serve as backgrounds and basis of this study; Chapter 3 discusses the design, statistical tools utilized in this study and analytical assessment of the obtained results; and Chapter 4 summarizes the questions and answers raised throughout the report, provides an interpretation of the obtained results as well as the corresponding analysis, and presents a direction for future research.

Chapter 2. Literature Review

2.1 Introduction

There has been a shift from a conservative approach to a more innovative approach in terms of designing and engineering bicycle facilities in recent years. Prior to 2013, Manual on Uniform Traffic Control Device (MUTCD) and American Association of State Highway and Transportation Officials (AASHTO) Green Book reigned supreme. Both guides were very auto-centric, with little deviation from 12-foot lane minimum requirements, and provided minimal pedestrian as well as bicycle accommodations. In 2013, FHWA issued a memorandum officially supporting use of the National Association of City Transportation Officials (NACTO) bicycle design guide, which marked a huge shift in terms of planning and designing bicycle facilities. From its publication in 2011, official acceptance by Federal Highway Administration (FHWA) and further endorsement of United States Department of Transportation (USDOT), NACTO has demonstrated that professionals are willing to embrace innovation and improvement in development of bicycle facilities.

Accommodating for bicycles in the roadway network is still reaching new frontiers. MUTCD recently pushed out an interim approval for bicycle signals, that still has many restrictions on how these devices can or cannot operate. In order to understand whether bicycle signals, or other experimental bicycle facilities, can be used with more or less restriction, it is imperative to understand the cyclist behavior and the relationship between cyclists and vehicles on the roadway network. Previous studies have examined the potential motivations for red light violations, the intrinsic influence due to social environment, and comparison between wide curb lane and bike lane, which can guide recommendations for bicycle facility improvements. The sections that follow will provide further details with respect to these aspects.

2.2 Level of Traffic Stress

In this study, level of traffic stress (LTS) developed by Furth et al. was adopted as an important factor to represent the treatment level. LTS provides a rating to road sections or crossings that indicates the stress imposed on bicyclists due to traffic (3). Since it characterizes stress level imposed on bicyclists, it may be considered as an indicator of how safe bicyclists feel when riding on a bike facility. LTS ranks stress from 1 to 4, with stress experienced by bicyclists increasing with higher numbers. In general, LTS 1 indicates that there exists either a segregation between roadway and bike trail or the bike trail is along streets with low traffic speed and volume and is suitable for children. LTS 2 indicates that cyclists have dedicated bike lanes and are physically separated from high-speed traffic. This level indicates that the bike facility is suitable for the majority of the biking population. LTS 3 indicates that bicyclists may have to interact with traffic at moderate speed. This indicates that the stress level is suitable for those classified as “enthused and confident” (2). LTS 4 indicates that bicyclist may be of close proximity to or involved in interaction with relatively high-speed traffic. The study provides several criteria for categorizing bike facilities.

Table 2-1 LTS for Segments by Facility Type, from Furth (3)

Segment Type	Level of Traffic Stress
Stand-alone paths	LTS = 1
Segregated paths (sidepaths, cycle tracks)	LTS = 1
Bike lanes	LTS can vary from 1 to 4; see Tables 2 and 3
Mixed traffic	LTS can vary from 1 to 4; see Table 4

Table 2-1 shows possible LTS that each type of bike facility could be categorized under. While stand-alone bike paths and completely segregated bike paths are always considered LTS 1 regardless of traffic condition, dedicated bike lanes and shared bike lanes could be categorized under LTS 1 through 4 depending on traffic and bike lane conditions.

Table 2-2 LTS Criteria for Bike Lanes Alongside Parking Lane, from Furth (3)

	LTS $\geq$ 1	LTS $\geq$ 2	LTS $\geq$ 3	LTS $\geq$ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.

Table 2-2 shows the criteria for categorizing LTS of dedicated bike lanes alongside a parking lane. To determine LTS, one is required to select the condition that best describes the bike lane under each criteria (row) and the criteria with highest LTS determines the LTS of the bike lane. For instance, if a bike lane is alongside a street with one lane per direction (LTS 1), a width of 16 ft (LTS 1), yet a prevailing speed of 35 mph (LTS 3) and rare blockage, the bike lane would be considered LTS 3 as the criteria with lowest LTS dominates.

Table 2-3 LTS Criteria for Bike Lanes Not Alongside Parking Lane, from Furth (3)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table 2-3 shows the criteria for determining LTS of a dedicated bike lane not alongside a parking lane. The criteria differ in terms of bike lane width and speed limit. Instead of considering a width of bike lane and parking lane combined, as shown in Table 2-4, only width of bike lane is considered. For prevailing speed, the condition for LTS 1 increases to 30 mph rather than 25 mph.

Table 2-4 LTS Criteria for Mixed Traffic Segments, from Furth (3)

	Street Width		
Speed Limit or Prevailing Speed	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 [a] or 2 [a]	LTS 3	LTS 4
30 mph	LTS 2 [a] or 3 [a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets without marked centerlines and with ADT ≤ 3000; use higher value otherwise.

Table 2-4 shows the criteria for determining LTS for shared bike lanes. In this case, the only factors are speed limit and number of lanes on the road. For a two-lane road with ADT < 3000, road users would tend to use the center of the road instead of along the curb, significantly reducing stress on bicyclists and thus for these streets, the smaller value of the two LTS's shown shall be used.

While Furth et al. provided a tool to categorize level of bicycle facility treatment, they provided little insight on cyclist behavior. Thus, literature with regard to cyclist behavior was further reviewed.

2.3 Potential Motivations for Violating Red Lights

Anecdotally, similar to pedestrian perceptions of jaywalking, many cyclists perceive failure to stop at a red light and/or stop sign as being a less severe infraction than for a motor vehicle. However, whether it is a cyclist or a vehicle violating a sign or signal indication, the violation is equally illegal. Depending on location, non-compliance rate can vary from 7% to 9% in Australia to 56% in China (5, 6). Yet, based on an observational study in Changsha, China, rate of running red light behavior for motorists is substantially lower, observed to be 0.14% while rate for cyclist violation is 17.84% at the same site (7).

Observations at sites in three cities in the United States, Santa Barbara, CA, Gainesville, FL and Austin, TX, show 8.4% of bicyclists are non-compliant at signalized intersections and 25.3% of cyclists are non-compliant at both red light and stop signs (8). According to drivers, a cyclist running a red light is often considered the most annoying behavior (9). While the association between non-compliance at red lights and crashes is reported to be low in Australia, there is a higher association reported in Taiwan, China (9, 10). In either case, red light violations pose a safety hazard for cyclists at intersections.

As an effort to explore the reasons motivating red light infractions, Johnson et al. conducted an online survey in Australia (9). Given that Australians drive on the left side of the road, turning left at a red light is equivalent to turning right at a red light in right-side driving countries, such as the United States. Cyclists are allowed to turn left at red lights legally at some locations in Australia, as long as safety is ensured, and the movement does not conflict with pedestrian right-of-way. The permissible turn-on-red rule is similarly observed in the United States, for most intersections generally allow right-turn-on-red unless specifically prohibited.

The results from Johnson et al. indicate four major motivations for red light violations: desire to make a left turn on red when not allowed, unable to activate inductive loop detector to trigger signal change, no other road users, and desire to use pedestrian crossing (9). Nearly a quarter of the cyclists claimed that loop detectors did not detect bicycles well (9), meaning that the actuated traffic signal would never turn green unless a vehicle arrived, leaving cyclists feeling as they had no choice other than to run the red light. The third reason indicated by the survey study reflects that approximately 16% of violations occurred when there were no other road users (9). This behavior is also reflected in Wu et al., which concluded that running red light behavior becomes more common as fewer riders are waiting (5). Johnson et al. suggested two probable explanations; one being that the violation is due to bicyclist failing to activate the loop detector and the other one being bicyclists perceiving less danger. The fourth reason mentioned in the Johnson et al. is infringement at pedestrian crossing (9). According to Johnson et al., the potential harm from vehicular traffic seems minor to a cyclist running a red vehicle light at a pedestrian crossing (9). On the other hand, this behavior imposes potential harm for pedestrians. Perhaps cyclists share motivating behavioral characteristics, from mildly-risk taking to high-risk taking. Though, the behavioral characteristic aspect was outside the scope of this study.

2.4 Intrinsic Factors Affecting Cyclist Crossing Behavior

Studying intrinsic factors can provide further insights into non-compliance behavior to target specific types of unsafe bicycle environments. Pai and Jou characterized cyclist non-compliance into three groups: risk-taking behavior, opportunistic behavior, and law-obeying to examine influential factors on red-light violations. Risk-taking behavior occurs when a cyclist simply ignores the presence of a red light; opportunistic behavior occurs when the bicyclist becomes too impatient at a crossing and rides through a gap in conflicting traffic; and the law-obeying behavior occurs when the cyclists stops at a red light and obeys the law (10). Cyclists were visually classified into three groups: young cyclists, students in uniform, and other. It was found that bicyclists in school uniforms are more likely to display risk-taking and opportunistic behaviors. Pai and Jou also discovered that risk-taking behavior is more common during off-peak hours (10). Moreover, this study delves into the effect of roadway characteristics, and found that roadways with a speed limit of 60 km/h (37.3 mph) lead to an increase in risk-taking and opportunistic behaviors. An evaluation of traffic volume was conducted and found that both high volume and low volume traffic resulted in higher non-compliance rates. Pai and Jou suggest that high non-compliance during high-volume hours was a result of congestion, during which traffic speeds are low and cyclists can easily identify gaps. At low traffic volume, cyclists tend to perceive less risks and thus non-compliance behavior becomes more frequent (10). The results from this study could influence decisions on what type of bicycle facility treatment could provide the most safety benefits near a school, for example.

Wu et al. conducted an observational field study in Beijing, China to investigate the intrinsic characteristics influencing bicyclists' and electric bike riders' running red light behavior. Video data was collected, and logistic regression was used to analyze the data. It was found that age group, that is, young vs. old and middle-age vs. old, is significant in predicting red-light running behavior, further confirming the findings of Pai and Jou. The effect of group size was considered, and Wu et al. found that reduced group size correlates to higher non-compliance.

Different from the previous studies, Wu et al. also studied the effect of cross traffic volume on non-compliance. The study indicates that a significant difference in non-compliance exists between low-traffic volume and high-traffic volume cross street traffic. This effect was also significant when comparing median traffic volume to high cross street traffic volume, yet not as strong. Using the three types of behaviors, law-obeying, risk-taking and opportunistic behaviors, characterized by Pai and Jou, Wu regrouped the observed data to test the effect of intrinsic behaviors. A Chi-Squared Test found that males showed a significantly higher non-compliance rate than females, and young and middle age riders tend to display more risk-taking behaviors compared to old riders. Since young to middle aged males are traditionally thought of as having more risk-taking tendencies, this finding makes intuitive sense. Wu et al. also discussed the time distribution of red-light running behaviors in terms of traffic signal phases (5). It was discovered that the majority of non-compliance occurred at early and late stages of a phase, rather than at the middle of a phase.

Fraboni et al. conducted a similar observational study to test the influence of presence of other bicyclists mentioned in the study of Wu et al. using behavior characterization developed by Pai and Jou, where data is collected through an App built via Qualtrics software on smartphones (11). Chi-Squared Tests were performed and the result indicated that risk-taking behavior is significantly more likely when no other cyclist is present and is significantly lower when 5 or more cyclists are present (11), consistent with the findings of Wu et al.

These studies have provided significant insights that bicyclists can be influenced by their surrounding social environment. Thus, there are reasons to believe that the surrounding built environment could impose an influence on cyclist behavior as well.

2.5 Cyclist Behavior Across Various Bicycle Facility Configurations

While the previous studies focused on intrinsic factors, that is, possible reasons behind running red light violation and the behavioral aspects of cyclists, limited studies have been conducted on the effect of intersection configuration in terms of bicycle facilities. Johnson mentioned that variations in non-compliance behavior were observed across different bike facility types, though no further insights were provided (12). Meng's report provided some insights on cyclists' non-compliance behavior with respect to width of crossings at intersections. Data was collected from three sites in the State of Massachusetts and revealed that the percentage of non-compliance reduces as the number of lanes to cross increases (13). This finding is consistent with the intuition that crossing more lanes is more challenging and induces a higher crash risk, and that cyclists would tend to behave more conservatively as perceived risk increases.

Duthie et al. conducted a study to observe the difference in bicyclists' riding behavior with respect to different bicycle facility configurations. Comparisons in riding behavior were made among Bike Lane (BL), Wide Outside Lane (WOL), Parking in Outside Lane (POL), BL with buffer and WOL with varying Total Lane Width (TLW). However, compliance at intersections was outside the scope of this study. This study characterized bicyclists' behaviors using Lateral Position of Bicyclist (LPB) and motorists' behaviors using Lateral Position of Motorists (LPM). The study concludes that BLs are superior to WOL, as BLs tend to increase LPB. As a comparison is made between Cincinnati Avenue. (WOL) and Parkfield North (BL), it is found that despite the fact that the total width of BL plus motor vehicle lane is similar to

WOL, bicyclists tend to ride further away from the doors of parked motor vehicles, leading to better comfort in riding experience and less safety hazard from opening vehicle doors.

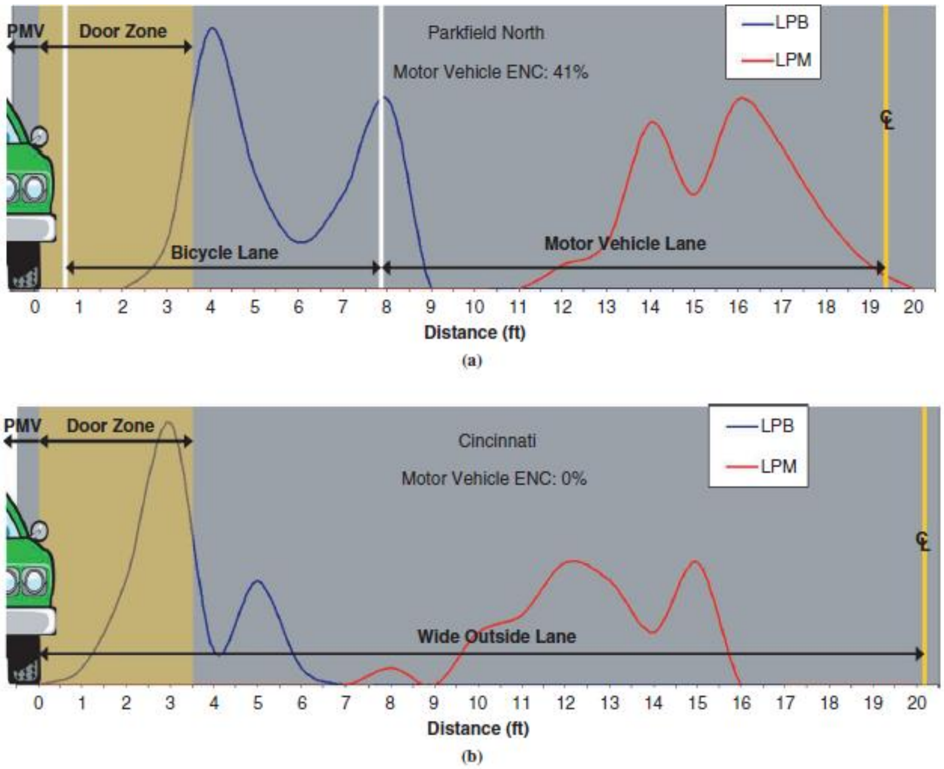

Figure 2-1 BL (a) vs. WOL (b), from Duthie et al. (14)

This study also suggested that the addition of a buffer between bicycle lane and parking spaces could be the most effective approach to ensure that bicyclists are riding outside the door zone (14).

In 1999, FHWA published a report analyzing cyclist behavior on Wide curb lanes (WCL) and bike lanes (BL). Observations were made in Austin, TX, Gainesville, FL and Santa Barbara, CA, as mentioned previously. The study revealed that while the overall wrong-direction violation rate was 5.6%, wrong-direction violation rate for WCL, 7%, was significantly higher than BL, 2.3%. Traffic signal and stop sign violations were categorized as safe, somewhat unsafe and definitely unsafe. For traffic signal violations, regardless of categories, no difference was found between the two facility types, though for stop sign violation, BLs were observed to have a lower violation rate, 19%, than WCLs, 45%. Yet, among all stop sign violations, BLs tend to have higher somewhat unsafe, 19% comparing to 5%, and definitely unsafe violations, 3% comparing to 0% (8). Conflicts were divided into midblock conflicts and intersection conflicts. The study indicates that among all midblock conflicts, WCL's had higher bike/pedestrian conflict rates and lower bike/bike conflicts rates, while the higher bike/pedestrian conflicts rate is reflective of the higher percentage of riders using sidewalks for bicycling. Among all intersection conflicts, BLs have significantly higher bike/bike conflicts rates while WCL has significantly higher bike/pedestrian conflict rates, similar to the case of midblock conflicts. Bike/motorist conflicts were evaluated separately in the study, and closer examination was conducted at high conflict rate sites. Situations leading to conflicts were identified to be motorists entering or exiting a parking facility, illegal stopping in BL or WCL and a turn lane at an intersection resulting in a narrow BL or WCL (8).

The District Department of Transportation (DDOT) in Washington, D.C. conducted an evaluation of various advanced bicycle facilities and concluded that there was a high violation rate at the three study locations – 16th Street NW/ U Street/ New Hampshire Avenue. NW, Pennsylvania Avenue NW and 15th St (15). This study focused more on facility use as a result of the new and innovative improvements as well as the perceptions surrounding these improvements, rather than the violations themselves. Along with violation percentages, this study reviewed crashes before and after facility installation as another measure of safety. However, bicycle crashes are rare events which makes it difficult to build solid conclusions about safety from these types of data. This study did not provide any other intersections that had a low or medium level of bicycle facility treatment to compare the effect on non-compliance.

2.6 Effect of Bicycle Facilities on Crash Rates

Unlike non-compliance rates that may not directly indicate the level of safety provided by bike facilities, crash rates provide a direct overlook at how much safety insurance bike facilities offer. However, it is important to understand that crashes are rare events and may not reflect all the effects of a facility on behavior. Jensen conducted a before-after analysis on 9 roads with bike tracks and 5 roads without bike tracks in Copenhagen, Denmark. The study found that rather than increasing safety level, the bicycle facility in fact causes a decrease in safety level and leads to higher crash rates as well as injury rates. Comparing before and after the construction of bike tracks, an overall increase of 10 percent in both crash rates and injuries rates was observed. Jensen stated that prohibiting parking was a major reason behind the increase in crash and injury rates, as a 24% increase in crash rates on links with parking ban and a 14% decrease in crash rate on links with parking permission was observed. Comparing before and after construction of bike lanes, an overall increase of 5 percent in crashes and 15 percent in injuries was observed (16).

Figure 2-2 Bike Track (left) vs. Bike Lane (right), from Jensen (16)

However, a study by Lusk et al. showed contradicting results, as cycle tracks were found to induce lower injury risk than reference streets (17). The study was conducted in Montreal, where six two-way cycle tracks were included, and each cycle track was compared with at least one reference street (17). That is, a street considered as an alternative to the existing cycle track, yet without the presence of a cycle track. The study used relative risk (RR) to compare the risk of injury with and without the presence of a cycle track. Out of the six streets with cycle tracks, three showed significantly lower injury risks while the rest showed no significant difference. The overall RR of injury across all six sites were 0.72 with statistical significance. That is, an overall reduction in injury risk was found. The study concluded that cycle tracks, at least, do not increase injury risks. The contradicting results imply that the effect of a bicycle facility may depend on the local population, and lessons learned in other locations may not be exactly applicable.

2.7 Summary

As Johnson et al. provided insights on the reasons behind running red light; Pai and Jou provided insights on the effect of age groups, traffic speed and time period in running red light violation. Wu further confirmed the finding of Pai and Jou by showing that age groups do have a significant correlation with red light running. Wu also showed that group size could have a significant impact on the likelihood of running red lights. As Meng provided insights that width of crossings could impact rates of non-compliance and Duthie et al. discovered that bike lane configuration has an impact on bicyclists' riding behavior in terms of lateral position of cyclists. The FHWA report by Hunter et al. further detailed the differences in cyclist behavior between WCL and BL. However, there is still a need to characterize bicyclist behaviors across a wider range of built environments. Jensen and Lusk both studied the effect of bicycle facility on crash and injury rates, yet contradicting results were found, implying that the effect of bicycle facility may depend on the local environment. Thus, further studies on the effect of biking environment on cyclist behavior should be conducted. By advancing the knowledge of bicycle behavior with respect to more environments, engineers can better understand the specific characteristics present at intersections contributing to the non-compliance behaviors. Better understanding can lead to better decisions in terms of how to influence bicyclist non-compliance behavior through bicycle facilities. This study aims to characterize cyclist non-compliance and bicycle-vehicle interactions to add to the knowledge presented in previous studies, as well as provide a scope for future analysis.

Chapter 3. Solution Methodology

3.1 Introduction

The objective of this study was to evaluate the external factors, that is, the characteristics or types of bike facilities potentially affecting cyclist behavior. To achieve this objective, video data was collected in the City of Austin as part of a before-and-after study on the effect of bicycle silhouette signal lens (bicycle signals) on intersection safety. The data collected and analyzed in this study was part of the "before" phase.

3.2 Study Location

The study involves 11 intersections mostly in the downtown Austin area. The intersections are:

- 4th Street & Red River Street,
- West Cesar Chavez Street & BR Reynolds Drive
- 3rd Street & Brazos Street,
- 3rd Street & Congress Avenue.,
- 3rd Street & Colorado Street,
- 3rd Street & Lavaca Street,
- 3rd Street & Guadalupe Street,
- 24th Street & Rio Grande Street,
- Martin Luther King Jr. Boulevard. & Rio Grande Street,
- Morrow Street & N. Lamar Boulevard,
- Airport Boulevard & Wilshire Boulevard.

Following are overviews of each intersection.

4th Street & Red River Street

Figure 3-1 Google StreetView of 4th Street & Red River Street

East 4th Street has one lane in each direction and a rail track for Capital Metro's commuter Red Line train, while Red River Street has two lanes in each direction. The speed limit on both streets is 30 mph. There is a two-way bike facility on the left-hand side of the street that has a small buffer zone between the painted stripe and the buttons next to the train line. The red signal on the left-hand side of the intersection is for bicycles, while the green light signal on the right-hand side of the image is for motor vehicles. The LTS at this intersection is 2.

West Cesar Chavez Street & BR Reynolds Drive

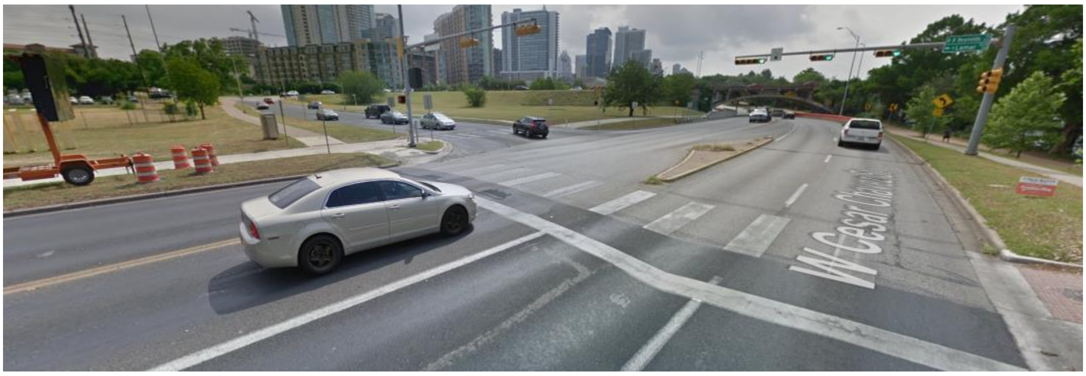

Figure 3-2 Google StreetView of West Cesar Chavez Street & BR Reynolds Drive

Eastbound West Cesar Chavez Street has two through lanes and one turn lane and westbound Cesar Chavez has three lanes. On the other hand, B.R. Reynolds Drive has two lanes in each direction. The speed limits on West Cesar Chaves Street and BR Reynolds Drive are both 30 mph. The bicycle path at this location is a cycle track that is completely separated from motor vehicle traffic. The cyclists at this location use the pedestrian signal to cross the intersection. The LTS at this intersection is 2.

3rd Street & Brazos Street

Figure 3-3 Google StreetView of 3rd Street & Brazos Street

3rd Street has one lane in each direction and one parking lane on the right-hand side of the street, while Brazos Street has two lanes in each direction. The speed limits on both streets are 30 mph. 3rd Street has a red-colored protected bike lane with a raised buffer. One side of the bicycle lane sits between the sidewalk and the parked cars, away from thru-moving vehicles. The LTS at this intersection is 2.

3rd Street & Congress Avenue

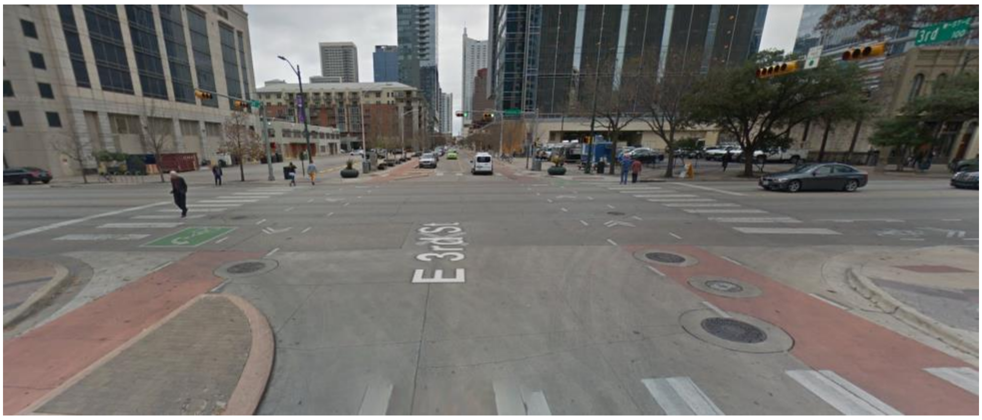

Figure 3-4 Google StreetView of 3rd Street & Congress Avenue.

3rd Street has one lane in each direction and one parking lane on the North side of the street, while Congress Avenue. has three lanes each direction. The speed limit on both streets is 30 mph. The bicycle facilities are identical to 3rd & Brazos Street and the LTS at this intersection is 2.

3rd Street & Colorado Street

Figure 3-5 Google StreetView of 3rd Street & Colorado Street

3rd Street has one lane in each direction and one parking lane, and Colorado Street has three general traffic lanes in the southbound direction. The speed limits on both streets are 30 mph. The bicycle facilities are identical to 3rd & Brazos Street and the LTS at this intersection is 2.

3rd Street & Lavaca Street

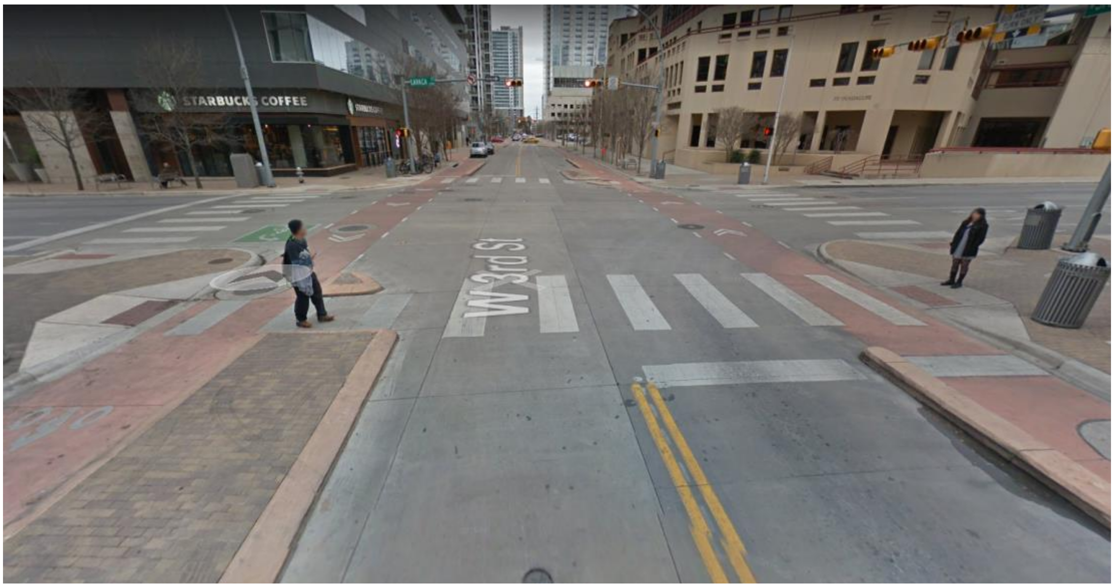

Figure 3-6 Google StreetView of 3rd Street & Lavaca Street

3rd Street has one lane in each direction and one parking lane, while Lavaca Street is a one-way street with three general traffic lanes and one bus lane in the northbound direction. The speed limits on both streets are 30 mph. The bicycle facilities are identical to 3rd & Brazos Street and 3rd & Colorado Street. The LTS at this intersection is 2.

3rd Street & Guadalupe Street

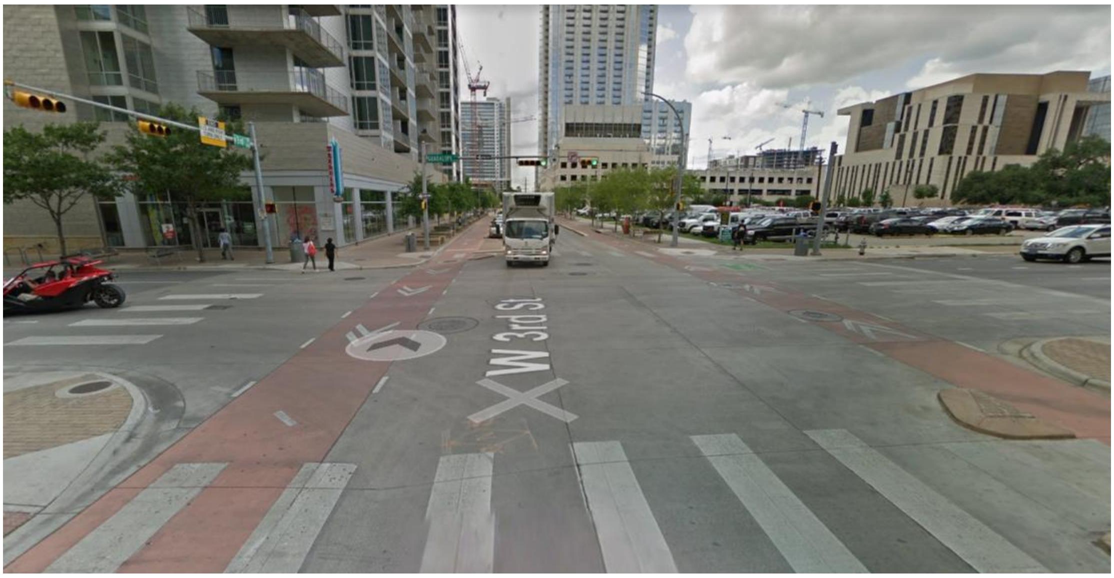

Figure 3-7 Google StreetView of 3rd Street & Guadalupe Street

3rd Street includes one lane each direction and one parking lane, while Guadalupe Street is a one-way street with four lanes and one bus lane in the southbound direction. The speed limit on both streets is 30 mph. The bicycle facilities are identical to 3rd Street & Colorado Street and 3rd & Lavaca Street The LTS at this intersection is 2.

24th Street & Rio Grande Street

Figure 3-8 Google StreetView of 24th Street & Rio Grande Street

Figure 3-9 Photograph of Rio Grande Street (North of Intersection)

24th Street has two lanes in each direction while Rio Grande Street is a one-way street with two lanes heading northbound. Figure 3-8 shows the basic intersection configuration. However, over the past year, changes have occurred on the north side of the intersection, where the original southbound lanes were restriped into bicycle lanes, shown in Figure 3-9. There is a two-way bicycle facility along with a left turn bicycle lane. The speed limit for both streets is 30 mph and the LTS at this intersection is 2.

Martin Luther King Jr. Boulevard. & Rio Grande Street

Figure 3-10 Google StreetView of MLK Jr. Boulevard & Rio Grande Street

Martin Luther King Jr. Boulevard. has two lanes each direction with the bicycle lane between the general traffic lanes, while Rio Grande Street turns from a two-lane two-way street south of the intersection into a two-lane one-way street north of the intersection. The speed limit on both streets are 30 mph. The bicycle facility existing along Rio Grande Street is a 6-foot striped green lane. The LTS at this intersection is 3.

Morrow Street & N. Lamar Boulevard

Figure 3-11 Google StreetView of Morrow Street & N. Lamar Boulevard

Along Morrow Street, the east side of the intersection has one lane in each direction and the west side of the intersection has two eastbound lanes and one westbound lane, while along N. Lamar Boulevard, both sides of the intersection have three lanes in each direction. The speed limit on N. Lamar Boulevard is 45 mph. Since a speed limit posting was not identified on Morrow Street, then the default speed limit of 30 mph applies. The LTS at this intersection is 3.

Airport Boulevard & Wilshire Boulevard

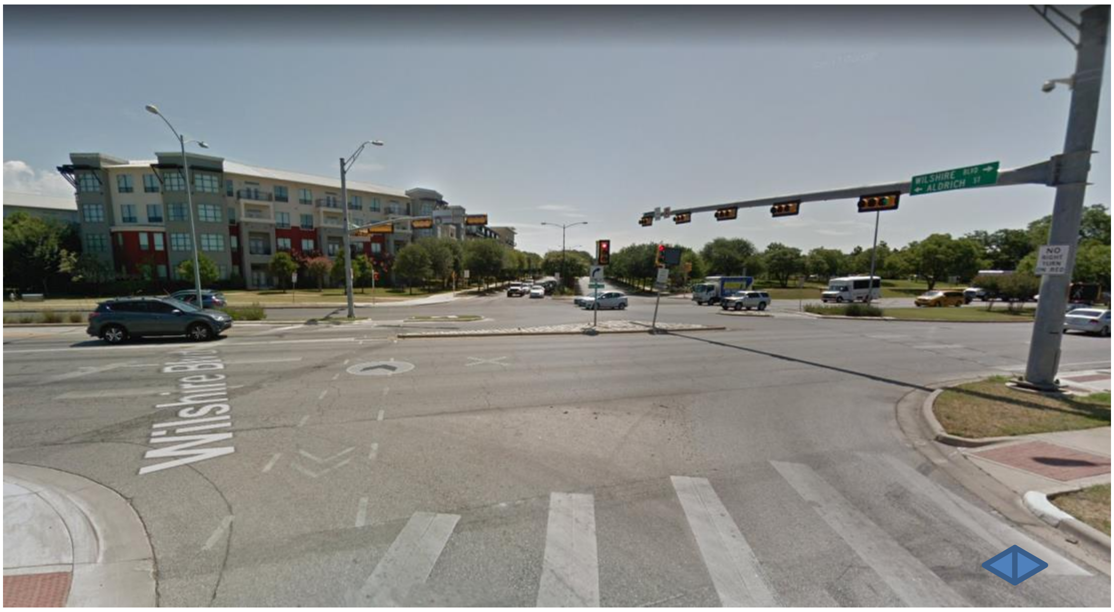

Figure 3-12 Google StreetView of Airport Boulevard & Wilshire Boulevard

Airport Boulevard has three lanes in each direction while Wilshire Boulevard only has one lane in each direction. The other side of the Airport Boulevard intersects with Aldrich Boulevard, which has two lanes in each direction. Cyclists at this location travel alongside the pedestrian path and use the pedestrian signals. The speed limit on Airport Boulevard is 45 mph while the speed limit on Wilshire Boulevard is 30 mph. The LTS at this intersection is 4.

For each intersection, data was collected using either a high-quality signal camera or a portable camera. Each intersection was recorded for 24 hours during October 2016 and was manually reviewed. The review entailed utilizing a software called CountPro to count vehicle traffic and a manual tally for the cyclist observations, including cyclist-vehicle interactions. All the observations were later aggregated into hourly counts. The review process followed the decision flow outlined in Figure 3-13.

The decision flow starts by considering whether the observed cyclists is present alone or interacting with another vehicle in the intersection. If the cyclist is alone, then the only concern is whether the cyclist is complying with the laws regarding bicycle riding. If there is a vehicle present, then the flow considers the interaction between the cyclist and the vehicle in addition to compliance. Since bicycle collisions are rare events, this characterization was used to capture whether or not there were problems with respect to intersection clarity and safety. The interactions that were of concern were: one-party reactions, two-party reactions, and near misses. One-party interaction was defined as either a motorist or a cyclist made a maneuver to avoid collision, such as turning, reducing speed and increasing speed, while two-party reaction is defined as both motorist and cyclist made maneuvers to avoid collision. If no maneuver was made and danger of collision was perceived, the interaction is defined as near miss. If the interaction between the cyclist and motor vehicle was safe, clear, and did not violate any traffic laws, then the Conflict Negotiated category applies.

This was the starting process for flagging interactions that would be later reviewed by a panel made up of three people to make a final decision on the categorization of the interaction. This panel review approach to categorizing vehicle-pedestrian interactions has been used in other bicycle studies conducted by Dr. Jennifer Dill at Portland State University.

3.3 Statistical Tools

Five statistical tools were used to analyze the data acquired through video collection and evaluate differences as well as correlations between bicyclist non-compliant behavior and characteristics of bike facilities. The following section further details the tools utilized.

Chi-Square Test of Independence

The Chi-Square Test of Independence is a statistical test used to evaluate independence of categorical data, such as the correlation between non-compliance and intersection. The test states that each observation consists of two factors, and the null hypothesis states that the two factors are independent of each other. For instance, each observation may contain two sets of variables: location and non-compliance. While location indicates the intersection where the observation is made, compliance indicates the number of non-compliance behaviors observed. Variables within each factor are independent of each other, meaning a cyclist is not present at multiple locations at the same time and a single cyclist may not fall into a state of being compliant and non-compliant at the same time.

A matrix of two dimensions can be constructed where each observation is allocated one cell within the matrix. Based on total observations in each category, locations and compliances, theoretical frequency can be computed as

$$E_{i,j} = \frac{(O_i * O_j)}{N},$$

where N is the total number of samples, $O_{i,j}$ is the total number of observations under column i across row j. Chi-square is defined as

$$\chi^2 = \sum_{j=1}^{n_{row}} \sum_{i=1}^{n_{column}} \frac{\left(O_{i,j} - E_{i,j}\right)^2}{E_{i,j}},$$

and degrees of freedom is defined as,

$$DF = (n_{row} - 1) * (n_{column} - 1),$$

where n_{row} is the number of columns (intersection or groups) and n_{column} is (non-compliance or compliance), respectively. The null hypothesis is rejected if

$$P(\chi^2 > \chi^2_{critical}) < \alpha,$$

where α is the significance level selected by the analysis and $P(\chi^2 > \chi^2_{critical})$ indicates the probability of making a Type I error (false-positive finding).

By rejecting the null hypothesis, the analysis may only conclude that the variables are not independent of each other. The Chi-Square test only shows the probability of independence between the two factors and nothing else. Thus, a correlation test would be needed to evaluate the correlation between a measured variable and the factors.

Kendall Rank Correlation Test

One of the hypotheses this study aims to test is whether traffic stress is correlated to cyclist non-compliance. It seems that perhaps as cyclists experience more stress, they might feel a higher risk when engaging in a non-compliant maneuver.

The Kendall Rank Correlation Test is a statistical test used to evaluate the ordinal or rank-based correlation between two variables. A τ-test can be performed to investigate the dependence between ranks of the two variables. As two variables are ranked more similarly to each other, τ coefficient approaches one. As two variable ranks depart further away from each other, the τ coefficient approaches negative one.

For the purpose of this study, variables investigated are LTS and percentage of non-compliant bicyclists. The reason that a percentage measure was used rather than the total number of non-compliant cyclists is because some intersections have much higher level of cyclist traffic than others and may have a higher total number of non-compliant cyclists, but a lower non-compliance percentage. By using ranks, these differences are essentially normalized. Thus, τ may be computed as

$$\tau = \frac{S}{\frac{N(N-1)}{2}},$$

where N is the total number of ranks for one variable, four in this case, and S is the difference between total number of concordant pairs and total number of discordant pairs and further defined as

$$S = (\#\ of\ concordant\ pairs) - (\#\ of\ discordant\ pairs).$$

Generally, τ is considered normally distributed if $N \geq 10$, however for this study, $N = 4$.

The null hypothesis states that the ranks between two variables are not correlated with each other and can be rejected if the computed τ is greater than the critical τ. By rejecting the null hypothesis, the analysis may conclude that the ranks between the two variables are not uncorrelated.

Though the Kendall Correlation Test provides information about how the ranks of measured variables correlate with an independent variable, it does not evaluate the change in the numeric value of the measured variable with respect to the independent variable. Thus, ordinary least squares analysis can evaluate the correlation between dependent and independent variables.

Ordinary Least Squares Regression Analysis

Often referred to as linear regression, ordinary least squares regression analysis is a statistical method that evaluates the relationship between a dependent variable and independent variables by assuming a linear relationship. The null hypothesis is that the slope of the best fit line with least squared error is equal to zero (19). This method is commonly used when both dependent (y) and independent (x) variables are interval level data or above and the estimated relationship between x and y variables is

$$y_{predict}^{i} = \beta_1 x_1^i + \beta_2 x_2^i + \cdots + \epsilon,$$

where β's are regression parameters, x's are independent variables called explanatory variables, and i's are the observations made. This method chooses regression parameters β_i to minimize the squared sum of the differences between the observed dependent variable, $y_{observed}$, and the predicted dependent variable, $y_{predict}^{i}$. Using this tool, the coefficient of determination r^2 can be computed as

$$r^2 = \frac{\sum\left(y_{predict}^{i} - \bar{y}\right)^2}{\sum\left(y_{observed}^{i} - \bar{y}\right)},$$

where r^2 represents the percentage of observations explained by $y_{predict}$. When $r^2 = 1$, the best fit line perfectly matches the observed data.

One-Way ANOVA

One-Way Analysis of Variance (ANOVA) is commonly used to evaluate whether a difference in response exists among different groups present in an experiment. In ANOVA, factors can be either continuous or categorical. In One-Way ANOVA particularly, there is only one factor in the model containing multiple factor levels. For example, if the factor is intersection, then the different levels of the intersection factor would be the individual intersections names, and the response variable is cyclist non-compliance. The null hypothesis tests whether the factor level means are equal to each other. ANOVA can be essentially thought of as an extension of the t-test. ANOVA assumes that variance is the same for every group, is normally distributed, and could yield inaccurate results if these assumptions are violated. This test was performed using the Statistical Analysis System (SAS).

Two-Way ANOVA

Two-way ANOVA is generally considered an extension of one-way ANOVA. However, two-way ANOVA takes two factors into account, Factor A and Factor B, with both Factor A and Factor B containing multiple factor levels. This study selected LTS and time periods as the two factors containing different factor levels. The combination of factor levels within Factor A and factor levels within Factor B are called treatments. Thus, the two-way ANOVA null hypothesis states that there is no difference in response between treatments means. After the running two-way ANOVA, a pairwise comparison may be conducted to evaluate the difference in treatment effects between groups.

3.4 Analysis

This chapter describes the results from the aforementioned statistical tests that were used to examine the behaviors of bicyclists and their association with different intersection characteristics. The investigation reviews two aspects of bicyclists' behavior: non-compliance and motorist-cyclist interaction. While non-compliance is defined as bicyclists running through red lights or traveling in the wrong direction, interaction is defined as either a bicyclist, a motorized vehicle driver, or both parties attempting to changing speed and/or position to avoid a potential collision.

The idea of utilizing the two indicators is primarily motivated by the following questions:

1. Does cyclist behavior differ across built environments?
2. If so, what are the factors that account for these differences?
3. Are there correlations between these factors and cyclist behavior?

Level of Traffic Stress for Observed Facilities

LTS, discussed in the literature review, was selected as the method to characterize the built environment to determine its effect on cyclist behavior. The LTS determination procedure follows three steps: determining LTS for each approach to an intersection, selecting roadway LTS based on the approach with higher LTS, and selecting intersection LTS based on the link with highest LTS. To determine the LTS for the intersection of 3rd Street & Brazos Street, the section of 3rd Street between San Jacinto Boulevard and Brazos Street was considered.

Table 3-1 LTS Criteria Table for 3rd Street & Brazos Street (East of Brazos Street)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Since the segment east of 3rd Street between San Jacinto Boulevard and Brazos Street has a parking lane alongside the bike trail, Table 3-1 shows the criteria satisfied by the selected segment. As speed limit satisfies only LTS 2, the LTS for this approach of this segment is 2. The same process is repeated for the segment between Brazos Street and Congress Avenue. LTS of 2 is determined for this segment. Since a bike lane exists only along 3rd Street, the approaches along Brazos Street are not considered. With the highest LTS value taken among all approaches to this intersection, LTS of 2 is determined for the intersection of Brazos Street & 3rd Street. With this approach, LTS is determined for each of the 11 intersections studied and the results are shown in Table 3-2.

Table 3-2 LTS Categorization of Studied Intersections

LTS	1	2	3	4
4th & Red River Street	X			
Cesar & B.R. Reynold	X			
3rd & Brazos		X		
3rd & Colorado		X		
3rd & Congress		X		
3rd & Guadalupe		X		
3rd & Lavaca		X		
24th & Rio Grande		X		
Rio Grande & MLK			X	
Morrow & Lamar			X	
Airport & Wilshire				X

Intersection Descriptive Statistics

This section illustrates the data acquired prior to statistical testing. The displayed data are of the following types: daily non-compliance count and corresponding non-compliance rates across intersections, daily interaction count, and corresponding interaction rates across intersections.

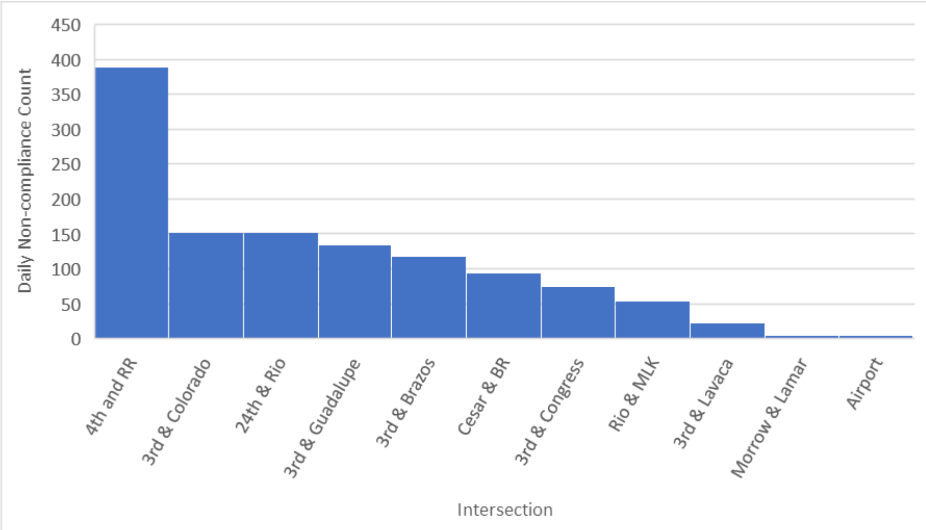

Figure 3-13 Daily Non-compliance Count, Ranked from High to Low

Figure 3-13 shows the daily non-compliance count at all intersections. At 4th Street & Red River Street, the non-compliance count is the highest, while at Airport Boulevard & Wilshire Boulevard, the non-compliance count is the lowest.

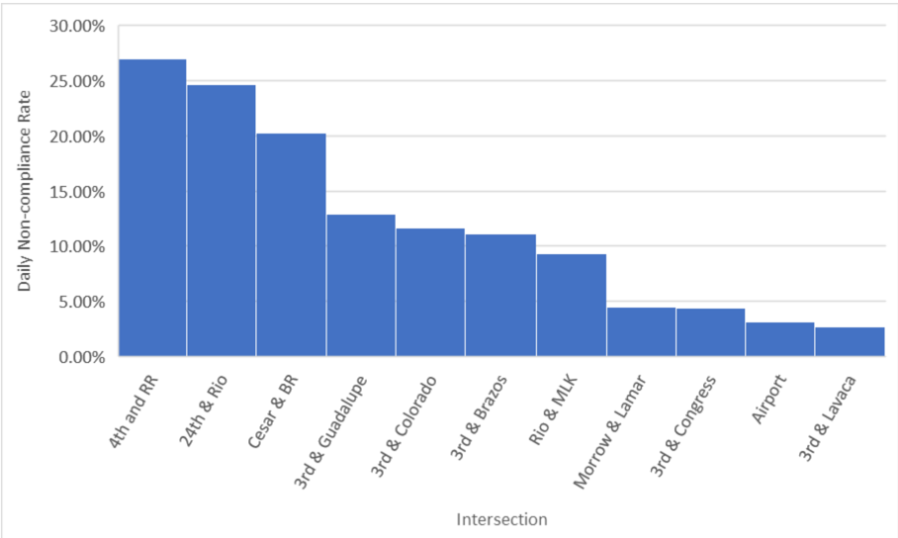

Figure 3-14 Daily Non-Compliance Rate, Ranked from High to Low

Figure 3-14 shows the daily non-compliance rate at each intersection. At 4th Street & Red River Street, the non-compliance rate is highest, while at 3rd Street & Lavaca Street, the non-compliance rate is the lowest.

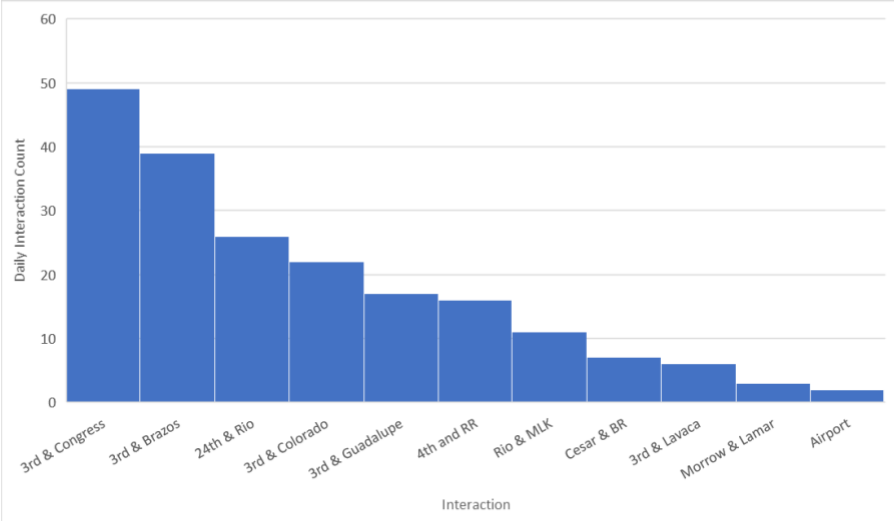

Figure 3-15 Daily Interaction Count, Ranked from High to Low

Figure 3-15 shows the daily interaction count at all intersections. At 3rd Street & Congress Avenue, the interaction count is the highest, while at Airport Boulevard & Wilshire Boulevard, the interaction count is the lowest.

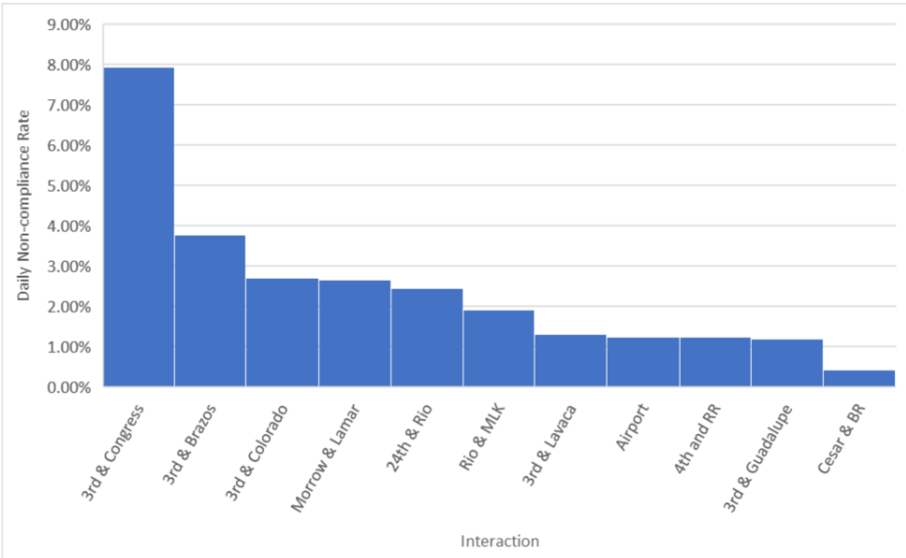

Figure 3-16 Daily Interaction Rate, Ranked from High to Low

Figure 3-16 shows the daily interaction rate at each intersection. At 3rd Street & Congress Avenue, the interaction rate is highest, while at West Cesar Chavez Street & BR Reynolds Drive, the interaction rate is the lowest.

Chi-Squared Test of Independence

Recall the first question raised at the beginning of this chapter: do bicyclist behave differently under different built environments? To address this, a Chi-Squared Test of Independence was performed with respect to intersections.

A contingency table containing non-compliance/compliance counts at each intersection was constructed, as indicated in Table 3-3, and Chi-Squared was computed to be 572.60, greater than the critical Chi-Squared value of 18.3 at $DF = 10$ and $\alpha = 0.05$.

Table 3-3 Chi Square Test Statistics

Chi-Square Test Statistics	
x^2	572.60
DF	10
x^2 Critical 95%	18.3
Result	Rejected

The null hypothesis that the non-compliance level of each intersection is independent is rejected. Therefore, the level of non-compliance is not independent across intersections.

A closer inspection of the Chi-Squared value contributed by each intersection indicates the values contributed by intersections of:

- 3rd Street & Congress Street,
- 3rd Street & Lavaca Street,
- 24th Street & Rio Grande Street,
- 4th Street & Red River Street,
- West Cesar Chavez Street & BR Reynolds Drive, and
- Airport Boulevard & Wilshire Boulevard,

were comparably greater than the others. By inspecting the percentage of non-compliance at each intersection, the analysis found that the intersections of

- 3rd Street & Congress Street,
- 3rd Street & Lavaca Street, and
- Airport Boulevard & Wilshire Boulevard,

had a lower non-compliance percentage than average while the intersections of

- 24th Street & Rio Grande Street,
- 4th Street & Red River Street, and
- West Cesar Chavez Street & BR Reynolds Drive,

had greater percentages of non-compliance than average. As non-compliance behavior differed with respect to intersections, the study proceeded to find the factors that affect bicyclists' non-compliance behavior and how they were correlated.

Based on the categorization provided in Section 4.1, intersection specific observations were aggregated into groups, and the aggregated rates of non-compliance are displayed in Table 3-4.

Table 3-4 Chi-Squared Test for Non-compliance vs. LTS

LTS	1	2	3	4
Non-compliance Rate	25.33%	9.96%	8.50%	3.09%
$(O\text{-}E)^2/E$	229.90	43.48	10.33	12.06
	33.99	6.43	1.53	1.78

The columns characterized with 1, 2, 3, and 4 represent LTS while non-compliance rate represents the aggregated percentage of non-compliance.

Table 3-5 Chi-Square Test Statistics

Chi-Square Test Statistics	
x^2	325.65
DF	3
x^2 Critical 95%	7.82
Result	Rejected

As Table 3-5 shows, Chi-Squared = 325.65 while the critical Chi-Squared at $DF = 3$ and $\alpha = 0.05$ equals 7.82. Thus, the null hypothesis that non-compliance level is independent of LTS was rejected, concluding that non-compliance level is related to LTS. Most of the Chi-Squared value was contributed by LTS 1 and LTS 2, as shown by (O-E)2/E values tabulated in Table 3-4, whereas the non-compliance level of LTS 1 is much greater than the rest of groups. With a closer inspection, it can be observed that as LTS level increases, the percentage of non-compliance decreases.

Kendall Rank Correlation Test

The preliminary evaluation of the observed non-compliance rate of each LTS group, showed a trend. To confirm this finding, Kendall Rank Correlation Test was applied. Rather than using percentage of non-compliance, the rank of the percentage of non-compliance was used, as Kendall Rank Correlation Test is only applicable to ordinal level data. The test first ranks LTS from low to high. For each LTS, the corresponding percentage of non-compliance was assigned a rank as well.

Table 3-6 Ranks for LTS and Percentage of Non-Compliance

LTS	**1**	**2**	**3**	**4**
Rank of LTS	1	2	3	4
% Non-compliance	25.33%	9.96%	8.50%	3.09%
Rank of % non-compliance	1	2	3	4

From Table 3-6, S was computed to be 6. Test statistics τ was computed as

$$\tau = \frac{S}{\frac{1}{2}N(N-1)} = \frac{6}{6} = 1,$$

whereas the required τ for $\alpha = 0.05$ is 1. Thus, the null hypothesis that there is no correlation between the ranks of LTS and the ranks of non-compliance is rejected, concluding that a correlation exists between the ranks of LTS and the ranks of non-compliance percentage. The result from this test provides a potential answer to the third question raised: what is the correlation between the inspected factors and bicyclists behavior? That is, there exists a positive correlation between LTS and ranks of percentage of non-compliance. In other words, a higher LTS indicates a higher percentage of non-compliance. This is possibly because bicyclists are more cautious when riding on roadways with fewer safety features. Under this circumstance, bicyclists would avoid risky behaviors, leading to a lower rate of non-compliance.

One-Way ANOVA Analysis

Though both Chi-Squared and Kendall Rank Correlation tests showed significance, neither of the tests took variance within each group into account. Thus, One-Way ANOVA was used to further evaluate the result with within-group variance taken into consideration. The test was setup using Statistical Analysis System (SAS).

Table 3-7 Test Statistics from SAS

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	404.84	134.95	2.80	0.1183
Error	7	337.30	48.19		
Corrected Total	10	742.14			

Table 3-7 shows the test statistics computed by SAS. For the given data, mean square between groups (MSB) was computed to be 134.95 while the mean square of error (MSE) was computed to be 48.19. The F-value was given as the ratio between MSB and MSE, computed to be 2.80, resulting in a p-value of 0.1183, greater than $\alpha = 0.05$. Thus, the analysis failed to reject the null hypothesis.

A closer inspection of the distribution of non-compliance rate was conducted, as the result contradicted previous findings.

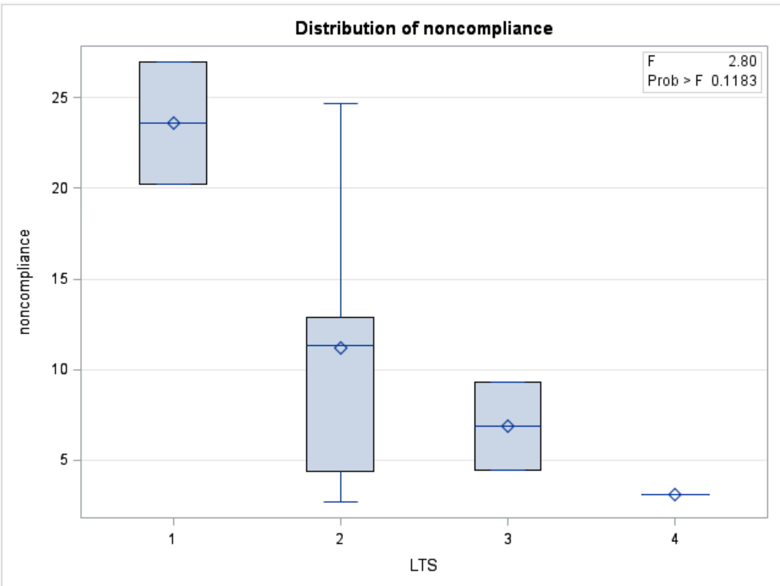

Figure 3-17 Distribution of Ranks Within Each LTS Group

As Figure 3-17 indicates, the span of non-compliance rate within group LTS 2 is much greater than the span of non-compliance rate within other groups, yielding a greater variance compared to the other groups. As One-way ANOVA assumes that variance within each group should be the same, violation of this assumption may yield inaccurate results. Thus, since the assumption of equal variance is violated, it is suspected that the results may not represent the actual p-value.

Non-Compliance Vs. Time of Day

Based on a preliminary inspection of the data set, it was suspected that occurrence of non-compliance behavior could be correlated with time of day. Intuitively, bicyclists that remain active when few pedestrians and motorists are utilizing the roadway tend to behave more aggressively, as their behaviors are not seen by others. The collected data set seems to explain this behavior, as the percentage of non-compliance during early morning off-peak (0:00 to 7:00) tends to be the highest at all intersections. To test this hypothesis, two tests were utilized, Chi-Squared Test of Independence to discover whether non-compliance behavior is independent of time of day and ANOVA to determine whether non-compliance behavior at one time of day is significantly different from other times. In this case, time of day was divided into five groups (Table 3-8).

Table 3-8 Time Periods

Time Periods	
Morning Off-Peak (MOP)	0:00 - 7:00
Morning Peak (MP)	7:00 - 10:00
Midday Off-Peak (MDOP)	10:00 - 16:00
Midday Peak (MDP)	16:00 - 20:00
Night Off-Peak (NOP)	20:00 - 0:00

Chi-Squared Test of Independence

The Chi-Squared Test of Independence was performed similarly to previous cases, where a contingency table was constructed with total counts of compliance and non-compliance at each time of day. Since the effect of intersection was not considered, data were aggregated.

Table 3-9 shows the non-compliance rate during each time period, whereas the highest non-compliance rate occurs during morning off-peak. Table 3-10 shows that Total Chi-Squared = 130.89 while the critical Chi-Squared (at $DF = 3$ and $\alpha = 0.05$) = 9.49. The null hypothesis that non-compliance behavior is independent of time of day was rejected. The majority of the Chi-Squared value is contributed by morning off-peak, as Table 3-9 shows. With a closer inspection, it was observed that the percentages of non-compliance during the morning peak, midday off-peak, midday peak, and night off-peak were all within five percent of each other. On the other hand, the percentage of non-compliance during the morning off-peak is nearly 13% above the second highest time group.

Table 3-9 Chi-Squared Test for Non-compliance vs. Hour Group

Time Periods	MOP	MP	MDOP	MDP	NOP
Non-compliance Rate	27.74%	12.91%	14.93%	10.14%	10.87%
$(O-E)^2/E$	82.86	0.00	7.54	18.67	4.97
	12.25	0.00	1.11	2.76	0.73

Table 3-10 Chi-Square Test Statistics

Chi-Square Test Statistics	
x^2	130.89
DF	4
x^2 Critical 95%	9.49
Result	Rejected

Non-Compliance Vs. Time Vs. LTS

Though One-way ANOVA failed to reject the null hypothesis, it was suspected that the differences in variance among groups resulted in an inaccurate conclusion. In addition, aggregating hourly non-compliance rates into daily non-compliance rates caused some unexplained error. By taking time periods into account, two-way ANOVA could be performed. As the dependent variable, non-compliance rate represented in percentage, satisfied the continuous variable requirement, normality was assumed for the distribution of measurements within each LTS group and time group.

Table 3-11 Class Level Information

Factor	Number of Factor Levels	Factor Levels
LTS	4	1 2 3 4
Time	5	MDO MDP MOP MP NOP

Table 3-11 shows the treatments chosen, as LTS levels are represented using numerical values 1 through 4, time periods are represented as Midday Off-Peak (MDO), Midday Peak (MDP), Morning Off-Peak (MOP), Morning Peak (MP) and Night Off-Peak (NOP).

Table 3-12 Test Statistics for Two-Way ANOVA

Effect	F Value	Pr > F
LTS	7.04	0.0005
Time	6.44	0.0003

Table 3-12 represents the test statistics given by SAS. With a p-value smaller than $\alpha = 0.05$ for both Time and LTS, the null hypotheses were rejected, and it was concluded that the means of the dependent variable across both factors were not equal. To further explore the significance in differences between groups, pairwise comparisons were conducted.

Table 3-13 Difference of Least Squares Means Among LTS Groups

LTS	LTS	t Value	Pr > |t|	Adj P	Lower	Upper	Adj Lower	Adj Upper
1	**2**	4.05	0.0002	0.0011	6.79	20.2013	4.32	22.68
1	**3**	2.78	0.0078	0.047	3.91	24.3935	0.13	28.17
1	**4**	3.85	0.0004	0.002	9.35	29.8395	5.58	33.62
2	**3**	0.15	0.88	1.00	-8.28	9.5943	-11.58	12.89
2	**4**	1.37	0.18	1.00	-2.84	15.0403	-6.14	18.34
3	**4**	0.93	0.36	1.00	-6.38	17.2707	-10.74	21.64

Table 3-13 shows the pairwise comparison among all LTS groups. The t-values represent the computed test statistics. This corresponds to the computation:

$$t = \frac{\mu_1 - \mu_2}{standard\ error},$$

where μ_1 and μ_2 are the estimated means.The term $Pr > |t|$ represents the unadjusted probability of having a Type I error. Since the chance of error occurs when multiple null hypotheses are tested, the Bonferroni adjustment was adopted to take the increase into account, resulting in the adjusted P value.

From Table 3-13, statistical significance exists between LTS 1 and LTS 2, LTS 1 and LTS 3, as well as LTS 1 and LTS 4. In practice, this could represent that upgrading or downgrading the facility between LTS 3 and LTS 4, or between LTS 2 and LTS 4 will not show a significant change in the rate of non-compliance. This can be significant if the rate of non-compliance is used as an indicator of safety. Given an assumption that higher non-compliance indicates bicyclists feel safer – inappropriate, yet let us assume so – upgrading an existing facility categorized as LTS 3 to LTS 2 will not result in a significant increase in bicyclists' sense of safety. Rather, if more funding can be employed to upgrade the facility to LTS 1, significance can then be observed.

Similarly, pairwise comparisons were conducted for time groups, as Table 3-14 indicates. Comparing the adjusted p-value and $\alpha = 0.05$, significance exists between MDO and MOP, MDP and MOP, MOP and MP, as well as MOP and NOP. That is, morning off-peak (MOP) shows a significant difference compared to any other time group, and no significance difference was found among other time groups. By evaluating the bicyclists count collected through video data, it was found that morning off-peak has the least number of bicyclists compared to the rest of the day. In fact, for all intersections observed, the number of bicyclists observed during the morning off-peak (0:00 to 7:00) contributes to less than 10% of the daily count. Two explanations are possible for this high non-compliance behavior:

1. As the study of Johnson et al suggested, bicyclists tend to show non-compliance when no other road user is present (*9*). It was suspected that during the morning off-peak when few road users are sharing the road, the bicyclists feel much safer due to less conflicting traffic so that they show more violations.

2. As Wu et al. suggested, with fewer bicyclists waiting at an intersection, the likelihood of non-compliance behavior occurring increases (*5*).

Since few motor vehicles and bicycles were present during morning off-peak, both explanations could be true and in fact the high non-compliance could be attributed to a combination of both behaviors mentioned above.

Table 3-14 Difference of Least Squares Means Among Time Groups

Time	Time	t Value	Pr > |t|	Adj P	Lower	Upper	Adj Lower	Adj Upper
MDO	MDP	1.14	0.26	1.00	-3.45	12.49	-7.15	16.19
MDO	MOP	-3.05	0.0038	0.038	-20.06	-4.11	-23.76	-0.41
MDO	MP	0.66	0.51	1.00	-5.35	10.60	-9.05	14.30
MDO	NOP	1.35	0.18	1.00	-2.61	13.34	-6.31	17.04
MDP	MOP	-4.19	0.0001	0.0012	-24.58	-8.63	-28.28	-4.93
MDP	MP	-0.48	0.63	1.00	-9.87	6.08	-13.57	9.78
MDP	NOP	0.21	0.83	1.00	-7.13	8.82	-10.83	12.52
MOP	MP	3.71	0.0005	0.0054	6.74	22.68	3.04	26.38
MOP	NOP	4.40	<.0001	0.0006	9.48	25.42	5.78	29.12
MP	NOP	0.69	0.49	1.00	-5.23	10.71	-8.93	14.41

Equivalent Lane Volume

Other attempts were made to identify factors with which bicyclist behaviors are correlated. One suspect was equivalent lane volume (EQLV). As data was collected through surveillance cameras, only part of an intersection could be captured. In order to approximate the traffic state at the intersection with incomplete data, one assumption that traffic volume on each roadway section is the same for each lane was made. EQLV is thusly defined as

$$EQLV = \frac{\sum Observed\ Volume_i}{N},$$

where N represents the total number of observable lanes and volume represents the traffic volume on each observable lane. Using this concept, traffic volume at the intersection was approximated.

Non-compliance Vs. EQLV

Non-compliance level is correlated with time, and one major factor that varies with time of the day is traffic volume. During the morning off-peak, when traffic volume is very low, bicyclists tend to behave more aggressively. Thus, it is suspected that a correlation may exist between non-compliance and EQLV among intersections. Since the dependency of non-compliance on time across all intersections was uncertain, two linear regression tests, one based on daily non-compliance vs. daily EQLV and one based on non-compliance vs. EQLV during the morning peak, were performed. However, since EQLV was only collected for 5 out of the 11 intersections, regression can only be performed on these intersections.

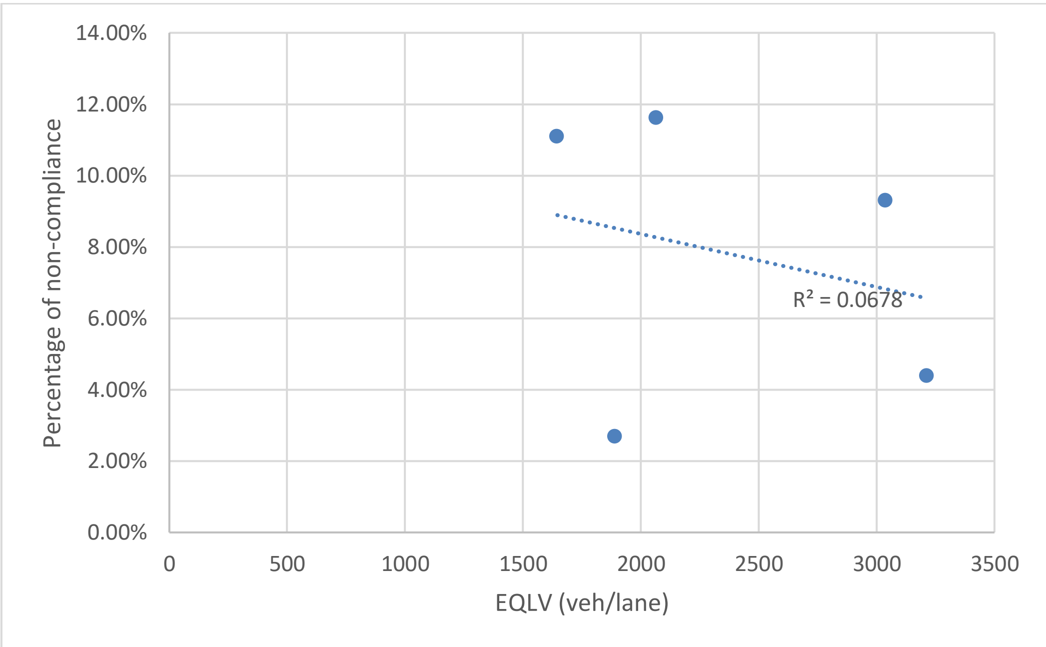

Figure 3-18: Daily Percentage of Non-Compliance with Respect to Daily EQLV

Figure 3-18 shows the linear regression fitted to the known data points. As r2 indicates, the correlation between daily non-compliance and daily EQLV is likely insignificant. A regression test is performed to further confirm this finding. As the test result indicates the t-score is -0.698 and p-value is 0.557, therefore the null hypothesis that non-compliance is uncorrelated with EQLV cannot be rejected.

To accommodate for the dependency of non-compliance on time, the test was repeated for non-compliance vs. EQLV of morning off-peak.

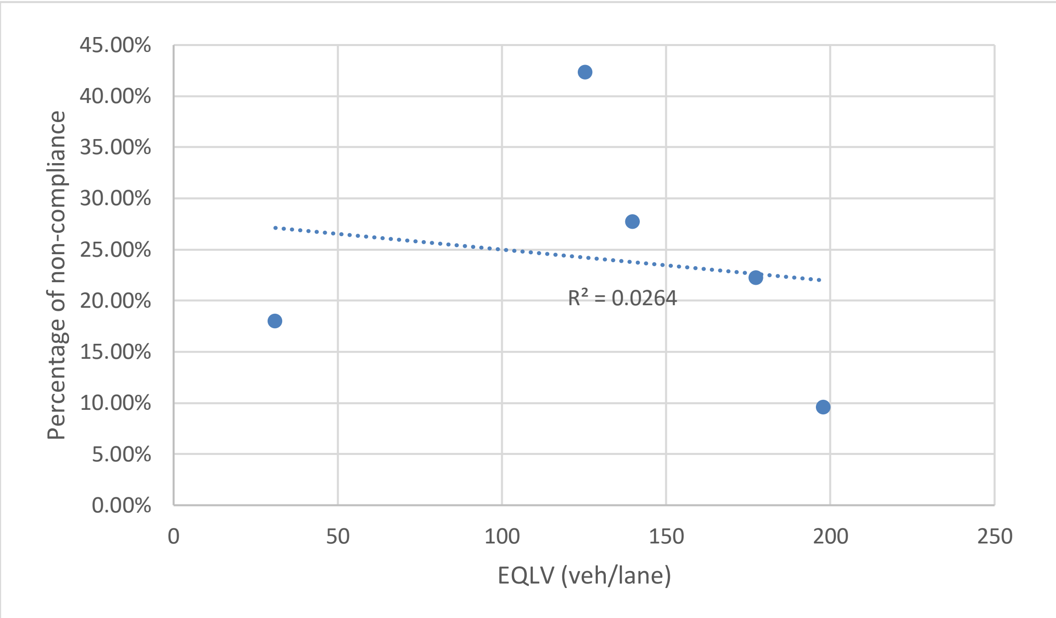

Figure 3-19: Percentage of Non-Compliance Versus EQLV during Morning Off-Peak

As the r^2 values in Figures 3-18 and 3-19 imply, non-compliance and EQLV, regardless whether periodical or daily, are uncorrelated. To further confirm this finding, linear regression analysis was repeated for this study as well.

The test statistic indicates that, with t-score for slope being -0.285 and p-value being 0.794, the analysis failed to reject the null hypothesis that non-compliance and EQLV during the morning off-peak is uncorrelated.

Interaction

A different aspect in characterizing bicyclist behavior is interaction. As non-compliance behavior like running red lights may indicate that cyclists feel safe, interaction commonly reflects that cyclists or motorists have perceived potential harm. Intuitively, neither a motorist nor bicyclist would make a maneuver to avoid each other if they were confident that no collision would occur. Thus, when an interaction occurs, it may be an indicator that at least one party has perceived danger. To an extreme extent, if a bike lane is completely segregated from the roadway, few or no interactions should be expected; on the other hand, if bicyclists share the roadway with motorized vehicles, it is much more likely for interactions to occur. Though the main purpose of this study was to evaluate non-compliance behavior, a preliminary analysis was conducted on interaction. To test whether interaction is correlated with LTS, a Chi-Square Test was conducted.

Table 3-15 Chi-Square Test Statistics for Interaction vs. LTS

LTS	1	2	3	4
Interaction Rate	0.76%	3.03%	2.25%	1.82%
$(O-E)^2/E$	26.392	17.114	0.123	0.121
	0.573	0.371	0.003	0.003

Table 3-15 shows the daily interaction rate of each LTS group, whereas LTS 1 has the lowest interaction rate among all groups.

Table 3-16 Chi-Square Test Results for Interaction vs. LTS

Chi-Square Test Statistics	
x^2	44.58
DF	3
x^2 Critical 95%	7.82
Result	Rejected

Since $\chi^2 = 44.58$ and critical $\chi^2_{critical} = 7.82$ (Table 3-16), the null hypothesis is rejected, therefore interaction and LTS are not independent. Reviewing the comparative rates of interaction, it was observed from Table 3-15 that LTS 1 has a much lower interaction rate compared to the other groups the general trend is that higher LTS led to lower interaction rates. This trend may be explained as LTS 1 represents bike lanes that are completely segregated or are nearly completely segregated from motor traffic, leading to few potential opportunities for interaction. For the other groups, interaction behavior may follow a similar pattern to non-compliance, where bicyclists become more cautious and aware of their surroundings when riding on facilities with higher stress level.

Linear regressions were conducted to test the correlation between interaction and EQLV (within LTS group and among all intersections). Trends were implied in both regression plots, yet no statistical significance could be found due to several reasons. Although LTS group seems to have an influence on interaction rate, the among intersection analysis was less adequate. Yet, as LTS 1 includes two intersections, LTS 3 includes one intersection and LTS 4 includes two intersections, only LTS 3 was eligible for the regression analysis. Another issue was that the reduced number of intersections due to considering only one LTS group reduced the power of regression analysis, leading to greater difficulties in rejecting the null hypothesis. Since the focus of this study was not on interaction, no further tests were conducted, yet it may be an interesting subject for future analysis.

Chapter 4. Summary and Conclusions

4.1 Introduction

This chapter summarizes the findings and provides interpretations for the results as well as direction for future research. As mentioned in Chapter 1, this study aims to answer three questions:

1. Do cyclists behave differently under different built environment?
2. If a behavioral difference exists, what is/are the factor(s) that accounts for this difference?
3. If a trend exists, what is the correlation between the found factor and level of non-compliance?

In this chapter, an answer is provided for each of the questions together with its correspondence with the reviewed literature.

4.2 Summary and Conclusions

The first question proposed at the beginning of this article can now be answered: Yes, the behaviors of bicyclists differ under different built environments. These differences are due to a variety of factors and possibly a combination of these factors. As the study focused on non-compliance behavior, it was found that the rate of non-compliance is correlated with LTS. As the Kendall Correlation Test showed, higher LTS corresponds to lower non-compliance rate. This result was further confirmed in two-way ANOVA, when the pairwise comparison was conducted. It was also discovered that non-compliance rate during the morning off-peak hours (0:00 to 7:00) was significantly higher than other time periods. This finding is consistent with the findings of Pai and Jou as well as Johnson, whereas Pai and Jou concluded that non-compliance is more common during off-peak hours and Johnson concluded that non-compliance is more common at night. The test explored the statistical significance of differences between pairs of LTS groups and showed a statistically significant difference between LTS 1 and other LTS groups. The study further evaluated EQLV and its correlation with non-compliance rate, but no statistical significance was found. This result could be due to a lack of within-group data, since EQLV data was collected for only five intersections and not all of those intersections belong to the same LTS group.

An attempt was made to evaluate motorist-cyclist interactions. A Chi-Squared test showed that interaction is related to intersection, though no correlation was further discovered. The Kendall Correlation Test evaluated the trend between interaction and LTS, yet no significance was discovered. Further evaluation showed that a decreasing trend in interaction rate may exist with increasing LTS when LTS is 2 or above. This can be explained since LTS 1 means completely or nearly completely segregated bike paths which provide little opportunity for interaction. Regression analysis evaluated the correlation between interaction and EQLV. It was concluded that among-intersection analysis was inadequate, for interaction is correlated with LTS. No further analysis was conducted as within-group analysis lacked data.

Though this study does not fully accomplish the purpose of discovering factors in the built environment that impact bicyclist behaviors, it opens the gate for future studies. Since LTS could be used as an indicator for the rate of non-compliance behavior, and LTS is defined using a variety of criteria, future analysis could focus on discovering the defining characteristics that may be responsible for the differences in the rate of non-compliance.

4.3 Directions for Future Research

Since this part of the study was performed prior to the installation of bicycle signals, the built environment might not have provided clear instruction for bicyclists, leading to a result that bicyclists behaved based on their perception of safety. That is, as the results of this study indicated, as LTS increases, the non-compliance rate decreases. Yet, if the lack of clear instructions was a critical cause of the current state of cyclist behavior, the installation of bicycle signals might impose a difference on how cyclists behave. That is, one might wonder whether the installation of bicycle signals could change the apparent negative impact of better bicycle facilities on non-compliance.

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Appendix A

Table A-1: LTS Determination Table for Red River Street and 4th Street (Eastbound of 4th Street)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-2: LTS Determination Table for Red River Street and 4th Street (Westbound of 4th Street)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-3: LTS Determination Table for West Cesar Chavez Street and BR Reynold Drive

Segment Type	Level of Traffic Stress
Stand-alone paths	LTS = 1
Segregated paths (sidepaths, cycle tracks)	LTS = 1
Bike lanes	LTS can vary from 1 to 4; see Tables 2 and 3
Mixed traffic	LTS can vary from 1 to 4; see Table 4

Table A-4: LTS Determination Table for 3rd Street and Brazos Street (East of Brazos)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.

Table A-5: LTS Determination Table for 3rd Street and Brazos Street (West of Brazos)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Table A-6: LTS Determination Table for 3rd Street and Colorado Street (East of Colorado Street)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Table A-7: LTS Determination Table for 3rd Street and Colorado Street (West of Colorado Street)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Table A-8: LTS Determination Table for 3rd Street and Congress Avenue. (East of Congress)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Table A-9: LTS Determination Table for 3rd Street and Congress Avenue. (West of Congress)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.

Table A-10: LTS Determination Table for 3rd Street and Lavaca Street (East of Lavaca)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.

Table A-11: LTS Determination Table for 3rd Street and Lavaca Street (West of Lavaca)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Table A-12: LTS Determination Table for 3rd Street and Guadalupe Street (East of Guadalupe)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)
[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.				

Table A-13: LTS Determination Table for 3rd Street and Guadalupe Street (West of Guadalupe)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	(n.a.)	2 or more	(n.a.)
Sum of bike lane and parking lane width	15 ft or more	14 or 14.5 ft[a]	13.5 ft or less	(n.a.)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

[a] If speed limit < 25 mph, or land use is residential with little parking turnover, then any width is acceptable for LTS 2.

Table A-14: LTS Determination Table for 24th Street and Rio Grande Street (North of 24th)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-15: LTS Determination Table for 24th Street and Rio Grande Street (South of 24th)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-16: LTS Determination Table for MLK Jr. Boulevard and Rio Grande Street (East of Rio Grande)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-17: LTS Determination Table for MLK Jr. Boulevard and Rio Grande Street (East of Rio Grande)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-18: LTS Determination Table for MLK Jr. Boulevard and Rio Grande Street (South of MLK)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-19: LTS Determination Table for MLK Jr. Boulevard and Rio Grande Street (North of MLK)

	LTS ≥ 1	LTS ≥ 2	LTS ≥ 3	LTS ≥ 4
Street width (thru lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(n.a.)
Bike lane width	6 ft or more	5.5 ft or less	(n.a.)	(n.a.)
Speed limit or prevailing speed	30 mph or less	(n.a.)	35 mph	40 mph or more
Bike lane blockage	rare	(n.a.)	frequent	(n.a.)

Table A-20: LTS Determination Table for Morrow Street and N. Lamar Boulevard (East of Lamar)

	Street Width		
Speed Limit or Prevailing Speed	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 [a] or 2 [a]	LTS 3	LTS 4
30 mph	LTS 2 [a] or 3 [a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets without marked centerlines and with ADT ≤ 3000; use higher value otherwise.

Table A-21: LTS Determination Table for Morrow Street and N. Lamar Boulevard (West of Lamar)

	Street Width		
Speed Limit or Prevailing Speed	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 [a] or 2 [a]	LTS 3	LTS 4
30 mph	LTS 2 [a] or 3 [a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets without marked centerlines and with ADT ≤ 3000; use higher value otherwise.

Since AADT for Morrow Street was 2,290 East of N. Lamar Boulevard in 2004, assuming a traffic growth rate of 3% per year, the compounded traffic in 2017 was 3,362, over the threshold defined in the criteria table. LTS 3 was used.

Table A-22: LTS Determination Table for Airport Boulevard and Wilshire Boulevard (East of Airport Boulevard)

	Street Width		
Speed Limit or Prevailing Speed	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 [a] or 2 [a]	LTS 3	LTS 4
30 mph	LTS 2 [a] or 3 [a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets without marked centerlines and with ADT ≤ 3000; use higher value otherwise.

The total number of lanes east of Airport Boulevard along Aldrich Street is five, and with a prevailing speed of 30 mph, LTS 4 was concluded.

Table A-23: LTS Determination Table for Airport Boulevard and Wilshire Boulevard (West of Airport Boulevard)

	Street Width		
Speed Limit or Prevailing Speed	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 [a] or 2 [a]	LTS 3	LTS 4
30 mph	LTS 2 [a] or 3 [a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

[a] Use lower value for streets without marked centerlines and with ADT $\leq$ 3000; use higher value otherwise.

Table A-24: Regression Analysis t-statistics for Interaction rate vs. EQLV on 3rd Street and MLK Boulevard. & Rio Grande Street

	Coefficients	*Standard Deviation*	*t Stat*	*P-value*
Intercept	-0.010	0.046	-0.214	0.845
X Variable 1	1.893E-05	1.858E-05	1.019	0.383

Table A-25: Regression Analysis t-statistics for Interaction rate vs. EQLV on 3rd Street (Within LTS Group)

	Coefficients	*Standard Deviation*	*t Stat*	*P-value*
Intercept	-0.039	0.034	-1.154	0.368
X Variable 1	3.552E-05	1.482E-05	2.395	0.139

Table A-26: Chi-Square Test Statistics for Non-Compliance Rate across All Intersections

Observed	3rd & Brazos	3rd & Colorado	3rd & Congress	3rd & Guadalupe	3rd & Lavaca	24th & Rio	4th and RR	Cesar & BR	Rio & MLK	Morrow & Lamar	Airport	Total
Non-Compliance	118	152	75	134	22	152	390	94	54	5	5	1201
Compliance	946	1158	1636	904	796	465	1056	371	527	108	157	8124
Total	1064	1310	1711	1038	818	617	1446	465	581	113	162	9325
	11.09%	11.60%	4.38%	12.91%	2.69%	24.64%	26.97%	20.22%	9.29%	4.42%	3.09%	12.88%
Expected	3rd & Brazos	3rd & Colorado	3rd & Congress	3rd & Guadalupe	3rd & Lavaca	24th & Rio	4th and RR	Cesar & BR	Rio & MLK	Morrow & Lamar	Airport	
Non-Compliance	137.04	168.72	220.37	133.69	105.35	79.47	186.24	59.89	74.83	14.55	20.86	
Compliance	926.96	1141.28	1490.63	904.31	712.65	537.53	1259.76	405.11	506.17	98.45	141.14	
$(O-E)^2/E$	2.64	1.66	95.89	0.00	65.95	66.21	222.94	19.43	5.80	6.27	12.06	
	0.39	0.24	14.18	0.00	9.75	9.79	32.96	2.87	0.86	0.93	1.78	
χ^2	572.60	Characterized by intersection										
DF	10											
χ^2 Critical 95%	18.3											
Result	Rejected											