AN ABSTRACT OF THE DISSERTATION OF

Douglas Phillip Cobb for the degree of Doctor of Philosophy in Civil Engineering presented on April 16, 2020.

Title: Evaluation of Cycling Behavior: Factors that Influence Bicyclists' Comprehension, Comfort, and Stress

Abstract approved:

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David Hurwitz

Travel demand has increased due to population growth, increase of vehicle ownership, and development patterns resulting in greater levels of congestion, pollution, and crash frequency. One approach to demand management is to increase the share of trips made by bicycles. With the increase in bicycling rates, there is a critical need for additional cycling infrastructure, which includes on and off-road bicycle lanes and paths, signs, markings, and signals. However, many of these infrastructure systems are implemented without detailed knowledge of bicyclist's behavior and comfort while interacting with them. Therefore, if we understand factors that influence bicyclist's behaviors and comfort on the roadway, planners and engineers will be better suited in implementing both bicycle technology and infrastructure. This study approached this challenge by *evaluating* a)

bicyclist's comprehension and preference to traffic control devices and b) bicyclist's behavior and physiological responses to varying roadway conditions. Next, the research was interpreted for the purpose of *improving practice* within the transportation field.

A survey questionnaire was used to evaluate bicyclists understanding and preferences of blue light detection feedback (BLDF) systems and bicycle signal countdown timers (BSCT). The results indicated that individuals understood and preferred the BLDF better with the additional novel signage that included text, symbols, and the blue dot. The study overwhelmingly showed that individuals "Strongly Agreed" that signage helped them understand the purpose of the BLDF, that they would support he implementation of the system, and that they felt better about waiting at an intersection with this system implemented. Individuals also generally understood the purpose of the BSCT, with the highest correct response from the numerical BSCT. Additionally, participants preferred the numerical BSCT, in comparison to the circular and vertical disappearing dot options.

The Oregon State University (OSU) bicycle simulator was used in conjunction with a survey questionnaire to evaluate bicyclists' galvanic skin response (GSR) responses, velocity, and lateral position to varying roadway conditions and bicycling infrastructure. The results showed that when individuals cycled within a bicycle lane, they had a GSR reading 1.25 peaks per min less than when cycling in a mixed traffic condition. In addition, when bicyclists rode in the bike lane, bicyclists GSR reading and velocity were not affected by variations in vehicular volume or speed. However, lateral position was affected by vehicular volume. When bicyclists were in mixed traffic conditions, the GSR reading was not affected by vehicle speed; however, it was affected by the vehicular volume. In mixed traffic conditions, none of the variables influenced bicyclist's velocity. For the lateral position, only the vehicular volume had a significant affect.

In summary, the recommendations from this work suggest a design for the BLDF system that will provide bicyclists with better understanding and comfortable at an intersection. Additionally, while preemption numerical countdown timers are not currently approved by MUTCD for vehicles or bicyclists, evidence suggests that a circular disappearing dots BSCT, was the preference of survey respondents.

Based on the results of the simulator research, bicyclist's stress response was not affected by the vehicular volume or the speed of vehicles while riding in a bicycle lane, which indicates bicyclists generally feel more comfortable while riding. Additionally, the vehicular speed did not play significant influence into bicyclists' stress response or behavior; therefore, limiting the amount of traffic provided on the roadway can still make bicyclists feel less stress, even if a bike lane is not present. Therefore, recommendations for bicycle facilities should aim to provide striped bike lanes if possible or limit vehicular volumes on roadways where bicyclists operate in mixed traffic conditions.

Evaluation of Cycling Behavior: Factors that Influence Bicyclists' Comprehension, Comfort and Stress

by
Douglas Phillip Cobb

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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Douglas Phillip Cobb, Author

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CONTRIBUTION OF AUTHORS

David Hurwitz was involved in the scoping and design of the elements of these studies. He also provided feedback and revisions to me for the entirety of this dissertation. Chris Monsere and Sirisha Kothuri provided support and assistance on Blue Light Detection Feedback Systems and Bicycle Countdown Timers manuscripts. Hisham Jashami provided guidance, support, and content for all three manuscripts, and assisted in the statistical analyses used in the studies.

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DEDICATION

For my husband and son, who are my everything and who make me want to be better.

1 INTRODUCTION

1.1 Motivation

Travel demand has increased due to population growth, increase of vehicle ownership, and development patterns resulting in greater levels of congestion, pollution, and crash frequency. A proposed solution to lessen current transportation system demands is to increase the share of trips made by bicycles. While mitigating congestion, use of bicycles has also been shown to require little space, not emit pollution, and promote public health through exercise (Felix et al., 2016).

Cycling infrastructure (e.g., bicycle lanes, bicycle safety features, bicycle technology) is intended to promote bicycle ridership for all populations. Despite these efforts to increase ridership, levels of cycling in the U.S. remain relatively low, with less than 3% of all trips made by bicycle (Buehler & Pucher, 2012). In comparison, over the past 10 years cycling as a transportation mode choice has grown significantly in countries such as Denmark (e.g. Copenhagen), Netherlands (e.g. Amsterdam), and Germany (e.g. Berlin) (European Cyclists' Federation, n.d.). In an effort to expand the cycling ridership in the United States, researchers and practitioners determined that growth of this form of active transportation was dependent on the types of riders and their various needs (i.e. cycling infrastructure and facilities). As a result, researchers and practitioners developed bicyclist typologies based on characteristics such as comfort level, frequency, trip purpose, and demographics to categorize people and potentially outline different needs (i.e., cycling infrastructure).

Current cycling research that identifies cyclists' infrastructure and route preferences incorporates cyclist typology due to its significant role in how infrastructure and routing preferences are determined. Roger Geller's four classifications of cyclists is referenced widely in bicycle research (Broach et al, 2012; Caulfield et al., 2012; Felix et al., 2016). To promote cyclist ridership, Geller classified riders with the view that if the largest category of riders could be identified, then future planning and engineering developments could be focused on these particular riders. Geller grouped adult riders by comfort level while riding into four categories: Strong and Fearless, Enthused and Confident, Interested but Concerned, and No Way, No How (Geller, 2006). Dill and McNeil (Dill & McNeil, 2012) then validated Geller's methodology in 2012 by conducting a survey study to determine if sampled individual's cyclist's typologies still correlated with the distributions found by Geller. Current cycling research that identify cyclists' infrastructure and route preferences now regularly incorporates Geller's validated cyclist typologies and is considered in how infrastructure and routing preferences are developed (Broach et al., 2012; Caulfield et al., 2012; Felix et al., 2016).

With the use of cyclist typologies, researchers have evaluated elements of preferred cyclist infrastructure and routes, and identified vehicle/roadway impacts (e.g., cycling infrastructure, vehicular volumes, speeds, roadway configurations) and environmental impacts (e.g., slope, weather impacts, pollution). However, few have evaluated ways to promote bicycle ridership by removing infrastructure related barriers or by adoption of new solutions at intersections and on roadway segments. Specifically, intersections serve as viable connections for cyclist to navigate roadway networks; however, because intersections include various inherent characteristics (e.g., signals, vehicle and pedestrian conflicts, etc.) that cyclists must interact with, intersections remain one of the most dangerous points for cyclists within the roadway network. Specifically, many cyclists at intersections disregard signal indications and often prematurely enter an intersection on circular red signal indication due to impatience or belief that there is adequate gap acceptance in the cross-street traffic. This risk-taking behavior can lead to dangerous conflict points or potential cyclists' crashes. In an effort to reduce the impacts intersections have on cyclists, bicycle technology and signage can be implemented to both increase cyclists' comprehension of right-of-way conflicts and improve the overall cycling experience. Specifically, if cyclists were given feedback systems regarding there detection at intersection or the amount of time they have until they receive circular green indication, this would likely encourage cyclists to obey traffic laws and stop at red circular signal indication until given right-of-way to proceed through the intersection. Additionally, roadway segments typically provide consistent cross-sectional infrastructure for cyclists to promote comfortable riding; however, roadway segments still include factors (i.e., vehicle volume, vehicle speeds, bicycle pavement markings) that likely influence cyclist's stress levels. If cyclists have induced stress while riding, the likelihood of positive experiences degrades, which could reduce ridership. Therefore, if factors that induce higher amounts of stress on cyclists can be identified, transportation professionals can use this knowledge to mitigate those negative influences.

This research evaluated and determined user's comprehension and preference for both blue light detection feedback (BLDF) systems and bicycle signal countdown timers

(BSCT) at signalized intersections. Second, the research evaluated how various roadway elements (e.g., vehicle volume, vehicle speed, bicycle pavement markings) influence cyclists' behavior and physiological responses (i.e. actual stress that is induced on the body). While there has been research in both areas, very few survey or laboratory experiments have been conducted to determine the comprehension of bicycle technology and the role that bicycle infrastructure plays into cyclist' behavior and physiological stress responses. The specific goals of my research are to:

- Determine user's comprehension and preference of BLDF
- Determine user's comprehension and preference of BSCT
- Determine factors that play influence into cyclist's behavior and physiological responses and determine the relationship between perceived safety to actual safety.

This research will help to fill gaps in the existing state-of-knowledge regarding cyclists' understanding and perceptions of various bicycle technology and infrastructure and how different roadway conditions correlate to cyclist's behavior and physiological stress. With this information, transportation engineers and planners can better develop future cycling infrastructure and facilities with the goal to increase cycling ridership.

1.2 Approach and Scope

In an effort to help to improve safe riding and increase overall ridership, this research evaluated user comprehension of BLDF and BSCT, and explored the behavioral and physiological effects of varying bicycle infrastructure.

First, this study explored user comprehension and understanding of BLDF at signalized intersections using a broadly disseminated online survey-based evaluation. The objective of this analysis was to determine user preference and comprehension of various BLDF designs.

Second, this study explored user comprehension of BSCT at signalized intersections using a survey-based evaluation. The objective of this analysis was to determine user's preference and comprehension of various BSCT designs.

Third, this study explored cyclist behavior and physiological responses using the performance measures of velocity, horizontal displacement, and galvanic skin response (GSR). Oregon State University's (OSU) Bicycling Simulator was used to observe these driver behaviors in a simulated bicycling environment. These measurements were analyzed to provide quantitative data that could be used by transportation agencies to understand which types of infrastructure influence cyclists' stress responses in an effort to help with future investment planning.

1.3 Organization of the Manuscripts

This work is comprised of three related manuscripts that address the scope of this dissertation. The first (Chapter 2), entitled "Driver and Bicyclist Comprehension of Blue Light Detection Feedback Systems" identifies and analyzes the comprehension and understanding of BLDF. The second (Chapter 3), entitled "Evaluation of Motorist and Bicyclist Comprehension of Bicycle Sign Countdown Timers" identifies and analyzes the comprehension and understanding of BSCT. "Bicyclists Behavioral and Physiological

Responses to Varying Roadway Conditions and Bicycle Infrastructure," and the third manuscript in the sequence (Chapter 4), explores bicyclists behaviors and physiological responses with respect to the various roadway conditions and bicycle infrastructure. A conclusion (Chapter 5) summarizes the major findings and discusses practical applications for the findings of this dissertation.

2 DRIVER AND BICYCLIST COMPREHENSION OF BLUE LIGHT BICYCLE DETECTION FEEDBACK SYSTEMS

Douglas Cobb, Hisham Jashami, Christopher Monsere, Sirisha Kothuri, Amy Wyman, and David S. Hurwitz,

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2.1 Abstract

With the increase in bicycling rates, there is a critical need for additional cycling infrastructure. Intersections, which have historically been designed and operated to promoted the efficient movement of vehicular traffic, can present an increased crash risk for bicyclists. Bicyclists have been known to prematurely enter an intersection on red signal indication due to lack of detection feedback, impatience, or belief of adequate gap acceptance in cross traffic (Johnson et al., 2013). This study used a survey questionnaire to identify and analyze motorist and bicyclist understanding of and preference for blue light detection feedback (BLDF). The study found that initially, participants of the survey did not understand the meaning of the BDLF; however, with the implementation of the additional signage, the comprehension of the system rose by 40 to 50%. Respondents overwhelmingly indicated that that they preferred the sign option that included symbols, text, and the blue dot, in comparison to the sign options that only included symbol and text or text and blue dot. Additionally, respondents indicated that they "Strongly Agree" that the supplemental signage helped with understanding the purpose of the BLDF, that they would support the system at intersections, and that it made them feel better about waiting at an intersection with light. It is recommended to include supplemental signage that includes the symbol, text, and blue dot as supplemental information for the BLDF.

Keywords: Blue Light Detection Feedback, Bicyclist Behavior, Understanding, Preference, Survey

2.2 Introduction

Bicycling is increasing in the United States - the number of trips made by bicycle more than doubled from 1.7 billion trips in 2001 to 4 billion in 2009 (NHTS, 2009). With the increase in bicycling rates, there is a critical need for additional cycling infrastructure, which includes on and off-road bicycle lanes and paths, signs, markings, and signals. Investing in active transportation can help create a safer, more connected, and more accessible transportation system (ODOT, 2016). One of the key goals in the Oregon Bicycle and Pedestrian Plan is to improve the mobility and efficiency of the entire transportation system by providing high-quality walking and biking options for trips of short and moderate distances (ODOT, 2016).

Signalized crossings, particularly of high volume and high-speed roadways, are an important link in a bicycle network. At these intersections in Oregon, bicyclists are primarily detected by in-pavement inductive loops, often by the same loops used for vehicle detection. While vehicles are almost always detected due to their size and predictable stopping location, that is not the case for bicycles. If bicyclists do not position themselves for optimal detection, there can be failures in detection resulting in unnecessary delays. These delays lead to a lower quality experience and may lead to increased risk-taking behaviour (i.e. signal non-compliance). Improved detection for bicycles can be accomplished by proper loop placement, calibration of loop sensitivity, alternative detection technologies, or with pavement markings that communicate the correct stopping location for bicyclists. The MUTCD 9C-7 bicycle stencil has been used to communicate where a person on a bicycle should position themselves. Recent research explored alternatives to the 9C-7 marking (Boudart et al., 2015). However, there has been interest in the adoption of a BLDF to better communicate presence detection of bicycles.

The goal of this study is to evaluate the comprehension of BLDF and to determine if supplemental signage is warranted.

2.3 Literature Review

2.3.1 Inductive Loop Detector

The inductive loop is the most commonly used to detect vehicles and bicycles because of its accuracy and flexibility to suit a wide range of conditions. The inductive loop consists of a wire that is coiled to form a loop in typical shapes such as a rectangle, square, or circle. When a vehicle passes over the loop, a change in magnetic field is detected and the inductance of the loop is decreased. The presence of a vehicle is recorded by observing the change in resonant frequency caused by a change in inductance (Kidarsa et al., 2006). The inductive loop is insensitive to inclement weather conditions such as fog, snow, and rain and is able to provide basic traffic parameters. However, the operation of the inductive loop detector may be impacted by pavement deterioration, improper installation, street and utility repair, and weather-related effects (Klein et al., 2006).

2.3.2 Bicyclist Compliance with Traffic Signals

While, crossing an intersection against a red indication can contribute to bicyclist-motor vehicle collisions (Watson and Cameron, 2006), there is limited literature on bicyclist compliance at intersections. Some studies have found that non-compliance by bicyclists is considered common behavior by drivers (O'Brien et al., 2002; Kidder, 2005; Fincham, 2006).

Richardson and Caulfield examined the compliance of bicyclists in Dublin City, Ireland using an observational survey and an online questionnaire (Richardson and Caulfield, 2015). The results from the observational study revealed a non-compliance rate of 61.9% with males demonstrating a higher likelihood of non-compliance (Richardson and Caulfield, 2015). Overall, 49% of survey respondents stated that they would not comply with the signal indication (Richardson and Caulfield, 2015).

Boudart et al. (2015) studied bicyclist behavior at traffic signals with a BLDF at one location in Portland, OR. Their findings revealed 92.7% of bicyclists complying with traffic signals at the location with the BLDF system, and that the BLDF system had a negligible effect on compliance.

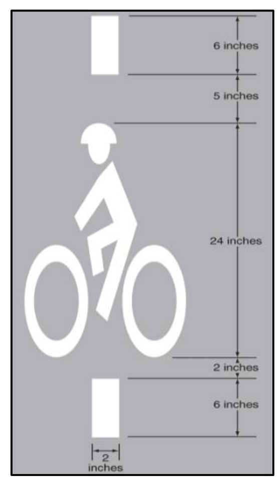
2.3.3 Providing Detection Feedback with Far-Side Blue Light

A BLDF that provides information to the bicyclist that they have been detected at a signalized intersection. An official request to experiment from FHWA is in place for the City of Portland, OR and the Oregon DOT. The research team has identified additional deployments in Palo Alto, CA, Edmonton, AB, Fort Collins, CO, and Austin, TX through their research and professional networks. There are likely other installations. In the typical application, the blue light is placed on the far side of the intersection near the signal head that the bicyclist is monitoring for information (could be a vehicular or bicycle signal head). When the bicyclists are detected and a call is placed, the blue light illuminates. Photos of example installations are shown in Figure 2.1.

Boudart et al. first evaluated the impacts of a BLDF at one signalized intersection in Portland, OR (Boudart et al., 2015). Video data were collected in three phases – before condition, after blue light installation, and after blue light and informational sign installation. In the before condition, bicyclists primarily used the pushbutton to be detected, despite the presence of 9C-7 pavement detector marking (the R10-22 sign was absent). After the blue light and informational sign installation, a statistically significant decrease in bicyclists using the pushbutton was observed (Boudart et al., 2015).

Portland, OR BLDF (Photo: J. aus)

Austin, TX, BLDF (Photo: C. Monsere)



MUTCD 9C-7 (MUTCD)

Salem, OR Commercial and Union Streets BLDF and Explanatory sign (ODOT)

Figure 2.1 Photos of BLDF

Boudart et al. continued their work and tested the modified UM-Columbia pavement marking (includes bicycle symbol, “wait here for green” text, and green dot) along with the BLDF at two intersections in Portland, OR (Boudart et al., 2017). A postcard intercept survey was also administered at the two sites, with the postcard containing a link to an online survey. A total of 213 respondents responded to the online survey. The findings of the survey revealed differences in comprehension regarding the BLDF at the two sites, 86% and 58% (Boudart et al., 2017). The authors hypothesized that the higher comprehension at one site could be related to the longer length of time the BLDF had been active at that location compared to the other location (Boudart et al., 2017).

Recently, ODOT conducted an experiment at the intersection of Commercial and Union Streets in Salem, OR with the BLDF (ODOT, 2018). In the before test, a bicycle stencil (MUTCD Bicycle Lane Symbol Marking) was located on the westbound approach to indicate where bicyclists should position themselves. In phase 1, a BLDF was installed on the eastbound and westbound approaches. In phase 2, an explanatory sign was placed next to the BLDF. In each phase including the pre-installation phase, 40 bicyclists were observed via video footage. The findings revealed that in phases 1 and 2, higher rates of the call being held until the bicyclist entered the intersection (31% before, 42% phase 1, 47% phase 2). More bicyclists were also observed to arrive and wait within the video camera’s detection zone after phases 1 and 2.

An alternative to far-side BLDF would be to place BLDF on the near-side, perhaps more easily visible to the waiting bicyclist. In Christchurch, New Zealand a nearside indication device has been in use for some time. As described on the “Cycling in Christchurch” blog, the city adapted the standard pedestrian pushbutton confirmation device to work for bicycles. The button is dark when the call is not active but lights up red when bicycles are detected. Figure 2.2 shows the device illuminated (left) and dark (right).

Figure 2.2 Nearside Confirmation System in Christchurch, NZ (Source: G. Korrey)

2.3.4 Summary

There are many technologies available for detecting bicycles at intersections, however, the basic inductive loop remains the most common. Detecting bicycles at signalized intersections gained additional attention following the policy directive by CalTrans in 2009 which required detection for bicyclists at all actuated signalized intersections.

The purpose of these BLDF for persons on bicycles is to improve the quality of service for bicyclists (knowing that they are detected) which should reduce signal compliance issues. For bicycles, variations of BLDF have been tested in combination with a variety of pavement markings and signs. These deployments have mostly been mounted on the far side of the intersection near the signal face the bicyclist is monitoring for green. A recent installation in Salem OR included a basic sign to help communicate the purpose of the device. Bicyclist comprehension of the blue light remains an issue as many roadway users do not understand BLDF and often demonstrate incorrect response behavior. However, if supplemental signage was used to assist in comprehension of the BLDF, roadway users may interact more correctly and sustain safe riding conditions for themselves and adjacent roadway users.

2.4 Research Questions

An experiment was designed to evaluate the comprehension of BLDF by drivers and bicyclists, to determine if supplemental signage is needed and whether they influence the quality of the cycling experience. The research answers the questions:

- How well do alternate designs for BLDF with or without informational signs are understood by the general public?
- How does the information provided by the BLDF affect the overall cycling experience?

The following sections summarize the design, administration, deployment, and results of the survey evaluations.

2.5 Alternative Design Survey

2.5.1 Methods

2.5.1.1 Survey objective

The objective of the survey was to determine which feedback device is best understood by users. The survey was designed to elicit common correct, incorrect, or partially incorrect interpretations of the feedback device meanings.

2.5.1.2 Design and Refinement

The first step in designing the survey was the development of a generic template for survey images. The research team designed the initial image template by considering a recent ODOT report (Hurwitz et al., 2018). A Google Sketch Up image was used instead of a real photo, to enable explicit modification of the scene. Every effort was made to present questions neutrally, allowing participants to provide meaningful answers reflecting their comprehension of the signal indications. Several rounds of review and refinement followed the internal development of the survey questions. Transportation graduate students at OSU and PSU and ODOT employee’s tested a pilot survey and provided feedback for further improvements of the format and content of the survey questions. Once the research team was satisfied with the survey design, the survey was finalized. The finalized survey, distribution methods, and record handling were reviewed and determined exempt by the IRB of PSU (196376-18).

2.5.1.3 Instrument

The survey consisted of a mix of open-ended, close-ended questions. The survey design included random branches so that open-ended questions could be presented in an unbiased manner (Kothuri et al., 2020). Figure 2.3 illustrates the flow of the survey for the evaluation of the BLDF.

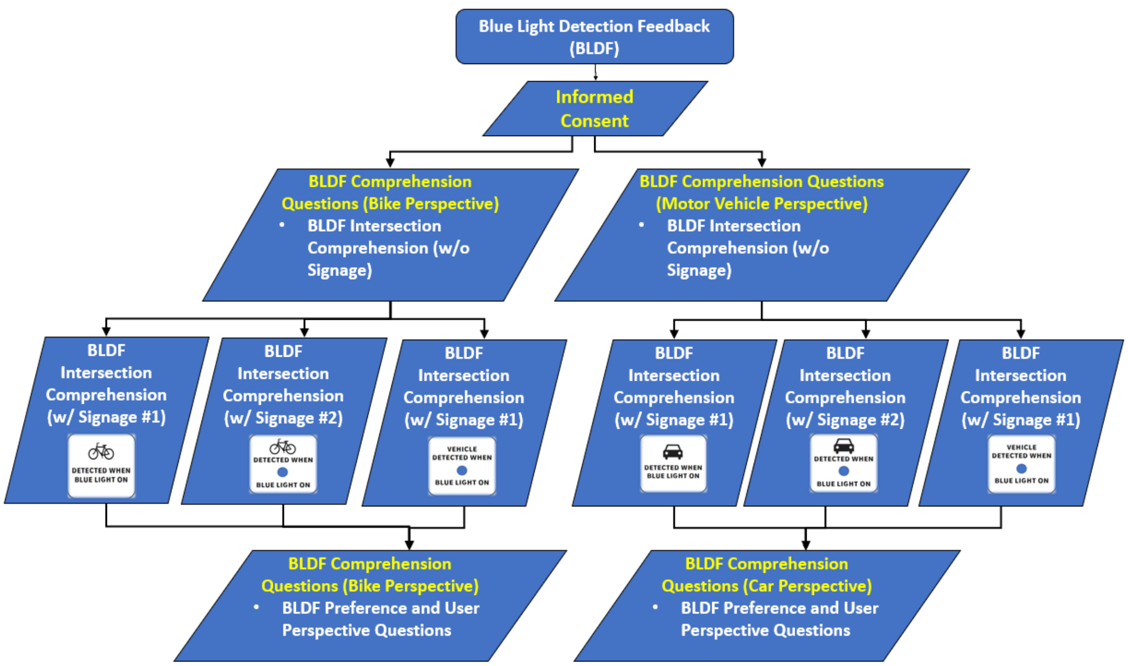


Figure 2.3: Survey Flow

Before being shown the questions, all participants had to provide informed consent for the survey, certifying that they are over 18 years of age. The survey included open-ended questions, which asked participants to report their understanding of a BLDF on the traffic signal head. In this section, the survey randomly branched into two options: a) one where the user was assumed to be a bicyclist (i.e., bicycle is provided in the foreground of the image) or one where the user was assumed to be a driver (i.e., car is provided in the foreground of the image). Based on the randomized choice of the survey (i.e., either bicyclist or vehicle based), participants were initially presented a computer image of an intersection from either a bicyclists' or driver's perspective and were asked to indicate their meaning of the BLDF on the signal head, without supplemental signage included. For purposes of the survey, the signal heads and signage were slightly enlarged to make the displays more prominent in the image. Next, participants were presented a computer image of an intersection from either a bicyclists' or driver's perspective and were asked to indicate their meaning of the BLDF on the signal head, with supplemental signage included. Three supplemental signs were tested in the survey, and it was designed such that all participants were presented one version of the three possible sign options randomly. After completing these, participants were then asked to both indicate which of the three sign options conveyed the best meaning for the BLDF and to provide feedback regarding their perspective of the use of the signage.

The closing of the survey consisted of close-ended multiple-choice demographic questions on the participant's income and education levels, cycling and driving habits, and eyesight.

2.5.1.4 Administration

A survey response rate of 6–8% was assumed based on a previously conducted postcard/online design by researchers at PSU (Currans et al., 2015). A sample size of 10,004 participants was selected based on the assumed response rate. A sampling scheme was designed based on the proportion of the population in each medium/large city in

Oregon. Only cities were chosen for the postcard mailing because of the higher prevalence of bicycling in urban areas. Based on this scheme, a random sample of addresses within each city was purchased through Info USA. After removing incorrect/ missing addresses from the purchased address sample, there remained 10,003 households to which recruitment materials could be sent.

Additionally, a social media post containing pertinent information about the survey objectives and the online link was distributed through purchased advertisements on Facebook.

2.5.1.5 Response Rate

Responses were collected from both post card recruitment and social media. The results are presented in the following sections.

2.5.1.6 Postcard Response Rate

Postcards were mailed to 10,003 addresses. A total of 568 respondents clicked the online link to respond to the survey. A total of 271 postcards were returned as undeliverable, resulting in a response rate of 5.8%.

2.5.1.7 Social Media Response Rate

A social media post was provided on Facebook with pertinent information regarding the study and an online link to the survey. A total of 1,550 respondents clicked the online link to begin the survey; however, only 555 respondents completed the survey. The calculated response rate was 35%.

2.5.1.8 Demographic Summary

Of the 1,340 people who responded to the survey (568 postcard, 772 social media), 1,084 people provided some or all of the requested demographic information. The records with no demographic information were removed for analysis resulting in 529 usable responses from the postcard survey and 555 responses from the social media survey. The responses from the social media survey were further categorized into those from Oregon (zip code starting with 97) and national (all other zip codes except Oregon).

Older, educated white males were overrepresented as survey respondents on the postcard survey compared to 2010 Census estimates for Oregon and the United States (US Census). Male respondents from the postcard survey had the highest overrepresentation (60% male compared to 49% male for the total population in both Oregon and US). Survey respondents were slightly older than the general population, with overrepresentation in the 55–64 and 65+ years categories, for data collected from Oregon (48.5% postcard survey, 34.4 social media (OR)) as compared to the census estimates (29.9 (OR); 27.6% (national)). The social media survey administered nationally yielded a larger representation in the 25-34 year category (32.8%) as compared to the census (13.7%). Postcard respondents were 81% White/Caucasian (vs. 77% reported in the Census) and overrepresentations were also seen with both social media national and Oregon data. Proportions of higher income respondents ($100,000 or greater) on both postcard and social media surveys were overrepresented when compared with census estimates (34.2% (postcard), 33.3% (social media Oregon), 38% (social media national) vs. 26.2% (national) and 23.8% (social media Oregon). Respondents with a Bachelor’s degree were overrepresented on all forms of the survey as compared to the census proportions.

Respondents from Oregon via the postcard tended to cycle far less than 5 miles per week (74%) in comparison to respondents from Oregon on social media who tended to cycle over 10 miles per week (74%). Furthermore, respondents from Oregon via the postcard had a lower propensity of utilizing a bike ride for either fun/exercise or for transportation within the last month (28% for fun/exercise and 15% for transportation), in comparison to respondents from Oregon and nationally on social media who had higher propensity to use a bike ride for fun/exercise or for transportation within the last month (86% for fun/exercise and 73% for transportation for Oregon social media; 65% for fun/exercise and 38% for transportation for national social media).

2.5.2 Results

2.5.2.1 Open-ended Comprehension Questions

Each respondent was asked two open-ended questions to determine their comprehension of the BLDF without and with supplemental signage. Respondents were presented with the following wording for the two displays.

BLDF (without signage)

“Imagine that you are waiting at an intersection on a bicycle. What does the BLUE LIGHT (to the left of the arrow) mean to you? Please type your response in the box below and be as descriptive as possible.”

BLDF (with signage)

“There has been a sign added to the photo. Again, imagine that you are waiting at an intersection on a bicycle. What does the BLUE LIGHT mean to you now? Please type your response in the box below and be as descriptive as possible.”

Responses to the questions were reviewed and classified as correct, partially correct, or incorrect. A discussion of these signal display indications follows.

<u>Coding</u>

Since the survey contained open-ended questions designed to assess comprehension of the BLDF, the responses needed to be categorized for further analysis. The research team reviewed each open-ended response. Responses were coded as correct, partially correct, or incorrect based on established criteria shown in Table 2.1. The same coding convention was followed for coding both the responses from all forms of the survey (postcard and social media).

Table 2.1: Error Coding of Narrative

DISPLAY INDICATION	CORRECT	PARTIALLY CORRECT	INCORRECT
BLDF Intersection Scenario (w/o signage) with car or bicycle	Blue light indicates that either the bicyclist or vehicle has been “detected” at the intersection	Blue light indicates that a car or bike has been “detected” nearby or that that traffic signal has been triggered.	Anything else
BLDF Intersection Scenario (w/ signage) with car or bicycle	Blue light indicates that either the bicyclist or vehicle has been “detected” at the intersection	Blue light indicates that a car or bike has been “detected” nearby or that that traffic signal has been triggered.	Anything else

For the BLDF without supplemental signage, responses were coded as correct if the respondents indicated that either the bicycle or vehicle has been "detected" at the intersection. In the coding, several non-technical responses were accepted to indicate this level of comprehension. A response was coded as partially correct, if the respondent indicated that there was some form of detection, but maybe indicating the someone else was being detected or that the light cycle has been triggered (e.g., a vehicle or car has been detected nearby or indicating that the light cycle has been triggered to change). A response was coded as incorrect if the respondents indicated anything else. This same response was coded as correct for the scenario with supplemental signage included.

BLDF Intersection Scenario (without signage)

Respondents were presented a digital image of an intersection with a blue light on the signal head. Half of the respondents were presented the intersection scenario as a bicyclist (i.e., Figure 2.4), while the other half were presented the intersection scenario as a vehicle (i.e., Figure 2.5). Respondents were then prompted to describe what the blue light means to them. Responses were coded as following the coding convention outlined in Table 2.1.

Figure 2.4: Image used for open-ended question on BLDF for bicyclists (without signage)

Figure 2.5: Image used for the open-ended question on BLDF for vehicles (without signage)

Results of the analysis of the responses are shown in Table 2.2, which was answered by 1,084 respondents (548 with bicycle scenario and 536 with vehicle scenario). Most respondents (approximately 90% average of all three sources) incorrectly indicated that they did not know what the blue light meant or provided a response that was not accurate. Of the respondents who correctly answered the question, Oregonians, both from the postcard and social media sources, generally showed higher rates of correctness (7.6% for PC-OR and 23.3% for SM-OR) compared to the national respondents (4.3% for SM-US). For the social media respondents from Oregon, 29.7% had a correct response to the blue light.

Table 2.2: Responses to open-ended question on BLDF (without signage)

RESPONSE	BICYCLE (n=537)			VEHICLE (n=527)			TOTAL (n=1064)			
	Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)		Total Average
	OR	OR	USA	OR	OR	USA	OR	OR	USA	-
Correct	7.6%	29.7%	4.3%	7.5%	18.9%	3.9%	7.6%	23.3%	4.1%	17.7%
Partially Correct	1.4%	2.7%	0.9%	4.4%	0.0%	0.9%	2.8%	1.1%	0.9%	2.4%
Incorrect	88.4%	67.6%	92.7%	88.1%	81.1%	95.2%	88.3%	75.6%	94.0%	90.3%
Did Not Respond	2.5%	0.0%	2.1%	0.0%	0.0%	0.0%	1.3%	0.0%	1.1%	<1%

BLDF Intersection Scenario (with signage)

Respondents were presented with a digital image of an intersection with a blue light on the signal head with the supplemental signage included on the mast arm. The signage was randomly chosen between the three options provided for the bicyclist and vehicle scenarios, as shown in Figure 2.6 and Figure 2.7.

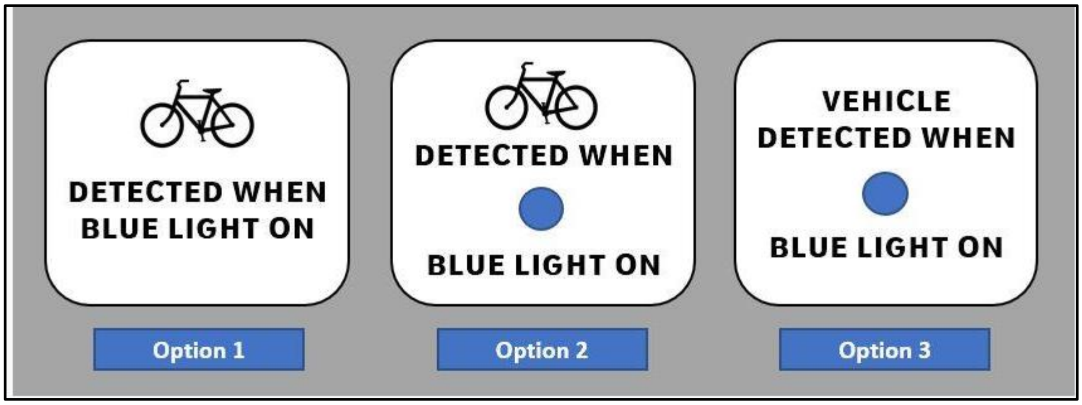


Figure 2.6: Images used sign options with BLDF for bicyclists

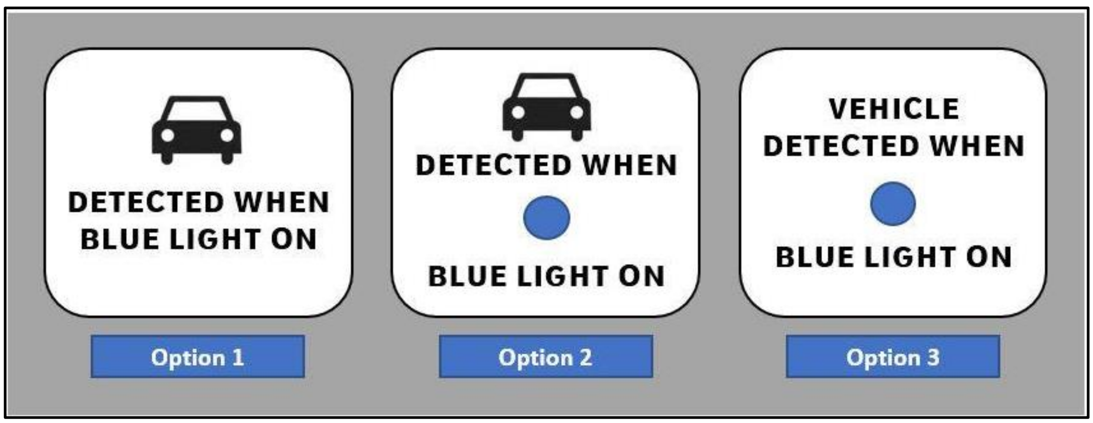


Figure 2.7: Images used sign options with BLDF for vehicles

Respondents were then presented the same intersection scenario that was shown to them earlier as either a bicyclist (i.e., Figure 2.4) or a vehicle (i.e., Figure 2.5), with the additional signage, drawn from one of the three sign options randomly (Figure 2.8, Figure 2.9). Respondents were then prompted to describe what the blue light meant to them. The objective was to assess if the addition of the sign increased the comprehension rate of the BLDF. Responses were coded as following the coding convention outlined in Table 2.1.

Figure 2.8: Image used for the open-ended question on BLDF for bicyclists (with signage)

Figure 2.9: Image used for the open-ended question on BLDF for drivers (with signage)

Table 2.3 summarizes the findings for this question, which was answered by 1,084 respondents (548 with Bicycle Scenario and 536 with Vehicle Scenario). For Sign Option #1 (i.e., Symbol without Blue Dot), respondents generally were split between correct and incorrect responses (44% for correct vs. 45% for incorrect responses) the understanding of the BLDF. In comparison, respondents with the bicycle scenario were more likely to correctly respond (47% average of three sources) versus respondents with the vehicle scenario who had a lower propensity to answer correctly (40% average of three sources). An additional 10% were coded partially correct because they did not provide additional detail on the location of detected vehicle or only indicated that signal was triggered.

Similar to the Sign Option #1, Sign Option #2 (i.e., Symbol with Blue Dot) respondents generally were split between correct and incorrect responses (44% for correct vs. 45% for incorrect responses) the understanding of the BLDF. In comparison, respondents with the bicycle scenario were more likely to correctly respond (48% average of three sources) versus respondents with the vehicle scenario who had a lower propensity to answer correctly (41% average of three sources). An additional 11% were coded partially correct because they did not provide additional detail on the location of detected vehicle or only indicated that signal was triggered.

For Sign Option #3 (i.e., Text with Blue Dot), respondents indicated more incorrect responses to correct responses (41% correct vs. 49% incorrect averages of three sources). However, compared to the first two signs, the use of text indicated a decline in comprehension rates from respondents in both scenarios (41% average vs. 44% for Sign Options 1 and 2). An additional 10% were coded partially correct because they did not provide additional detail on the location of detected vehicle or only indicated that the signal was triggered.

Table 2.3: Responses to open-ended question BLDF (with signage)

RESPONSE	BICYCLE (n=548)			VEHICLE (n=536)			TOTAL (n=1084)		
	Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)	
	OR	OR	USA	OR	OR	USA	OR	OR	USA
Sign Option #1 (Symbol without Blue Dot) (n=191 for Bicycle; n=189 for Vehicle)									
Correct	58.6%	35.7%	37.8%	50.0%	44.4%	30.1%	54.3%	40.6%	34.1%
Partially Correct	9.2%	7.1%	14.4%	5.7%	0.0%	12.0%	7.4%	3.1%	13.3%
Incorrect	29.9%	51.7%	44.4%	44.3%	55.6%	57.8%	37.1%	56.3%	50.9%
Did not Respond	2.3%	0.0%	3.3%	0.0%	0.0%	0.0%	1.1%	0.0%	1.7%
Sign Option #2 (Symbol with Blue Dot) (n=178 for Bicycle; n=191 for Vehicle)									
Correct	52.2%	25.0%	45.0%	46.7%	16.7%	40.7%	49.5%	19.2%	42.9%
Partially Correct	5.6%	12.5%	10.0%	10.9%	22.2%	13.6%	8.2%	19.2%	11.8%
Incorrect	42.2%	62.5%	45.0%	42.4%	61.1%	45.7%	42.3%	62.5%	45.3%
Did not Respond	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sign Option #3 (Text with Blue Dot) (n=177 for Bicycle; n=158 for Vehicle)									
Correct	39.2%	46.7%	35.4%	45.3%	35.3%	42.4%	41.9%	40.6%	38.9%
Partially Correct	9.3%	6.7%	18.5%	4.0%	11.8%	12.1%	7.0%	9.4%	15.3%
Incorrect	51.5%	46.7%	46.2%	50.7%	52.9%	45.5%	51.2%	50.0%	45.8%
Did not Respond	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Statistical Analysis

To better understand respondents' comprehension scores, two binomial proportion tests were used for both vehicle and bicycle scenarios to test whether the additional signage, regardless of the sign option (e.g., symbol without blue dot, symbol with blue dot, text with blue dot) and survey mode (e.g., post card versus social media), could increase the probability of getting less incorrect responses.

For respondents who received the vehicle scenario, results showed that the proportion of correct responses by participants increased from six percent (6%) when the sign was not presented to approximately fifty-one percent (51%) when it was presented, which is statistically different and significant (P-value < 0.001). However, for respondents who received the bicycle scenario, similar test was used and the results showed that the proportion of obtaining correct responses by participants increased from six percent (6%) when the sign was not presented to approximately forty-seven percent (47%) when it was presented, which is statistically different and significant (P-value < 0.001). Based on these results, there is an evidence that the additional signage helped participants to well understand the meaning of the Blue light indication.

2.5.2.2 Multiple-Choice and Likert Scale Questions

Multiple-Choice and Likert Scale questions were provided to each respondent regarding their preferences, level of agreement, and experience with BLDF signage. A discussion of these questions is listed below.

BLDF Signage Preference

Respondents were presented all three sign options based on whether they were initially presented the intersection scenario as a bicyclist or vehicle, as shown in Figure 2.6 and Figure 2.7, respectively. Respondents were then asked to choose the sign that conveyed the meaning of the sign best to them and to provide justification for their choices. After making their preference selection, respondents were then provided a Likert scale to evaluate their level of “agreement” with designated statements regarding the signage. Table 2.4 summarizes results for this question, which was answered by 1,084 respondents (548 with bicycle scenario signage and 536 with vehicle scenario signage). Respondents who were provided the bicycle scenario signage, as shown in Table 2.8, generally indicated that Option #2 (67% for PC vs. 81% for SM-OR vs. 68% for SM-US) conveyed the best meaning, followed by Option #3 (24% for PC-OR vs. 8% for SM-OR vs. 20% for SMUS). Similarly, respondents who were provided the vehicle scenario signage, as shown in Table 2.8, generally indicated that Option #2 (57% for PC vs. 60% for SMO vs. 55% for SMUS) conveyed the best meaning, followed by Option #3 (35% for PC vs. 60% for SMO vs. 35% for SMUS); however, overall, there was a higher propensity for respondents with the vehicle scenario signage to indicate that Option #3 was viable, in comparison to respondents with bicycle scenario signage.

Table 2.4: Responses to Closed-Ended Question on BLD Sign Preference

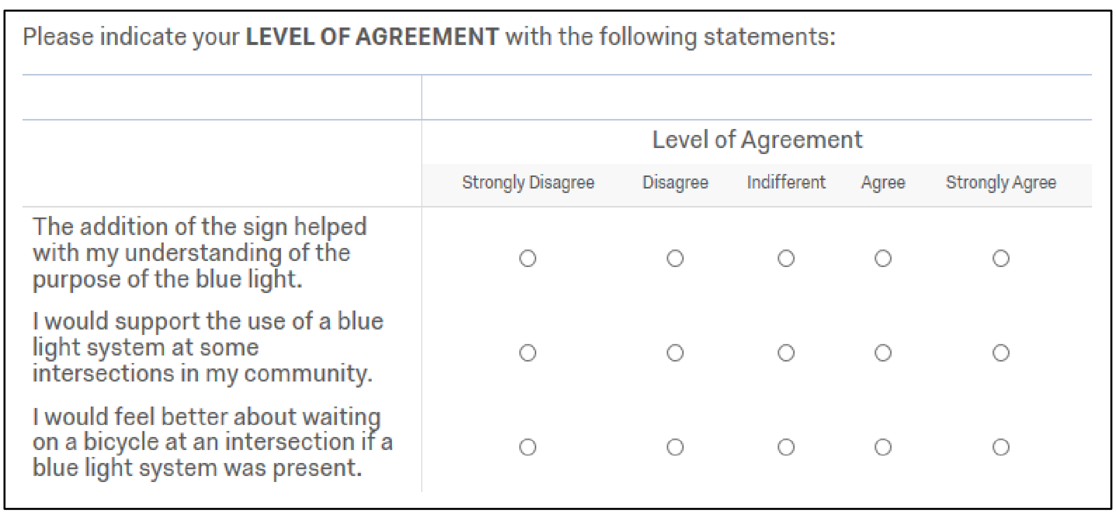
RESPONSE	TOTAL		
	Post Card	Social Media (Facebook)	
	OR	OR	USA
Sign Options for Bicycle Scenario			
Option #1	8.4%	10.8%	11.1%
Option #2	67.2%	81.1%	68.4%
Option #3	23.7%	8.1%	20.1%
Did not Respond	0.7%	0.0%	0.4%
Sign Options for Vehicle Scenario			
Option #1	7.8%	5.7%	9.5%
Option #2	56.5%	60.4%	54.5%
Option #3	34.9%	34.0%	35.5%
Did not Respond	0.8%	0.0%	0.4%

BLDF Signage “Level of Agreement” Questionnaire

After making their preference selection, respondents were then provided a Likert scale to evaluate their level of “agreement” with designated statements regarding the signage, as shown in Figure 2.10.

Table 2.5 summarizes results for the three Likert questions, which were answered by 1,084 respondents (548 with bicycle scenario and 536 with vehicle scenario). For Question 1, respondents generally indicated that they “Strongly Agree” (57% average of all three sources) followed by “Agree” (27% average of all three sources) that the addition of the sign helped with their understanding of the purpose of the blue light. Similarly, for Question 2, respondents generally indicated that they “Strongly Agree” (45% average of all three sources) followed by “Agree” (29% average of all three sources), that they would support the use of the BLDF at some intersections in their community.

For Question 3, respondents were spread evenly indicating that they “Strongly Agree” (34% average of all three sources), followed by “Agree” (27% average of all three sources) and “Indifferent” (21% average of all three sources), that they would feel better about waiting on a bicycle at an intersection if a BLDF was present.


Please indicate your **LEVEL OF AGREEMENT** with the following statements:

	Level of Agreement				
	Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
The addition of the sign helped with my understanding of the purpose of the blue light.	○	○	○	○	○
I would support the use of a blue light system at some intersections in my community.	○	○	○	○	○
I would feel better about waiting on a bicycle at an intersection if a blue light system was present.	○	○	○	○	○

Figure 2.10: “Level of Agreement” questionnaire for BLDF

Table 2.5: Responses to "Level of Agreement" of Statements Regarding BLDF

RESPONSE	BICYCLE (n=548)			VEHICLE (n=536)			TOTAL (n=1084)		
	Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)	
	OR	OR	USA	OR	OR	USA	OR	OR	USA
Q1: The addition of the sign helped with my understanding of the purpose of the blue light.									
Strongly Disagree	7.3%	8.1%	3.8%	8.2%	9.4%	9.1%	7.8%	8.9%	6.5%
Disagree	3.7%	5.4%	3.8%	7.1%	3.8%	4.3%	5.3%	4.4%	4.1%
Indifferent	4.0%	16.2%	3.4%	5.1%	7.5%	5.2%	4.5%	11.1%	4.3%
Agree	27.5%	24.3%	25.6%	25.5%	39.6%	25.1%	26.5%	33.3%	25.4%
Strongly Agree	57.5%	45.9%	62.4%	54.1%	39.6%	55.8%	55.8%	42.2%	59.1%
Did not Respond	0.0%	0.0%	0.9%	0.4%	0.0%	0.4%	0.2%	0.0%	0.6%
Q2: I would support the use of the blue light system at some intersections in my community.									
Strongly Disagree	12.1%	5.4%	6.4%	8.2%	11.3%	9.9%	10.2%	8.9%	8.2%
Disagree	5.5%	5.4%	3.4%	7.0%	3.8%	4.3%	6.2%	4.4%	3.9%
Indifferent	12.1%	5.4%	10.3%	5.1%	13.2%	17.2%	8.7%	10.0%	13.8%
Agree	27.5%	27.0%	29.6%	25.4%	30.2%	33.6%	26.5%	28.9%	31.6%
Strongly Agree	42.5%	56.8%	49.4%	53.9%	41.5%	34.1%	48.0%	47.8%	41.7%
Did not Respond	0.4%	0.0%	0.9%	0.4%	0.0%	0.9%	0.4%	0.0%	0.9%
Q3: I would feel better about waiting on a bicycle at an intersection if a blue light system was present.									
Strongly Disagree	11.4%	5.4%	6.9%	13.7%	7.5%	10.8%	12.5%	6.7%	8.8%
Disagree	4.4%	5.4%	5.2%	12.1%	7.5%	7.8%	8.1%	6.7%	6.5%
Indifferent	16.1%	13.5%	15.0%	25.8%	32.1%	24.1%	20.8%	24.4%	19.6%

Agree	27.5%	29.7%	30.0%	20.7%	28.3%	31.0%	24.2%	28.9%	30.5%
Strongly Agree	39.9%	45.9%	42.1%	27.0%	24.5%	25.4%	33.6%	33.3%	33.8%
Did not Respond	0.7%	0.0%	0.9%	0.8%	0.0%	0.9%	0.8%	0.0%	0.9%

BLDF Experience at Intersections

Respondents were then asked whether they had ever experienced the BLDF at an intersection before. Table 2.6 summarizes results for this question, which was answered by 1,084 respondents (545 with bicycle scenario and 539 with vehicle scenario). Respondents generally indicated "No" (89% average of all three sources) for having experienced the BLDF at the intersection before. However, in both scenarios presented, respondents nationally from social media had a higher proportion of "No" (97%) responses for experiencing this system in comparison to the respondents from Oregon via the postcard (86%) and social media (70%).

Table 2.6: Responses to Experience with BLDF at Intersections

RESPONSE	BICYCLE (n=533)			VEHICLE (n=531)			TOTAL (n=1064)		
	Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)		Post Card	Social Media (Facebook)	
	OR	OR	USA	OR	OR	USA	OR	OR	USA
Yes	13.9%	32.4%	1.7%	14.5%	28.3%	3.5%	14.2%	30.0%	2.6%
No	86.1%	67.6%	97.4%	85.5%	71.7%	95.7%	85.8%	70.0%	96.6%
Did not Respond	0.0%	0.0%	0.9%	0.0%	0.0%	0.9%	0.0%	0.0%	0.9%

2.6 Intercept Survey

2.6.1 Methods

An intercept survey of bicyclists was conducted to understand how well they comprehend: (1) the use of a two-inch diameter circular LED blue light for detection confirmation with an accompanying sign. Open-ended, multiple-choice, and Likert scale questions were developed to elicit each user's understanding and self-reported response to traffic signals with BLDF implementation. The intercept survey was administered to bicyclists at six intersections (12 intersection approaches) in Oregon. This chapter describes the development and administration of the survey and the results of the analysis.

2.6.1.1 Intercept Survey Objective

The objective of the intercept survey was to determine the bicyclists' comprehension of the BLDF at traffic signals equipped with the accompanying sign. Two versions of the signs were design – on in which the blue light was embedded in the sign, and the other where the blue light was located in the signal backplate separate from the sign. The survey was designed to elicit common correct, incorrect, or partially incorrect interpretations of the BLDF meanings.

2.6.1.2 Design and Refinement

The first step in designing the survey was the development of questions that were designed to elicit bicyclists' comprehension of the BLDF when combined with an accompanying sign. Two versions of the sign were developed for field installation – one where the blue light was static on the sign but instead embedded in the signal backplate (Figure 2.11) and another where the blue light was embedded as part of the sign itself (Figure 2.12).

Figure 2.11 BLDF in Traffic Signal Housing with Accompanying Sign

Figure 2.12 BLDF Embedded in Sign

Table 2.7 shows the six intersection locations along with the 12 approaches where the BLDF were installed along with the accompanying signs. The intercept survey was administered at these six intersections. Every effort was made to present questions neutrally, allowing respondents to provide meaningful answers reflecting their comprehension of the signal indications. Several rounds of review and refinement followed the internal development of the survey questions. Transportation graduate students at OSU and PSU tested a pilot survey and provided feedback for further improvements in the format and content of the survey questions. Once the project team was satisfied with the survey design, the survey was finalized.

Table 2.7 BLDF Locations and Type of Accompanying Sign

Location	Approaches	City	Type	Letter Codes
N Ainsworth St and N Interstate Ave	N Ainsworth St EB and WB	Portland	Embedded	AA
NE US Grant Pl and NE 33rd Ave	NE US Grant Pl EB and WB	Portland	Embedded	BB
NE 53rd Ave and NE Glisan St	NE 53rd Ave NB and SB	Portland	Separate	CC
SW Terwilliger Blvd and SW Capitol Hwy	SW Terwilliger Blvd NB and SB	Portland	Separate	DD
Monroe St and W 6th Ave	Monroe St NB and SB	Eugene	Embedded	EE
W 5th Ave and Blair Blvd	W 5th Ave EB and WB	Eugene	Embedded	FF

2.6.1.3 Instrument

The survey consisted of 17 questions, which included a mix of open-ended and close-ended questions. The survey design included random branches so that open-ended questions could be presented in an unbiased manner. Figure 2.13 illustrates the organization and flow of the survey.

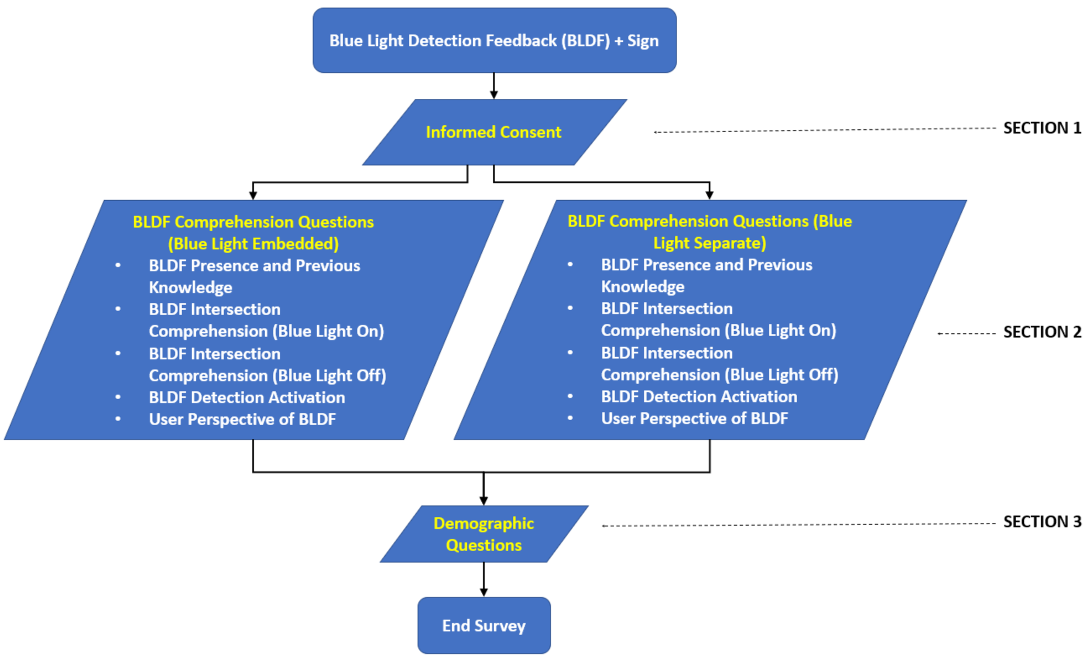


Figure 2.13 Survey Flow

Before being shown the questions, all respondents had to provide informed consent for the survey, certifying that they are over 18 years of age. Section 2 of the survey asked the respondents to first enter the letter and number code from the postcard that they were handed at the intersections. There were six-letter codes (AA – FF) corresponding to the six intersections along with number codes ranging from 001-300 as shown in Table 2.7. Two branches of the survey were developed, depending on the letter code that was entered by the respondent. Letter codes AA, BB, EE, and FF corresponded to the embedded BLDF version, where the respondents were shown pictures of the blue light embedded in the sign (Figure 2.12). Letter codes CC and DD corresponded to the version of the survey where the blue light was present separately from the sign in the traffic signal backplate. Within each of these branches, respondents were asked whether they had noticed or observed the blue light and sign at the intersections previously and whether they read any media articles about the blue lights. There were also a couple of open-ended questions, which asked respondents to report their understanding of a BLDF when it was ON and OFF, with the supplemental sign included. Respondents were also asked to note how they could activate a blue light and their perspective regarding the inclusion of BLDF at signalized intersections. Section 3 of the survey consisted of close-ended multiple-choice demographic questions on the respondent's income and education levels, cycling and driving habits, and eyesight.

2.6.1.4 Administration

A recruitment postcard containing pertinent information about the survey objectives, and the online link was handed out by researchers at PSU and OSU to bicyclists as they approached and waited at six intersections where the blue lights were installed. Survey responses were never linked to the names of respondents answering the survey, thus ensuring the confidentiality of responses. Recipients were provided with the option of providing their contact information at the end of the online survey, to be entered into a drawing for one of five $100 Amazon.com gift cards. These postcards contained unique codes by intersection so that the images displayed reflected the BLDF configuration they were exposed to at the intersection.

2.6.1.5 Response Rate

A total of 337 postcards were handed out at all six intersections as shown in Table 2.8.

Table 2.8 Response Rates by Location

Location	Codes	Type	Handed Out	Responses	Response Rate
N Ainsworth St and N Interstate Ave	AA	Embedded	67	27	40%
NE US Grant Pl and NE 33rd Ave	BB	Embedded	107	53	50%
NE 53rd Ave and NE Glisan St	CC	Separate	44	23	52%
SW Terwilliger Blvd and SW Capitol Hwy	DD	Separate	13	9	69%
Monroe St and W 6th Ave	EE	Embedded	51	22	43%
W 5th Ave and Blair Blvd	FF	Embedded	55	17	31%
Total			337	151	45%

A total of 156 responses were obtained, however five of the responses were incomplete and had to be discarded (i.e., respondents clicked the link and consented to take the survey but failed to complete the survey), resulting in a total of 151 complete responses. The overall response rate was 45%. The highest response rate was obtained at SW Terwilliger Blvd and SW Capitol Hwy, whereas the lowest response rate was obtained at W 5th Ave and Blair Blvd.

2.6.1.6 Demographic Summary

Proportions from the Census for Oregon are also provided in the table for comparison purposes. Older, educated white males were overrepresented as survey respondents compared to 2010 Census estimates for Oregon. Survey respondents were generally older than the general population, with larger representation in the 55–64 and 65+ years categories, for data collected from Oregon (60.78%) as compared to the census estimates (29.9%). The respondents were 89% White/Caucasian (vs. 77% reported in the Census). Proportions of higher-income respondents ($100,000 or greater) surveys were overrepresented (52.32%) when compared with census estimates (23.8%). Respondents with a Bachelor's and higher (Masters and Doctorate) degrees were overrepresented as compared to the census proportions.

Overall respondents on average reported using the bicycle for 22 days in a month, with the highest use being reported at W5th Ave and Blair Blvd intersection. Overall 93% of respondents possessed a driver's license. 14% of the respondents reported that they did not drive a car for transportation, and 45% reported driving less than 5,000 miles in a year. A small percentage of respondents (1%) indicated that they were colorblind. Majority of the respondents indicated that they used corrective glasses or contacts for vision (58%).

2.6.2 Results

2.6.2.1 Multiple Choice Questions

<u>BLDF Familiarity</u>

Respondents were shown a photo of an intersection similar to the one where they were handed the postcard and asked if they had noticed the blue light and the sign at the intersection that they traveled through. A follow-up question asked about their familiarity with media articles explaining the purpose of blue lights at intersections. Table 2.9 shows the responses. Overall, 84% of the respondents indicated that they had observed the blue light at the intersection and generally the percent of respondents who observed the blue light was higher at the Portland locations than Eugene locations except at the intersection of NE 53rd Ave and NE Glisan St. Additionally, within the Portland locations, the percent of respondents who indicated that they had observed the blue light was higher at the locations where the blue light was embedded in the sign (AA, BB) than at locations where it was separate (CC and DD). Seventy percent (70%) of the respondents also did not read the media articles on BLDF, although more respondents at the Portland locations read the articles compared to the respondents in the Eugene locations, possibly due to their familiarity with these devices and one of the major articles being published on bikeportland.org.

Table 2.9 BLDF Familiarity

Category	Response	AA	BB	CC	DD	EE	FF	Overall
Observed BLDF at Intersection	Yes	96.30	92.45	69.57	88.89	72.73	70.59	84.11
	No	3.70	7.55	30.43	11.11	27.27	29.41	15.89
Read Media Articles on BLDF	Yes	37.04	33.96	43.48	44.44	9.09	5.88	29.80
	No	62.96	66.04	56.52	55.56	90.91	94.12	70.20

2.6.2.2 Open-Ended Comprehension Questions

The survey contained open-ended question designed to assess comprehension of the BLDF.

Coding

The research team reviewed each open-ended response. Responses were coded as correct, partially correct, or incorrect based on established criteria shown in Table 2.10. The same coding convention was followed for coding both the responses for both open-ended questions (BLDF ON and OFF).

Table 2.10: Error Coding of Narrative

Display Indication	Correct	Partially Correct	Incorrect
BLDF ON	Blue light indicates that either the car or bike has been “detected” at the intersection	Blue light indicates that a car or bike has been “detected” nearby or that that traffic signal has been triggered.	Anything else
BLDF OFF	Blue light OFF indicates that either the car or bike has not been “detected” at the intersection	Blue light indicates that a car or bike has not been “detected” nearby or that that traffic signal has not been triggered.	Anything else

For the questions associated with the blue light being ON, responses were coded as correct if the respondents indicated that either the bicycle or vehicle has been “detected” at the intersection. A response was coded as partially correct, if the respondent indicated that there was some form of detection, but indicated that someone else was being detected or that the light cycle has been triggered (e.g., a vehicle or car has been detected nearby or indicating that the light cycle has been triggered to change). A response was coded as incorrect if the respondents indicated anything else. For the questions associated with the blue light being OFF, responses were coded as correct if the respondents indicated that either the bicycle or vehicle has NOT been “detected” at the intersection. A response was coded as partially correct if the respondent indicated that a bike or car was not detected nearby and that the traffic signal call was not placed. A response was coded as incorrect if the respondents indicated anything else.

BLDF Comprehension

For the BLDF comprehension, individuals were presented both a picture of the intersection they experienced with the BLDF ON and OFF and asked to explain what each scenario meant. Table 2.11 shows the results of these comprehension questions.

Table 2.11: BLDF Comprehension

Category	Response	AA	BB	CC	DD	EE	FF	Overall
BLDF ON	Incorrect	3.70	5.66	4.35	11.11	4.55	23.53	7.28
	Partially Correct	3.70	3.77	13.04	11.11	18.18	17.65	9.27
	Correct	92.59	90.57	52.61	77.78	77.27	58.82	83.44
BLDF OFF	Incorrect	11.11	3.77	4.35	0.00	13.64	29.41	9.27
	Partially Correct	11.11	3.77	8.70	33.33	9.09	11.76	9.27
	Correct	77.78	92.45	86.96	66.67	77.27	58.82	81.46

Overall the majority of the respondents understood the purpose of the BLDF correctly and comprehension rates were high irrespective of whether the blue light was ON or OFF. Comprehension was higher at the intersections of N Ainsworth St and N Interstate Ave and NE US Grant Pl and NE 33rd Ave compared to the other locations when the blue light was ON.

Respondents were also asked if there was anything that they could do as a bicyclist to activate the blue light. Respondents who chose “yes” as their response were asked to describe the actions they would take. Sixty-six percent (66%) overall thought they could take actions to activate the blue light, while 33% were not sure (Table 2.12). A high percentage of respondents (92%) were sure that they could activate the blue light at the intersection of NE US Grant and NE 33rd Pl, possibly because they were familiar with the operation of a BLDF as it was already present at this location prior to the installation of the embedded blue light in the sign as part of this study.

Table 2.12: BLDF Activation

Category	Response	AA	BB	CC	DD	EE	FF	Overall
BLDF ON	Not Sure	44.44	5.66	39.13	44.44	59.09	52.94	33.11
	No	0.00	1.89	0.00	0.00	0.00	0.00	0.66
	Yes	55.56	92.45	60.87	55.56	40.91	47.06	66.23

The most common response from the people who said they could take actions to activate the blue light was to reposition their bicycle on/close to the bike pavement marking if present, or on/close to the loop detector.

2.6.2.3 Likert-Scale Questions

Attitudes and Perceptions

Each respondent was asked to state their level of agreement with four multiple choice questions to explore their attitudes and perceptions regarding the visibility and utility of the BLDF.

Overall, 78% of the respondents felt that the blue light and sign were clearly visible to them at the intersection. Two intersections NE 53rd Ave and NE Glisan St in Portland and W 5th Ave and Blair Blvd had lower proportions of respondents stating that the blue light and sign were clearly visible, 57% and 64%, respectively. The level of disagreement (either somewhat or strongly disagree) with the statement that the blue light and sign were clearly visible varied between 7% and 26%.

Seventy-two percent (72%) of the respondents overall either somewhat or strongly agreed with the statement that the meaning of the blue light is easily understood at the intersection, while 24% somewhat or strongly disagreed. The highest levels of disagreement were seen at the intersections of NE 53rd Ave and NE Glisan St in Portland (35%) and W 5th Ave and Blair Blvd in Eugene (35%).

Eighty-one percent (81%) of the respondents overall stated that they felt better about waiting at the intersection with the blue light and sign, while 10% either somewhat or strongly disagreed. The proportion of respondents who disagreed with this statement were highest at NE 53rd Ave and NE Glisan St in Portland (17%).

Eighty-eight percent (88%) of the respondents felt that having information that they have been detected by the traffic signal was useful, while 7% somewhat or strongly disagreed with the statement. The high levels of agreement with this statement across all intersections reveals that respondents like having feedback from the traffic signal regarding their detection status.

2.7 Discussion and Conclusions

Below are the discussion and conclusion for both the alternative design survey and the intercept survey.

2.7.1 Alternative Design Survey

The survey was distributed based on a mixed method of post card and social media, and overall it was effective. Collectively a more balenced sample was received. This approach reduces the biased that may come from one source that favors specific demographics.

Respondents from Oregon via the postcard were less likely to use a bike for either fun/exercise or transportation within the last month in comparison to respondents from Oregon and nationally on social media who had higher propensity to use a bike ride for fun/exercise or for transportation within the last month. This overrepresentation of cycling propensity from social media users could be a result of the social media respondents being younger and therefore more likely to be physically capable of riding, versus post card recipients who were favored an older demographic which may not be as physically capable.

Overall, the survey received responses from a wide geographical area of both Oregon and the United States. It should be noted that there were responses collected from outside the United States in Australia. The research team reviewed each open-ended response and coded them as correct, partially correct, or incorrect by three reviewers independently, based on established criteria for each signal display.

Concerning the BLDF, the results revealed that most respondents (approximately 94% average of all three sources) indicated that they did not know what the blue light meant or provided a response that was not accurate. The American National Standard Criteria for Safety Symbols, as produced by American National Standards Institute, has indicated a minimum threshold of 85% comprehension for a traffic control device (ANSI Z535.1). Based on this standard, a 94% incorrect response rate falls well below acceptable comprehension rates for traffic control devices. Of the respondents who correctly answered the question, Oregonians, both from the postcard and social media sources, generally showed higher rates of correctness compared to the national sample. In general, the addition of supplemental signage increased the comprehension rates for both bicycle and vehicle scenarios. The correct response rates increased to 40 to 50% with the addition of an accompanying sign. Based on this significant increase in comprehension, supplemental signage would be both beneficial and recommended as part of the traffic control device system. Additional variations of the sign may need to be explored as the word “detection” may not be clear to the general public. There was a strong preference for sign option #2.

Based on the survey results, the use of supplemental signage that includes a combination of text, symbols, and a BLDF would help to improve comprehension and compliance of the BLDF. It is also recommended to include supplemental signage would be modeled similarly to what is provided in option #2.

2.7.2 Intercept Survey

Overall, 84% of the respondents had observed the blue light and sign at the intersection and generally the percent of respondents who observed the blue light was higher at the Portland locations than Eugene locations barring one exception. This was likely due to the familiarity of Portland bicyclists with the blue light devices. Additionally, within the Portland locations, the proportion of respondents who noticed the sign was higher at the embedded locations rather than at the locations where the blue light was separate from the sign. Although the sample size is small, this may indicate that the design where the blue light is embedded in the sign is more visible. Seventy percent (70%) of the respondents also did not read previous media articles on BLDF, although more respondents at the Portland locations read the articles compared to the respondents in the Eugene locations, and possibly due to their familiarity with one of the major articles being published on bikeportland.org.

2.7.3 Comparisons between Two Survey Methods

The comprehension of the BLDF and sign was 83% and 81% respectively when the light was ON or OFF. The results of a previous online survey which consisted of a sample of Oregon residents recruited by postcard, Oregon residents and national sample recruited via social media revealed that most respondents (approximately 90% average of all three sources) indicated that they did not know what the blue light meant or provided a response that was not accurate. Of the respondents who correctly answered the question, Oregonians, both from the postcard and social media sources, generally showed higher rates of correctness compared to the national sample. In general, the addition of supplemental signage increased the comprehension rates for both bicycle and vehicle scenarios. The correct response rates increased to 40 to 50% with the addition of an accompanying sign. The results from this study showed that the addition of a sign did indeed increase the comprehension rates significantly and was beneficial. Sixty-six percent (66%) overall thought they could take actions to activate the blue light, while 33% were not sure. The most common response from the people who said they could take actions to activate the blue light was to reposition their bicycle on/close to the bike pavement marking if present, or on/close to the loop detector.

All these results collectively reveal that users strongly prefer to have feedback information from the signal system that they have been detected and feel better about waiting on a bicycle at the intersection equipped with blue light and sign. While comprehension rates are high with the accompanying sign, 24% of the respondents still did not understand the meaning of the blue light and sign easily. Therefore, BLDF and sign installations may help in further increasing comprehension rates.

2.7.4 Limitations Survey Work

There were a few limitations associated with these surveys. Both surveys showed an overrepresentation of older white educated males. While this sampling provides good indication for this demographic, these survey results may not be representative of varying races, ages, and educational levels. In addition to the demographic bias, the surveys were designed in a stated-preference format, which requires respondents to answer questions in non-real-world conditions. While stated-preference surveys serve as an economical, easy, and accessible method to collect data, they are subject to the design of the survey and the questions, which could lead respondents to understand and answer questions differently than how the surveyor intended them to be comprehended and completed. Additionally, the recruitment for social media attracted more persons who cycle. We suspect that many of the samples are familiar with the blue light through experience or education in Portland.

In regards specifically to the intercept survey, the surveys were conducted at only a few locations in Eugene and Portland, heavily occupied with bicyclists, which could indicate that users are more likely to both adhere and respond positively to bicycle infrastructure changes.

2.8 Acknowledgements

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3 EVALUATION OF MOTORIST AND BICYCLIST COMPREHENSION OF BICYCLE SIGNAL COUNTDOWN TIMERS

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3.1 Abstract

With intersections serving as a dangerous node for vulnerable road users, there is a critical need to improve the way bicyclists interact and navigate these junctions. Specifically, signalized intersections currently provide no indication to drivers or bicyclists when they have been detected at an intersection, and this can cause both frustration and uncertainty for the road users when waiting at the signal. Furthermore, bicyclists have been known to prematurely enter an intersection on red signal indication due to lack of detection feedback, impatience, or belief of adequate gap acceptance in cross traffic (Johnson et al., 2013). This study used a survey questionnaire to identify and analyze 1,084 individuals understanding and preference of bicycle signal countdown timers (BSCT). The study found that respondents generally understood the purpose of the BSCT, with the highest correct response (57%) from the numerical BSCT. Additionally, respondents preferred the numerical BSCT, in comparison to the circular and vertical disappearing dot options. While the numerical BSCT was the most preferred, the MUTCD does not allow for intersections to provide preemption countdown on signals in numerical format; therefore, it is recommended that a request to experiment be undertaken for the circular BSCT with robust field evaluation.

Keywords: Bicycle Countdown Timer, BSCT, Survey, Bicyclist behavior

3.2 Introduction

Signalized intersections serve as an important element of roadway networks for all roadway users. Signalized intersections can create dangerous conflict points for road users, especially bicyclists. Bicyclists, in ideal conditions, are treated and expected to operate the same as vehicles at intersections; however, due to the size of bicycles, low presence of bicyclists on the roadway, and a general lack of exclusive bicycle facilities present challenges. The implementation of devices to provide bicycles with information regarding how much longer they need to wait before being given priority while staged at intersections can contribute to minimizing some of these challenges. Technology has been researched and developed to help provide feedback to vehicles including both red signal countdown timers (RSCT) and green signal countdown timers (RSCT); however, very little has been evaluated within the cycling paradigm.

One of the more problematic conditions that bicyclists experience is the inability to know whether they have been detected at an intersection and how long they have until the green indication will be displayed. Because of this, many bicyclists choose not to stop in response to red indications, and prematurely proceed through the intersection, creating a potentially dangerous condition for themselves and other roadway users. In an effort to reduce these illegal behaviors, BSCT have been used in various European countries, and experimented on in the US (i.e. Portland, OR) under a “request to experiment” (RTE) condition. These systems operate, in conjunction with the intersection signal systems, to provide the amount of time remaining before the onset of the green indication for bicyclists. Not only would these systems communicate to a bicyclist that they have been detected at the intersection, but it would give them timely reassurance that the green indication is approaching and that prematurely entering the intersection is unnecessary.

3.3 Literature Review

Countdown timers are clock-like displays that indicate the remaining time for a signal indication providing users with real-time information to make better decisions. In the U.S., they are only allowed for pedestrian operations though they are common internationally for both bicycles and vehicles as well. Pedestrian countdown signals were first approved and included in the 2003 MUTCD (FHWA, 2003). These countdown signals display the amount of time remaining in the clearance interval (FLASHING DON'T WALK). The MUTCD requires the use of pedestrian countdown timers when the pedestrian change interval is more than 7 seconds (FHWA, 2003). A number of studies have reported a reduction in pedestrian-motor vehicle conflicts and improved pedestrian safety as a result of the pedestrian countdown timer installation (Huang And Zegeer 2000; Markowitz et al. 2006; Chen et al., 2015; Lambrianidou et al., 2013; Schmitz 2011; Scott et al., 2012; Vasudevan et al., 2011; Eccles et al., 2004). Additionally, studies have suggested that pedestrians prefer countdown timer information, "…because it gives them more information and lets them make better crossing decisions (Signer and Lerner, 2004)." Pedestrian countdown timers were also found to improve driver safety (Kwifizile et al. 2015; Kitali et al., 2018). Drivers have been found to use pedestrian countdown timers to make informed decisions when approaching an intersection (Chen et al., 2015; Schmitz 2011; Elekwachi, 2010; Nambisan and Karkee, 2010).

Although vehicular countdown timers are not currently allowable in the U.S., they are in use in other countries and many studies have explored their impact. These studies have found that countdown timers can decrease vehicular delay (Chiou and Chang, 2010;

Limanond et al, 2010, 2009; Sharma et al., 2009) and increase throughput by efficient queue discharge (Chiou and Chang, 2010; Limanond et al., 2010; Sharma et al., 2009; Ibrahim et al., 2008; Liu et al., 2012) by providing drivers more information about the start-of-green. Islam et al. studied the impacts of a red signal countdown timer, which would alert the driver about an upcoming green indication (Islam et al., 2016). Using observed driver responses in a driving simulator, their findings revealed a headway reduction of 0.72 s for the first vehicle in the queue, which would lead to a reduction in start-up lost time, thus improving efficiency (Islam et al., 2016). In another study, Islam et al. explored driver responses to green signal countdown timers using a driving simulator experiment using 55 subjects (Islam et al., 2017). Their findings revealed increased in average driver stopping probability in the dilemma zone by 13.10% and also led to decrease in average driver deceleration rates by 1.5 ft/s^2, leading the authors to conclude that the implementation of green signal countdown timers could improve intersection safety (Islam et al., 2017). International studies examining the effects of implementing TSCTs all tend to suggest that drivers favor the idea of TSCT implementation, particularly the implementation of the GSCT (Factor et al., 2012; Rijavec et al., 2013).

No published research literature was found regarding BSCT. However, these are commonly used in northern European countries to inform bicyclists about the time remaining until onset of the green indication. In the Netherlands, the “Wacht” BSCT consist of a display of white LEDs in a circle that disappears one unit at a time as the time until the onset of the green indication decreases for the purpose of decreasing the startup lost time of bicyclists responding to the onset of green indications. In Copenhagen, a numerical BSCT is also sometimes used. Both of these are shown in Figure 3.1. Dutch traffic engineers have noticed that it increased the capacity of junctions from 10 to 15%, reducing lost time and improving the credibility of the signalized intersections (Bicycle Dutch, 2016). The city of Portland has installed a Wacht BSCT at the intersection of NE Oregon St and NE Interstate Ave to facilitate a diagonal crossing for bicyclists (it is on the far-side). According to PBOT's estimates, BSCT cost approximately $3,500 per installation.

"Wacht" BSCT (Source: Bicycle Dutch, 2016)

Copenhagen Numerical BSCT (All rights reserved by Mikael Colville-Anderson)

Figure 3.1 BSCT for Bicycles in Netherlands and Copenhagen

3.4 Research Questions

An experiment was designed to evaluate the comprehension of BSCT and to determine whether they influence the quality of the cycling experience. The research addressed the following questions:

- How well are the alternate designs for BSCT understood by the general public?
- How does the information provided by the confirmation and feedback device affect the overall cycling experience?
- How can this research guide practitioners regarding the use of BSCT?

The following sections summarize the design, administration, deployment, results and analysis of the survey evaluation.

3.5 Method

3.5.1 Survey objectives

The objective of the survey was to determine which BSCT is best understood by users. The survey was designed to elicit common correct, incorrect, or partially incorrect interpretations of the feedback device meanings.

3.5.2 Design and Refinement

The first step in designing the survey was the development of a generic template for survey images. The research team designed the initial image template by considering a recent ODOT report (Hurwitz et al. 2018). A PowerPoint image was used instead of a real photo, to enable explicit modification of the BSCT. Every effort was made to present questions neutrally, allowing respondents to provide meaningful answers reflecting their comprehension of the signal indications. Several rounds of review and refinement followed the internal development of the survey questions. Transportation graduate students at OSU and PSU and ODOT employees tested a pilot survey and provided feedback for further improvements of the format and content of the survey questions. Once the research team was satisfied with the survey design, the survey was finalized. The finalized survey, distribution methods, and record handling were reviewed and determined exempt by the IRB of PSU (196376-18).

3.5.3 Instrument

The survey included a mix of open-ended and close-ended questions. The survey design included random branches so that open-ended questions could be presented in an unbiased manner. Figure 3.2 illustrates the flow of the BSCT survey.

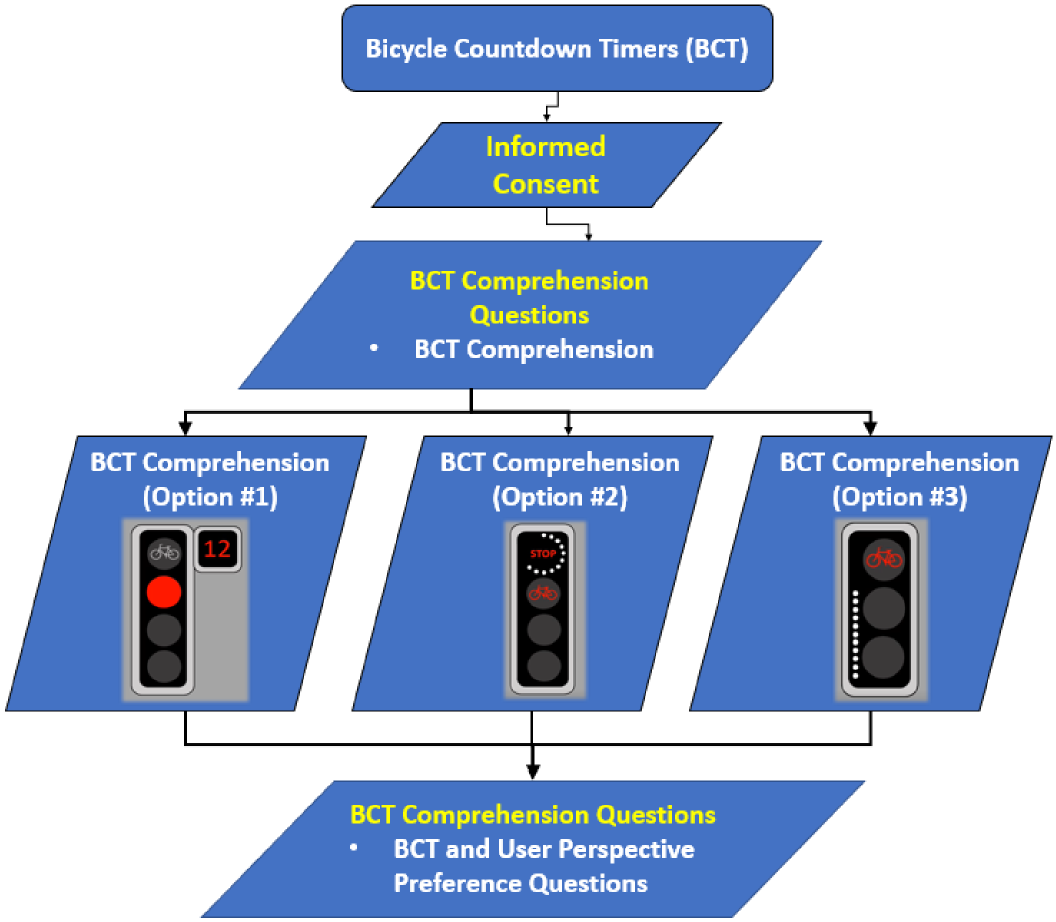

Figure 3.2: Survey Flow

Before being shown the questions, respondents had to provide informed consent for the survey, certifying that they are over 18 years of age. Initially, respondents were randomly presented one of three BSCT and asked to describe their meaning. Following this, respondents were presented all three options and asked to indicate which of the three BSCT options best conveyed their meaning.

The closing of the survey included close-ended multiple-choice demographic questions on the respondent's income and education levels, cycling and driving habits, and eyesight.

3.5.4 Administration

A survey response rate of 6–8% was assumed based on a previously conducted postcard/online design by researchers at PSU (Currans et al., 2015). A sample size of 10,004 respondents was selected based on the assumed response rate. A sampling scheme was designed based on the proportion of the population in each medium/large city in Oregon. Only cities were chosen for the postcard mailing because of the higher prevalence of bicycling in urban areas. Based on this scheme, a random sample of addresses within each city was purchased through Info USA. After removing incorrect/ missing addresses from the purchased address sample, there remained 10,003 households to which recruitment materials could be sent. Additionally, a social media post containing pertinent information about the survey objectives and the online link was posted to Facebook.

3.5.5 Response Rate

Responses were collected from both post card recruitment and social media. Postcards were mailed to 10,003 addresses and 271 postcards were returned as undeliverable. A total of 568 respondents clicked the online link to respond to the survey. The calculated response rate was 5.8%. A social media post was provided on Facebook with pertinent information regarding the study and an online link to the survey. A total of 1,550 respondents clicked the online link to begin the survey; however, only 555 respondents completed the survey. The calculated response rate was 35%.

3.5.6 Demographic Summary

The survey indicated that 1,084 people of the 1,340 that responded provided some or all of the requested demographic information. The records with no demographic information were removed for analysis resulting in 529 usable responses from the postcard survey and 555 responses from the social media survey. The responses from the social media survey were further categorized into those from Oregon (zip code starting with 97) and national (all other zip codes except Oregon).

Compared to 2010 Census estimates for Oregon and the United States (US Census), older, educated white males were overrepresented as survey respondents on the postcard survey. Postcard survey male respondents had the highest overrepresentation (60% male compared to 49% male for the total population in both Oregon and US). Respondents of the survey favored an older demographic compared to the general population, with larger representation in the 55–64 and 65+ years categories, for data collected from Oregon (48.5% postcard survey, 34.4 social media (OR)) in comparison to the census estimates (29.9 (OR); 27.6% (national)). The social media survey administered nationally compared to the census yielded a larger representation in the 25-34 year old category (32.8%) versus (13.7%), respectively. Respondents were overrepresented on all forms of the survey as compared to the census proportions, with whom possessed a Bachelor’s degree. Postcard respondents were 81% White/Caucasian (vs. 77% reported in the

Census) and overrepresentations were also seen with both social media national and Oregon data. Proportions of higher income respondents ($100,000 or greater) on both postcard and social media surveys were overrepresented when compared with census estimates (34.2% (postcard), 33.3% (social media Oregon), 38% (social media national) vs. 26.2% (national) and 23.8% (social media Oregon).

Respondents from Oregon via the postcard versus respondents from Oregon on social media tended to cycle less than 5 miles per week (74%) and cycle over 10 miles per week (74%), respectively. Furthermore, respondents from Oregon via the postcard in comparison to respondents from Oregon and nationally on social media had a lower propensity of utilizing a bike ride for either fun/exercise or for transportation within the last month (28% for fun/exercise and 15% for transportation) and had higher propensity to use a bike ride for fun/exercise or for transportation within the last month (86% for fun/exercise and 73% for transportation for Oregon social media; 65% for fun/exercise and 38% for transportation for national social media), respectively.

3.6 Results

3.6.1 Coding

Since the survey contained open-ended questions designed to assess comprehension of the BSCT, the responses needed to be categorized for further analysis. The research team reviewed each open-ended response. Responses were coded as correct, partially correct, or incorrect based on established criteria shown in Table 3.1. The same coding convention was followed for coding both the responses from all forms of the survey (postcard and social media).

Table 3.1: Error Coding of Narrative

DISPLAY INDICATION	CORRECT	PARTIALLY CORRECT	INCORRECT
BSCT	That either the dots or the number indicates the amount of time left until the bicyclist will be given the green signal.	That the system was used to instruct operations (e.g., “Stop” or “Go”) for the bicyclist.	Anything else

For the BSCT, a response was coded as correct, if the respondent stated that system (i.e., disappearing dots or numerical values) indicates the amount of time left until the bicyclist will be given the green signal (e.g., amount of time left till the signal turns green). Responses were coded as partially correct if the respondent indicated that the countdown indicated operations for the bicyclists but did not indicate anything about the countdown (e.g., people on bikes or bicyclists should not proceed until green). Responses were coded as incorrect if the respondents indicated anything else.

3.6.2 Open-ended Comprehension Questions

Each respondent was asked an open-ended question to determine their comprehension of BSCT. Respondents were presented with the following wording for the display.

“Imagine that you are stopped at an intersection on a bicycle on a red signal indication and you see the signal head above. What does the DISPLAY mean to you as a person on a bicycle? Please type your response in the box below and be as descriptive as possible.”

Responses to the question were reviewed and classified as correct, partially correct, or incorrect. A discussion of this signal display indication follows.

Respondents were randomly presented an animated GIF of one of the three BSCT options and asked a question designed to probe their comprehension of the system, as shown in Figure 3.3. Online, the BSCT would animate countdown operations (e.g., countdown numbers, white dots disappearing counterclockwise, change from red indication to green indication). Responses were coded following the coding convention outlined in Table 3.1.

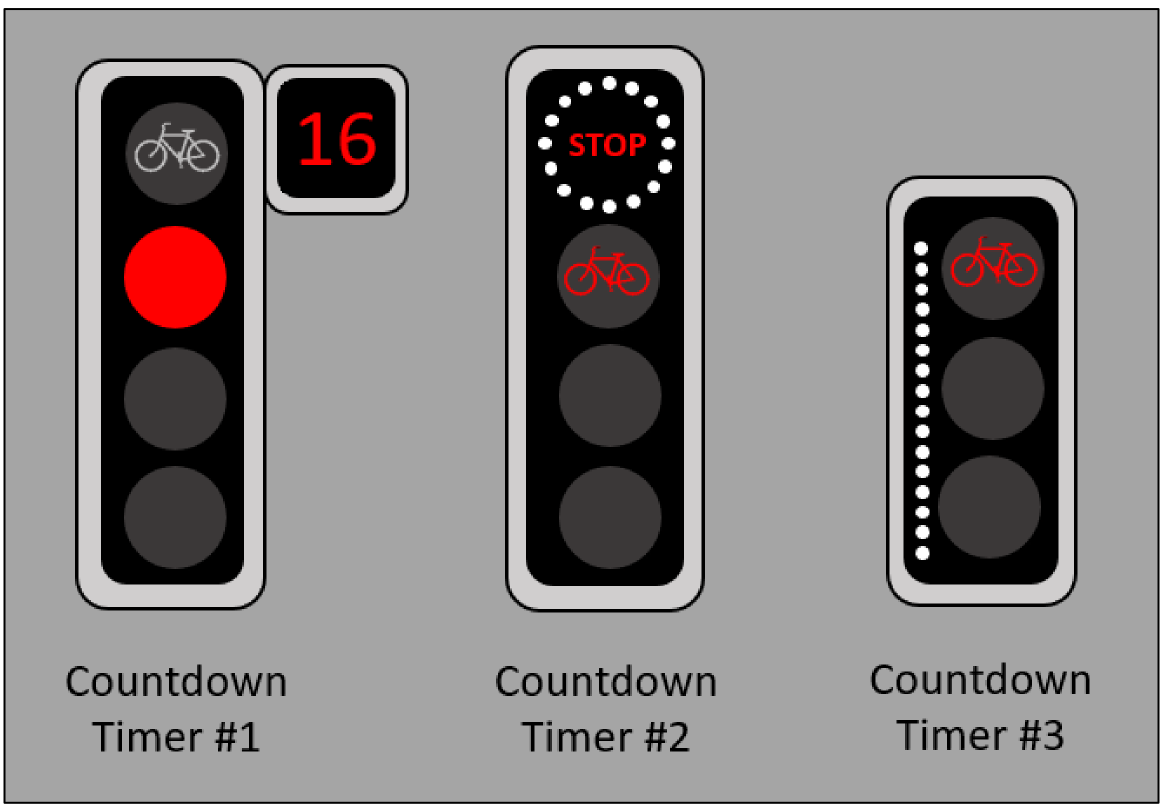

Figure 3.3: BSCT options (animated in the survey)

Table 3.2 presents the results for this question, which was answered by 1,084 respondents (361 with Option 1, 362 with Option 2, and 361 with Option 3). For BSCT #1 (i.e., Numeric Countdown), most respondents (57% average of three sources) understood the BSCT and indicated that it was counting down until they received a green indication or could proceed. An additional 11% were coded partially incorrect because respondents indicated the operations of the signal but did not indicate the purpose of the BSCT. Similarly, BSCT #3 (i.e., Vertical Disappearing Dots) had most respondents (52% average of three sources) understanding the BSCT and indicating the correct meaning. An additional 25% were coded partially incorrect because respondents indicated the operations of the signal but did not indicate the purpose of the BSCT.

In comparison, BSCT #2 (i.e., Circular Disappearing Dots) had 41% (average of three sources) of respondents indicate correct responses; however, there was a much higher propensity of respondents who were coded as partially correct (32% average of three sources). Many respondents who were coded as partially correct indicated the operations of “Stop” and “Go,” which appears during the animation of the BSCT, but did not describe or indicate the purpose of the disappearing dots serving as a countdown till the signal indication turns green.

Table 3.2: Responses to an open-ended question on the BSCT

RESPONSE	TOTAL		
	Post Card	Social Media (Facebook)	
	OR	OR	USA
BSCT #1 (Numeric; n=361)			
Correct	64.6%	60.9%	48.4%
Partially Correct	11.6%	17.4%	9.6%
Incorrect	23.8%	21.7%	39.5%
Did Not Respond	0.0%	0.0%	2.5%
BSCT #2 (Circular Disappearing Dots; n=362)			
Correct	42.6%	51.4%	38.0%
Partially Correct	34.6%	29.7%	29.4%
Incorrect	22.8%	18.9%	31.3%
Did Not Respond	0.0%	0.0%	1.2%
BSCT #3 (Vertical Disappearing Dots; n=361)			
Correct	44.1%	66.7%	42.8%
Partially Correct	28.0%	20.0%	26.9%
Incorrect	28.0%	13.3%	29.0%
Did Not Respond	0.0%	0.0%	1.4%

3.6.2.1 Statistical Analysis

To better understand respondents' comprehension scores to the BSCT, binomial proportion tests were used to test whether a particular BSCT could increase the probability of getting less incorrect responses.

For BSCT #1 versus BSCT #2 and BSCT #3, results showed that the proportion of correct responses by respondents was fifty-nine percent (59%) and sixty percent (60%) when respondents received option two and three, respectively, versus sixty-five percent (65%) when receiving option one. Although the statistical tests for both (BSCT #1 versus BSCT #2, and BSCT #1 versus BSCT #3) were not statistically significant (P-value = 0.25 and 0.31 respectively), there is approximately a six percent (6%) improvement in the correct responses. This increase explained why respondents preferred BSCT #1 over BSCT #2 and BSCT #3. Finally, when comparing BSCT #2 versus BSCT #3, the p-value of the binomial portion test was 0.88. This indicates that the correct response rates of BSCT #2 and BSCT #3 were not statistically different. In summary, BSCT #1 had the highest correct responses among others.

3.6.3 Multiple-Choice and Likert Scale Questions

Multiple-Choice and Likert Scale questions were provided to each respondent regarding their preferences, level of agreement, and experience with BSCT. A discussion of these questions is listed below.

3.6.3.1 BSCT Preference

Respondents were presented all three BSCT options, as shown in Figure 3.3. Online, the BSCT would animate countdown operations (e.g., countdown numbers, white dots disappearing, change from red indication to green indication). Respondents were then asked to choose the BSCT that best conveys the purpose of the system, and to provide justification for their choices. Responses were coded following the coding convention outlined in Table 3.1.

Table 3.3 presents the results for this question, which was answered by 1,084 respondents. Respondents indicated that BSCT #1 (Numerical Countdown (41% average for all sources) best conveyed the purpose of the system, followed by BSCT #2 (Circular Disappearing Dots Countdown) (32% average for all sources) and BSCT #3 (Vertical Disappearing Dots Countdown) (25% average for all sources).

Table 3.3: Responses to Closed-Ended Question on BSCT Preference

RESPONSE	TOTAL		
	Post Card	Social Media (Facebook)	
	OR	OR	USA
BSCT #1 (Numerical Countdown)	42.3%	40.0%	40.9%
BSCT #2 (Circular Disappearing Dots)	31.0%	30.0%	32.7%
BSCT #3 (Vertical Disappearing Dots)	26.1%	28.9%	24.1%
Did not Respond	0.6%	1.1%	2.4%

3.6.3.2 BSCT "Level of Agreement" Questionnaire

After making their preference selection, respondents were then provided a Likert scale to evaluate their "level of agreement" with designated statements regarding the BSCT, as shown in Figure 3.4.

Table 3.4 summarizes results for the three Likert questions, which were answered by 1,084 respondents. For Question 1, respondents generally indicated that they "Strongly Agree" (38% average of all three sources) and "Agree" (34% average of all three sources) that the disappearing white dots makes sense to them as a way to display the countdown to green. For Question 2, respondents indicated that they either "Strongly Agree" (31% average of all three sources) or they are "Indifferent" (25% average of all three sources) that they prefer the display of the actual number of seconds as a countdown to green signal.

Similar to Question 1, respondents for Question 3 generally indicated that they "Strongly Agree" (40% average of all three sources) or that they "Agree" (32% average of all three sources) that they would feel better about waiting on a bicycle at an intersection if a BSCT (e.g., numeric countdown or disappearing dots) was present.

Please indicate your **LEVEL OF AGREEMENT** with the following statements:

	Level of Agreement				
	Strongly disagree	Disagree	Indifferent	Agree	Strongly Agree
The disappearing white dots makes sense to me as a way to display the countdown to green signal.	○	○	○	○	○
I prefer the display of the actual number of seconds as a countdown to green signal.	○	○	○	○	○
I would feel better about waiting at an intersection if a countdown timer (e.g., numeric countdown or disappearing dots) was present.	○	○	○	○	○

Figure 3.4: "Level of Agreement" questionnaire for BSCT

Table 3.4: Responses to "Level of Agreement" of Statements Regarding BSCT

RESPONSE	TOTAL		
	Post Card	Social Media (Facebook)	
	OR	OR	USA
Q1: The disappearing white dots makes sense to me as a way to display the countdown to green signal.			
Strongly Disagree	8.5%	0.0%	5.6%
Disagree	12.9%	5.6%	7.7%
Indifferent	13.0%	6.7%	7.7%
Agree	31.2%	46.7%	35.5%
Strongly Agree	34.0%	41.1%	41.1%
Did not Respond	0.4%	0.0%	2.4%
Q2: I prefer the display of the actual number of seconds as a countdown to green signal.			
Strongly Disagree	11.0%	8.9%	8.6%
Disagree	19.5%	20.0%	16.6%
Indifferent	23.4%	28.9%	25.6%
Agree	13.2%	15.6%	16.8%
Strongly Agree	32.3%	26.7%	30.3%
Did not Respond	0.6%	0.0%	2.2%
Q3: I would feel better about waiting at an intersection if a countdown timer (e.g., numeric countdown or disappearing dots) was present.			
Strongly Disagree	7.6%	3.3%	4.9%
Disagree	6.4%	4.4%	4.3%
Indifferent	19.5%	20.0%	13.8%

Agree	31.8%	27.8%	30.8%
Strongly Agree	34.2%	44.4%	43.9%
Did not Respond	0.6%	0.0%	2.4%

3.7 Discussion and Conclusions

The survey was distributed based on a mixed method of post card and social media, and overall it was effective, bringing in responses from both Oregon (via post card and social media) and throughout the country (social media). Collectively a more balenced sample was received. This approach reduces the biased that may come from one source that favors specific demographics.

The scenarios with BSCT elicited higher proportions of correct responses across all three options that were tested. However, for individuals who received the BSCT #2 (Circular Disappearing Dots), there was a higher propensity (32%) of individuals that answered the comprehension question partially correct, with most indicating “Stop” and “Go” operations, rather than the intended purpose of the BSCT. In this scenario, it appeared that additional text and information in the BSCT tended to misguide respondents focus on the action rather than the purpose.

In regards to preference, a large portion (41%) of the respondents across all platforms also preferred BSCT #1 (Numerical Countdown) among the BSCT options. Individuals were also asked to indicate their reasoning for why they selected the option, and many individuals indicated that the numbers counting down was intuitive to the system and was easy to follow. However, while many respondents stated that they felt the numbers were easy to understand, some individuals noted that they were familiar with countdown numbers used for pedestrian signal countdown timers and indicated that because the use is different, it could potentially be confusing to users.

Majority of the respondents either strongly agreed or agreed that the disappearing white dots made sense to them as a way to display the countdown to the green signal and that they would feel better about waiting at an intersection which was equipped with a BSCT. The respondents did not feel as strongly about the provision of a BSCT that displayed the actual number of seconds as a countdown to the green indication.

Based on the results of the survey, providing BSCT appears to support the goal of providing the time till users will receive the green indication to reduce cyclist prematurely entering intersections on red indication. Furthermore, based on the respondent feedback, the numerical BSCT was preferred, so likely if installed, this would be the ideal design used. However, as most users are only familiar with pedestrian countdown timers, which provide the countdown till they cannot cross, training and educational campaigns would be vital to ensuring that these devices are properly used. With the implementation of a BSCT, signal timing plans would need to accommodate different minimum green, extension, yellow change, and red clearance times for cyclists, in comparison to vehicles, to safely navigate and clear the intersection.

3.7.1 Limitation and Future Work

There were a few limitations associated with this survey. The survey was a stated preference survey, meaning that respondents were answering questions under non real-time conditions. While stated preference surveys can be an easy way to collect data under an economically conscious method, there are limitations. Within stated-preference surveys, data is subject to the design of the survey and its questions; therefore, if a respondent reads or comprehends the question differently than the surveyor, then the results could be askew. In regard to demographics of the survey respondents, the study had an overrepresentation of white older educated high-income males. As many roadway users extend beyond this demographic, this survey may not be representative of varying races, ages, and education levels. Additionally, respondents from Oregon via the postcard tended to cycle far less than 5 miles per week in comparison to respondents from Oregon on social media who tended to cycle over 10 miles per week. This could be a result of the fact that many of the respondents from the postcard sample were older, and therefore may not be as physically able to ride for extended distances or time periods.

3.8 Acknowledgements

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4 BICYCLISTS BEHAVIORAL AND PHYSIOLOGICAL RESPONSES TO VARYING ROADWAY CONDITIONS AND BICYCLE INFRASTRUCTURE

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4.1 Abstract

Travel demand has increased due to population growth, increase of vehicle ownership, and development patterns resulting in greater levels of congestion, pollution, and crash frequency. A proposed solution to lessen current transportation system demands is to increase the share of trips made by bicycles. To promote this mode shift, one must understand what drives individuals to choose cycling as their preferred mode choice. Furthermore, as cycling is perceived by some as both a dangerous and stressful mode of transportation, understanding the factors that lead to less comfortable and stressful riding, can help drive bicycle infrastructure development. In an effort to establish a more robust understanding of the abilities and limitations of bicyclists and how transportation professionals can influence these characteristics through infrastructure design and operations, an experiment was designed to examine bicyclists behavior in varying roadway conditions using the performance measures of velocity, horizontal displacement, and Galvanic Skin Response (GSR). For this study, a bicycle simulator, in conjunction with a survey questionnaire, were used to examine bicyclist's behavior in varying roadway conditions using the performance measures of velocity, horizontal displacement, and GSR. Results showed that bicyclists in a bicycle lane, had a GSR reading 1.25 peaks per min less than when cycling in a mixed traffic condition. In addition, when bicyclists rode in the bike lane, bicyclist's GSR reading and velocity were not affected by the variations in vehicular volume or vehicular speed. However, lateral position was affected by vehicular volume. When bicyclists were in mixed traffic conditions, the GSR reading was not affected by vehicle speed; however, it was affected by the vehicular volume. In mixed traffic conditions, none of the variables played influence into the bicyclist's

velocity. For the lateral position, only the vehicular volume had a significant affect. Therefore, recommendations for bicycle facilities should aim to provide striped bike lanes if possible or limit vehicular volumes on roadway where bicyclists are in mixed traffic conditions.

Keywords: Bicycling Simulator, Level of traffic stress, LTS, Galvanic Skin Response, GSR, Comfort, Stress,

4.2 Introduction

Bicyclists behavior, comfort, and stress while riding has been evaluated by researchers and practitioners, however, many of the studies have been based primarily on three (3) methodologies: (1) stated preference questionnaires that ask respondents about their behaviors and comfort in relation to an entire ride or segments of a ride, either as forecasted conditions or following a naturalistic ride, (2) revealed preference data that uses Global Positioning System (GPS) to geocode bicyclists to particular routes in an effort to understand what factors (e.g., roadway geometry, topography, vehicular volumes, bicycling infrastructure) influence bicyclist's route choice, potentially correlating to higher levels of comfort or lower levels of stress, or (3) bicycle indices or bicycle level of service (BLOS) methodologies which evaluate how a combination of variables plays a role in calculating and classifying the service, bikeability, comfort, or stress for roadways segments and intersections. While all three methodologies provide beneficial information, little is known about the behavior of bicyclists and their physiological responses when riding and, furthermore, how specific characteristics of roadways, environment, and infrastructure influence these. Therefore, quantifying behaviors and physical stress will help to identify correlations between physiological stress and the responses that individuals have based on the naturalistic conditions.

Currently, there have only been a few studies that have evaluated behavioral and physiological stress impacts of bicyclists, and this area of research plays a vital role in bicyclists' route preferences (Doorley et al., 2015; Vieira et al., 2016; Caviedes et al., 2017; Fitch et al., 2017). The studies used (Galvanic Skin Response) GSR response, electrocardiograms (ECG), and heart variability to measure how they were influenced by various roadway, facility, time of day, and event conditions. The studies provide a preliminary step towards evaluating physiological stress responses in bicyclists; however, the goal here is to further expand the research of physiological stress that bicyclists experience during simulated riding conditions and how specific types of cycling infrastructure and roadway conditions play a role in bicyclists' behavior and physiological stress responses.

4.3 Literature Review

In an effort to understand the needs of bicyclists while riding, researchers have spent significant time investigating factors that influence bicyclist's behavior, comfort, and stress. Most research studies have accomplished this research based on three main methodologies. The first methodology utilizes stated preference questionnaires through surveys to determine bicyclists' preferences and how they influence behavior and comfort. These studies looked at individual's perspective of either a forecasted condition or a naturalistic ride (Dill and Voros, 2007; Winters et al., 2011; Li and Kamargianni, 2017; Konstantinidou and Spyropoulou, 2017; Abadi and Hurwitz, 2018). In general, these studies have found that availability of cycling infrastructure, ease of cycling, weather conditions, air quality, and vehicular volume played significant influence into individuals' choice to cycle, bicyclists' specific behaviors, and heightened comfort while riding. While these studies do not indicate bicyclist's perspective while riding in the real world, they do provide important insight into what influences bicyclist's behavior and stress.

The second methodology analyzes revealed preference (i.e., Global Positioning System (GPS) from staged bikes or crowdsourced data) to investigate real-time bicyclist decisions in regards to their respective conditions (e.g., location, route choice, weather conditions, topography, etc.) (Menghini et al., 2010; Charlton et al., 2011; Broach et al., 2012; Ma and Dill, 2015). These studies found that generally the presence of designated cycling infrastructure had a higher correlation with cycling route preferences, indicating that the level of comfort was adequate for individuals to select a particular roadway for traveling. While revealed preference data serves as a good basis for understanding bicyclists' decisions and feelings while riding, results may not be perfectly transferable to field conditions. In an effort to validate the decisions that bicyclists made or how they were feeling during a ride, some studies have provided post-ride survey questions. In 2015, Blanc and Figliozzi used a combination of both revealed preference and stated preference data to identify bicyclists' comfort and safety information. The study used crowdsourced GPS data, via a smartphone application, that collects bicyclists' comfort and safety information, and then provided follow-up questions for further evaluation and validation. The study found that separated facilities had a positive correlation with high levels of comfort, and that trip purpose and trip length had influence on the comfort the bicyclist (Blanc and Figliozzi, 2015).

The third methodology used or created by researchers are bicycle indices or bicycle level of service (BLOS) methodologies which evaluate how a combination of variables plays a role in calculating and classifying service, bikeability, comfort, or stress for roadway segments and intersections (Sorton and Walsh, 1994; Landis, 1994; Jensen, 2007; BEQI, 2009; HCM, 2010; Mekuria et al., 2012). Specifically, one of the more popular methodologies used throughout the country is Level of Traffic Stress (LTS). In 2012, Mekuria et al. developed the LTS methodology, which was updated in 2017, that uses a series of variables (e.g., effective ADT, prevailing speed, roadway configuration, type of cycling infrastructure, etc.) to determine the LTS classification for roadway segments and intersections (Mekuria et al., 2012). Table 4.1 shows the LTS classifications for a mixed traffic condition and for a bike lane adjacent a parking lane, as an example. As indicated in Table 4.1, in the mixed traffic condition, with increases in ADT and vehicular speed, the level of traffic stress increases, indicating that the roadway is less comfortable for most riders. Additionally, in the bike lane condition, with increases in vehicular speed and decreases in the bike lane reach width (i.e., bike lane width plus parking lane width), the LTS classification also increases, similarly indicating that the road is less comfortable for bicyclists.

Table 4.1: LTS Classifications for Mixed Traffic Condition and Bike Lane Condition

Mixed Traffic Condition (2-way street with centerline)		
ADT	**Speed**	
	25 mph	**45 mph**
751-1500	LTS 2	LTS 3
3000+	LTS 3	LTS 4
Bike Lane Condition (alongside a parking lane w/ 15+ feet of Bike lane Reach)		
Bike Lane Reach (bike + parking lane width)	**Speed**	
	25 mph	**45 mph**
15+ feet	LTS 1	LTS 3
12-14 feet	LTS 2	LTS 3

The LTS methodology has been used in many studies to identify low-stress links and nodes within networks, to better prioritize future investments (e.g., bicycle infrastructure) and expand connectivity of low-stress roads and intersections (Semler et al., 2017; Lowry et al., 2016; Scrivener, 2015). However, even with LTS's popularity and utilization throughout the United States, it has been questioned. Wang et al. conducted a study to evaluate whether LTS explains bicycle travel behavior and found that it may not be useful for prioritizing bicycle infrastructure to promote cycling (Wang et al., 2016). Furthermore, because LTS was not developed using empirical data, there is an opportunity to provide additional support for the methodology through experimental research findings.

All three methodologies provide a good foundation for understanding bicyclists' behavior, comfort and stress while riding, albeit with different limitations. In an effort to resolve some of the uncertainty, a few studies have been conducted to evaluate bicyclist's behavior and physiological stress responses during an actual ride.

Currently, there are only a few studies that have investigated bicyclist's behavior and stress responses while riding (Doorley et al., 2015; Vieira et al., 2016; Caviedes et al., 2017; Fitch et al., 2017). Doorley et al. conducted a study in Cork, Ireland to evaluate how risks while cycling related to heart rate variability (Doorley et al., 2015). The study measured cyclists heart rate variability while riding in three different cycling conditions and had participants conduct risk rating questionnaires and travel diaries in an attempt to validate and understand the cyclist's experience. The study found that higher risks correlated with higher heart rates and that roadways with higher volume and no bicycle lane were found to have a higher average risk (Doorley et al., 2015). Vieira et al. used a camera and electrocardiogram (ECG) belt to determine how various conditions (e.g., being overtaken by car, turning right or left) while riding play influence into a cyclist's physiological response (Vieira et al., 2016). The study found that higher stress responses were shown when cars passed too closely or when passing parked vehicles (Vieira et al., 2016). Fitch et al. conducted a heart variability analysis that found speed changes and road environment played significant roles in the heartbeat fluctuations measured (Fitch et al., 2017). Caviedes et al. evaluated how characteristics of the bike trip affected stress using GSR (Caviedes et al, 2017). The study used a GSR sensor to measure stress responses of five individuals (i.e. four males and one female) on a designated route. The study found that the stress response greater during peak hours, that separated facilities had lower stress response rates, and that intersections were high stress indicators (Caviedes et al., 2017). While setting the groundwork for understanding the physiological responses of cyclists while riding, the studies did have some limitations. Doorley et al. (2015) and Caviedes et al. (2017) had non-representative samples, focusing mainly on male cyclists. Fitch et al. (2017) also had a non-representative sample but focused only on females. Vieira et al. (2016) only used one participant, which doesn't provide a representative sample, and it did not specifically define different types of infrastructure that play a role in physiological changes, and this could significantly improve the understanding of how specific types of cycling infrastructure play a role in route preferences.

Naturalistic real-time studies that measure bicyclist's behavior and physiological stress responses have the potential to provide a greater understanding of bicyclist's decision making and overall comfort, help us to validate or adjust current methodologies used by many researchers and practitioners, and help us identify specific cycling infrastructure and roadway conditions that influence behavior and changes in stress.

4.4 Methods

To establish a more robust understanding of the abilities and limitations of bicyclists and our ability to influence these characterists through infrastructure design and operations, an experiment was designed to examine bicyclists behavior in varying roadway conditions using the performance measures of velocity, horizontal displacement, and GSR. Oregon State University's (OSU) Bicycle Simulator was used to observe these bicyclists behaviors in a simulated driving environment and the Shimmer3 GSR+ sensor was used to measure the GSR readings of participants.

4.4.1 OSU Bicycle Simulator

OSU features a bicycling simulator consisting of an instrumented urban bicycle placed on top of an adjustable stationary platform (Figure 4.1a). A 3.20 m × 2.54 m screen provides the forward view with a visual angle of 109° (horizontally) × 89° (vertically) and image resolution of 1024 × 768 pixels. Researchers build the environment and monitor subject bicyclists from the operator workstation (Figure 4.1b) which is in a separate room from participants in the bicycle simulator experiment.

The update rate for the projected graphics is 60 Hz. Ambient sounds around the bicycle are modeled with a 5.1 Logitech surround sound system. The computer system consists of a quad core host running Realtime Technologies SimCreator Software with an update rate for the graphics of 60 Hz. The simulator software is capable of capturing and outputting highly accurate values for performance measures such as speed, position, brake, and acceleration. Figure 4.1c shows views of the simulated environment created for this experiment from the participant's view.

The virtual environment was developed using simulator software packages, including Internet Scene Assembler (ISA), Simcreator, and Blender. The simulated test track was developed in ISA using Java Script-based sensors on the test tracks to display dynamic objects, such as a vehicle cutting in front of a bicyclist.

Figure 4.1 Views from (a) OSU bicycling simulator, (b) Operator workstation, and (c) Simulated environment

4.4.2 Shimmer3 GSR+ Sensor

GSR readings were collected using the Shimmer3 GSR+ sensor. The device was strapped to participants on their wrist, with two electrodes that were attached to participants middle and ring fingers on their least prominent hand, as shown in Figure 4.2. The less prominent hand was used, as this hand was more stationary on the handlebars of the bike which helped to mitigate a premature peak in GSR response. Additionally, to ensure that GSR readings could be synchronized with specific simulated events, a Logitech C920 HD Pro Camera was integrated into the system to record all participant runs. The GSR and video data were all collected and processed together in iMotions software (V8.3). This software serves as a data acquisition hub, where GSR responses, and video data can all be recorded with a consistent time stamp

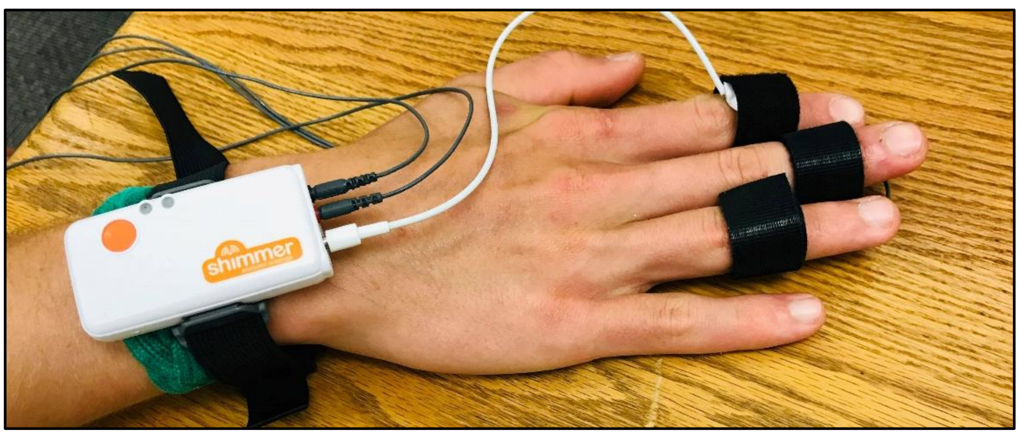

Figure 4.2 Shimmer3 GSR+ Sensor attached to hand

4.4.3 Research Objective

The study was designed to answer three primary research questions: 1) Is the velocity, horizontal displacement, and GSR of bicyclists influenced by the speed and volume of vehicles adjacent?, 2) How does the presence of a bicycle lane influence velocity, horizontal displacement, and GSR, and 3) Does LTS methodology properly correlate with physiological responses that bicyclists' experience?

4.4.4 Experimental Design

A factorial design was chosen for this experiment to enable exploration of the interactions between the independent variables. Four independent variables were included in the experiment: 1) Adjacent vehicle volume which had two levels (high and low), 2) two levels of adjacent vehicle speed (high and low), 3) bicycle lane not present or present, and 4) conflict or no conflict present.

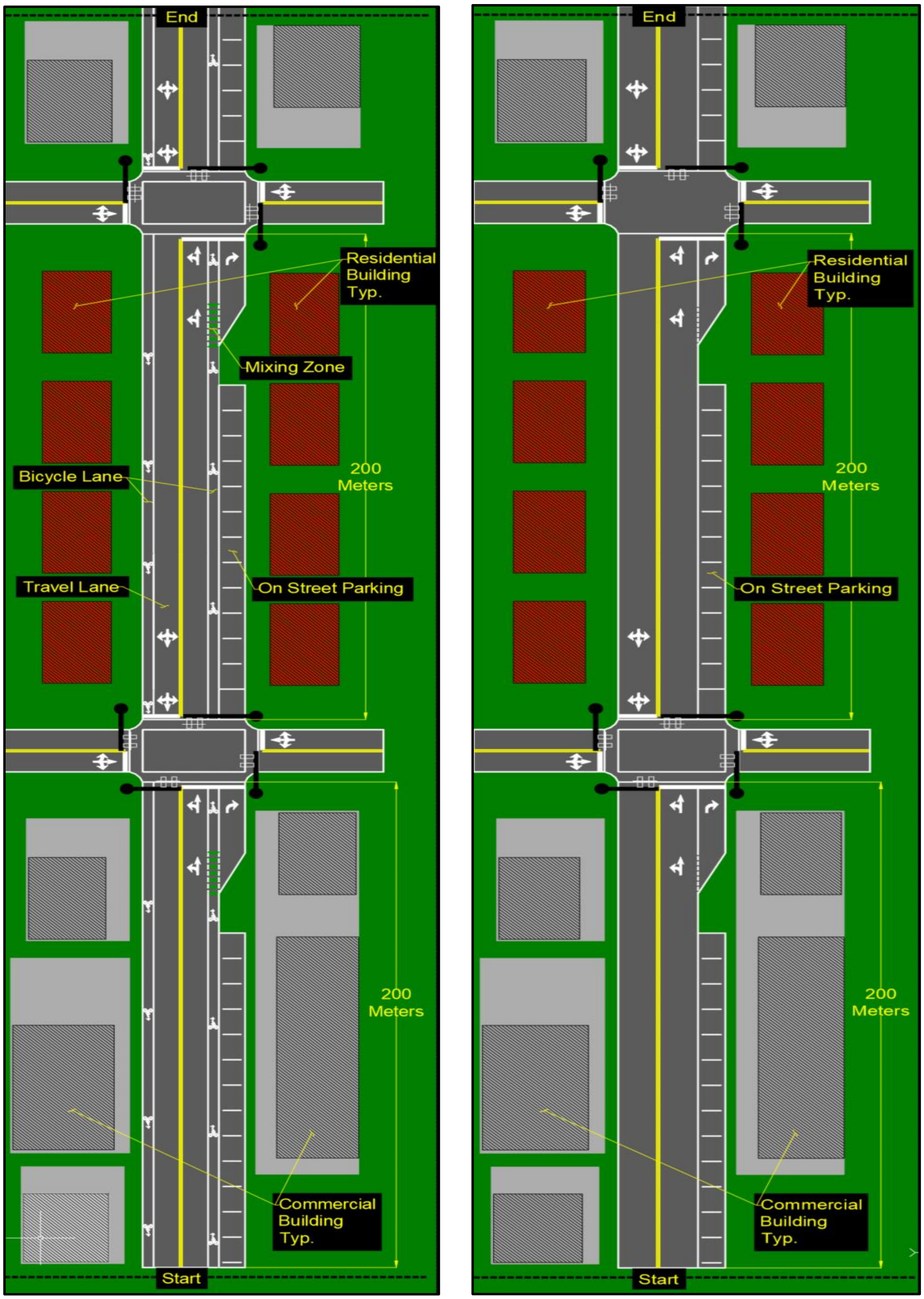

Figure 4.3 Grid layout with two blocks (a) with bike lane (b) without bike lane

The factorial design for the four independent variables, resulted in the inclusion of 2×2×2×2 scenarios, which were fully counterbalanced and presented within subjects. To control for practice effects (Cobb, 1998; Abadi et al., 2018), the placement of each scenario on each grid was randomly assigned and the order that each grid was presented varied between participants. Thus, different track layouts were developed and presented in random order to each participant. Each track had two blocks (see Figure 4.3), and each scenario (i.e. with bike lane or without bike lane) was randomly assigned one level for each of the two independent variables.

The roadway cross-section consisted of two scenarios: (a) 12-ft traffic lanes in each direction with a bike lane, and (b) 12-ft shared traffic lanes in each direction without bike lane. Additionally, in the “with bike lane” scenario, a green dashed mixing zone was included at the merge of the right-turn bay, as shown in Figure 3.3a. A yellow centerline, solid white edge line, small 1-ft paved shoulder, and 6.5-ft-wide pedestrian sidewalks on both sides of the road were constantly present. Traffic signal heads were created for use in the simulator scenarios. Figure 4.4 provides an example of the signal and dashed bicycle lane at an intersection approach.

As the bicyclists approached the intersection within the bicycle lane, a proximity sensor was triggered prompting and adjacent vehicle to pull infront of the bicyclist, merging into the right-turn lane, across the mixing zone. The scenario was designed so that the vehicle would be merging into the right-turn lane, across the mixing zone, as the bicyclists was approaching the intersection. This was calculated based on the vehicle speed and distance.

Figure 4.4 Example of signal and mixing zone within environment.

4.4.5 Participant Demographics

A total of 51 individuals (27 women), primarily from the community surrounding Corvallis, Oregon, were participants in the experiment. Participants were limited to individuals residing in Oregon over 18 years old and whom were able to ride a stationary bicycle. Recruitment efforts were made to distribute the participants in the sample evenly by gender. Approximately 2% of the subjects (1 woman) reported simulator sickness and did not complete the experiment. Responses from that participants were excluded from analysis. Failure to calibrate the experimental equipment accurately resulted in the loss of data for one additional participant. The final analyzed sample comprised 50 participants with an average age of 35.98 years (SD= 13.6). The subjects included 27 women (age μ= 31.48, SD=9.08 years) and 21 men (age μ=41.86, SD=16.7 years). In addition, participants generally were 25-35 years old (46.0%), had a master's degree (48.0%), were white (68.0%), and made less than $25,000 (24.0%).

4.4.6 Data Collection

After the motorist's eyes were calibrated to the bicycling simulator screens, participants completed a two-minute calibration ride to acclimate participants to the mechanics of the bicycle and the virtual environment of the simulator. If they did not exhibit signs of simulator sickness, participants were instructed to begin the experiment. Participants were instructed to ride straight through two blocks.

Three primary dependent variables were extracted from the experimental data. Driver decision making was observed from video recordings and measurements of velocity and horizontal displacement. Additionally, GSR (i.e., measure of the level of stress produced from skin conductance caused by sweat release) reading along the ride was recorded.

Driver's behavior and vehicle response data were collected by the SimObserver data acquisition platform during the experiment. A total of 48 hours of video and vehicle characteristics (e.g., velocity) were recorded. Additionally, GSR measurements were collected using a Shimmer3 GSR+ sensor and reduced down to provide average GSR peaks per minute for each individual, and for the overall sample.

4.4.6.1 Statistical Modeling

A Linear Mixed Effects Model (LMM) model was chosen for analysis because 1) of its ability to handle the errors generated from repeated subject variables as the participants are exposed to all scenarios, 2) it can handle fixed or random effects, 3) categorical and continuous variables can easily be accommodated, and 4) the probability of Type I error occurring is low (Jashami et al., 2019). A potential limitation of LMM is that more distributional assumptions need to be addressed (Jashami et al., 2020). The sample size for this study was 50 participants, which is greater than the minimum required for a LMM analysis (Barlow et al., 2019).

Six LMM models were performed for each dependent variable; GSR reading, velocity, and lateral position for both with bike lane and without. Models were developed using the statistical software Minitab for Windows (version 19.2) to consider the independent variables of ADT, and speed limit. These variables were included in the model as fixed effects. While the participant variable was also included in the model as a random effect. In the case of statistically significant effects, custom post hoc contrasts were performed for multiple comparisons using Fisher's Least Significant Difference (LSD). All statistical analyses were performed at a 95% confidence level. Restricted Maximum Likelihood estimates were used in development of this model. Finally, paired t-test was used to compare minimum average bicyclist's velocity of two scenarios while riding in the mixing zone (one vehicle cuts in front of bicyclist versus no vehicle) (Jashami et al., 2017).

4.5 Results

This section presents results of the simulator experiment. The following sections describe the summary statistics (from the pre-riding and post-riding survey) and the bicyclists performance in terms of velocity, horizontal position, and GSR responses.

4.5.1 Summary Statistics

4.5.1.1 Pre-Survey Survey

Participants were required to complete a pre-riding simulator survey. The survey included questions regarding demographics and riding experience. Table 4.2 shows the participants bicycling habits. Participants most frequently bicycled to commute (64.0%) and typically cycled between 10-20 miles a week (22.0%). Additionally, over 54% of participants considered themselves as “Enthused and Confident” bicyclists.

Table 4.2: Participant Bicycling Habits

Bicycling Habit	Possible Responses	Number of Participants	Percentage OF Participants
Types of Trips Taken by Bicycle	Commuting (i.e., traveling to/from work)	32	64.0%
	Exercise	26	52.0%
	Recreation	37	74.0%
	None	4	8.0%
Type of Bicyclist	Strong and Fearless	9	18.0%
	Enthused and Confident	27	54.0%
	Interested but Concerned	12	24.0%
	No Way No How	2	4.0%
Miles of Cycling Per Week	20-50 miles	9	18.0%
	10-20 miles	9	22.0%
	5-10 miles	7	18.0%
	1-5 miles	11	14.0%
	Less than 1 mile	9	18.0%
	Never	5	10.0%

4.5.1.2 Post-Survey Survey

After participants completed the bicycling simulator portion of the experiment, they were asked to complete a short survey regarding the bicycle simulator and the scenarios they encountered during their ride.

Evaluating whether bicyclists had ever experienced specific scenarios and how they felt in them was another goal of the research. Participants were asked whether they had ever ridden in a mixed traffic conditions, adjacent to on-street parking.

Forty-six participants (92.0%) indicated that they had experienced the riding conditions before, while 4 participants (8.0%) indicated that they had not experienced the riding condition. Following this, participants were asked how comfortable they felt while riding in the mixed traffic conditions. The average score for this question was 55.5, indicating a close split between participants who both felt less and more comfortable riding in the mixed traffic condition. Additionally, participants were asked how comfortable they felt when the vehicle crossed into the right turn lane while riding in the mixed traffic conditions. The average score for this question was 40.4, indicating that participants tended to feel less comfortable in this conflict scenario.

Individuals were then asked whether they had ever ridden in a bike lane, adjacent to on-street parking.

Forty-four participants (88.0%) indicated that they had experienced the riding conditions before, while 6 participants (12.0%) indicated that they had not experienced the riding condition. Following this, participants were asked how comfortable they felt while riding in the bike lane. The average score for this question was 78.6, indicating a that most participants felt comfortable riding in the bike lane. Additionally, participants were asked how comfortable when the vehicle crossed into the right turn lane while riding in the bike lane. The average score for this question was 47.5, indicating that participants tended to feel less comfortable in this conflict scenario; however, they felt more comfortable than when riding in mixed traffic conditions.

4.5.2 Bicycle Performance

4.5.2.1 GSR reading

To evaluate GSR responses for all participants, the data was reduced to provide average peaks per minute and used to determine significance of independent variables (iMotions, 2017). Initially, iMotions software (i.e., software used to process the GSR and video data) develops a baseline GSR reading for each participant based on their average responses throughout a scenario. Following this, anytime an individual has an amplified response above the baseline, this is classified as a peak and recorded (iMotions, 2017). After a participant processes through an entire scenario, the software calculates the peaks per minute for the individual, based on their relative amplified responses. Each individual rode for approximately 2-minutes in each scenario and their average peaks per minute was calculated. Following this, the sample average peaks per minute was modeled for each of the 16 scenarios.

An LMM was used to estimate the relationship between the independent variables and participant's mean GSR reading (peaks per minute), which is appropriate given the repeated measures nature of the experimental design, where each participant experienced each scenario (Jashami et al., 2019). Both fixed and random effects needed to be included in the model.

The results of the bike lane and no bike lane models are shown in Table 4.3. The random effects were significant for both (Wald $Z=4.18$, $p <0.001$, Wald $Z=4.12$, $p <0.001$) respectively, which suggests that it was necessary to treat the participant as a random factor in the models.

Table 4.3: Summary of Estimated LMM Models of GSR Reading

Model	Variables	Levels	Estimate	DF	p-value
GSR (Bike lane)	Subject random effect (SD)	-	2.94	-	<0.001
	Constant	-	6.57	39	<0.001
	ADT	High	0.03	117	0.82
		Low	Base Value	-	-
	Vehicle speed	45 mph	0.02	117	0.85
		25 mph	Base Value	-	-
	ADT x Speed Limit	45 mph x Low	0.13	117	0.21
		25 mph x Low	Base Value	-	-
Summary Statistics					
R^2	0.86	Observations			160
-2Log Likelihood	679.51	Subjects			40
AIC	683.60	Observation/subject			4
GSR (No bike lane)	Subject random effect (SD)	-	3.29	-	<0.001
	Constant	-	7.81	39	<0.001
	ADT	High	1.24	117	<0.001
		Low	Base Value	-	-
	Speed Limit	45 mph	-0.13	117	0.35
		25 mph	Base Value	-	-
	ADT x Speed Limit	45 mph x low	-0.02	117	0.86
		25 mph x low	Base Value	-	-
Summary Statistics					
R^2	0.84	Observations			160
-2Log Likelihood	744.31	Subjects			40
AIC	748.39	Observation/subject			4

For the bike lane condition, LMM showed that none of the independent variables and their interactions were statistically significant (Table 4.3). The effect of vehicle speed at 25 mph and 45 mph were not different from each other on bicyclists' GSR reading (p-value = 0.85). Similarly, when bicyclists rode in a low ADT or high ADT conditions, they had approximately the same GSR reading (p-value = 0.82). Additionally, the interaction term between vehicle speed and ADT was not significant (Figure 4.5). In Figure 4.5, the y-axis shows mean GSR reading (peaks/min). The x-axis shows the two levels of vehicle speed treatment at low and high ADT. Therefore, Figure 4.5 shows the interaction between the levels of vehicle speed (25 mph and 45 mph) and ADT (low traffic volume and high traffic volume).

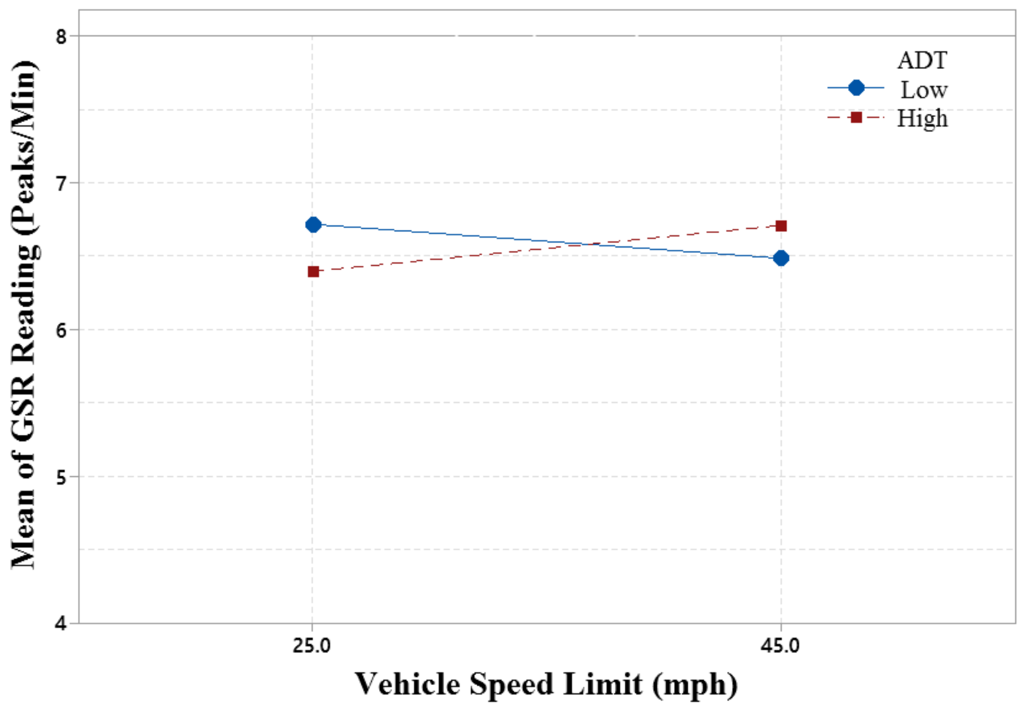

Figure 4.5 Two-way interactions on mean GSR reading for bike lane condition

For the no bike lane condition, LMM showed vehicle speed and its interaction with ADT variables were statistically insignificant (Table 4.3). The vehicle speed at 25 mph and 45 mph did not have an influence on the bicyclists GSR reading (p-value = 0.35). However, when bicyclists rode with low ADT conditions, they had approximately 1.25 peaks per minute lower than when riding with high ADT (p-value < 0.001). Additionally, the interaction term between vehicle speed and ADT was not significant (Figure 4.6). In Figure 4.6, the y-axis shows mean GSR reading (peaks/min). The x-axis shows the two levels of vehicle speed treatment at low and high ADT. Therefore, Figure 4.6 shows the interaction between the levels of vehicle speed (25 mph and 45 mph) and ADT (low traffic volume and high traffic volume).

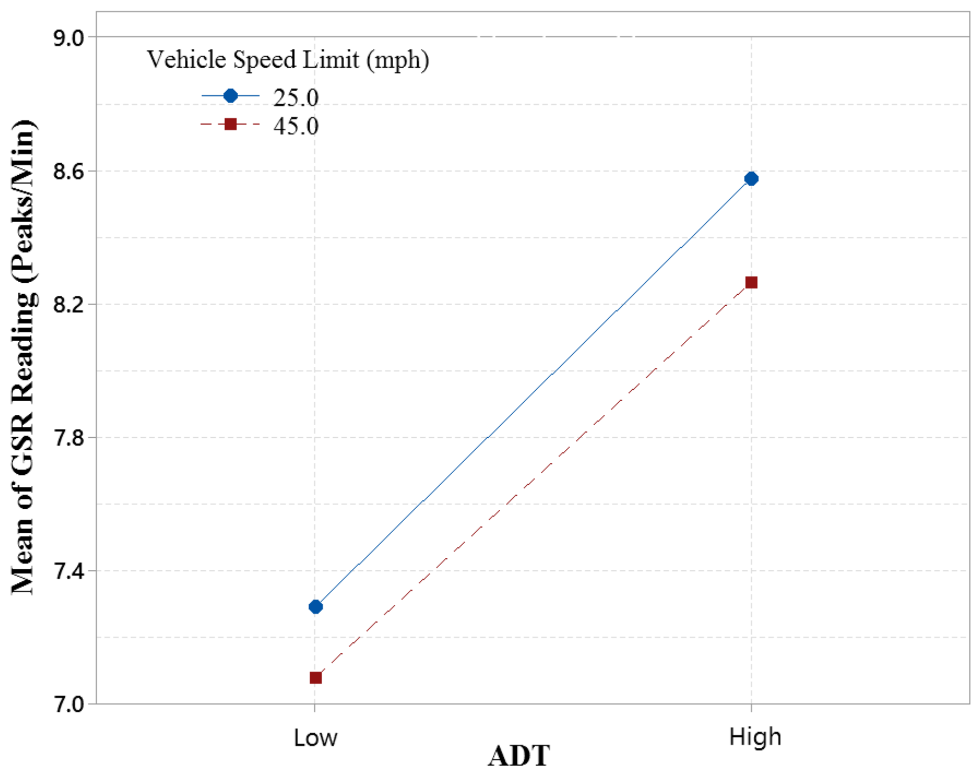

Figure 4.6 Two-way interactions on mean GSR reading for no bike lane condition

Regardless of vehicle speed and ADT, on average, participants' level of stress in mixed traffic had higher peaks per minute than in the bike lane condition. Paired t-tests were used to statistically test the difference between no bike and bike lane environments. The boxplot in Figure 4.7 shows that the average GSR reading for a bicyclist riding in the bike lane condition is 6.57 peaks per minute while a bicyclist riding in the no bike lane condition experiences 7.81 peaks per minute (p-value < 0.001).

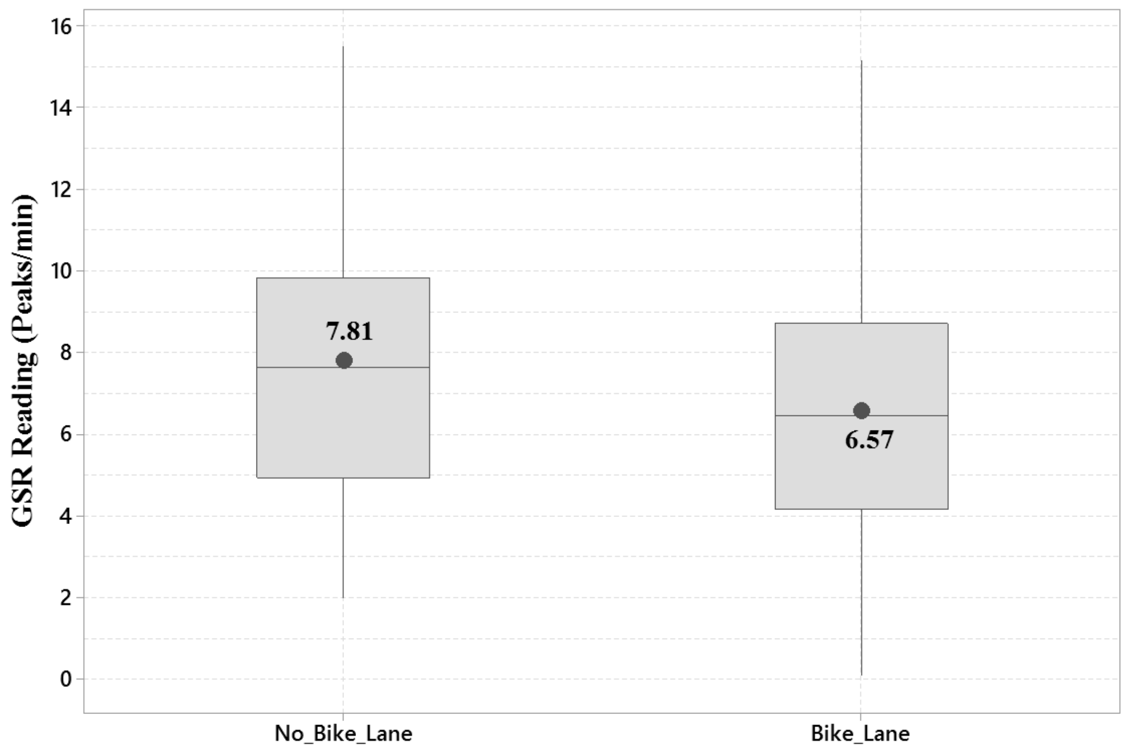

Figure 4.7 Boxplot of GSR reading for no bike lane versus bike lane condition

4.5.2.2 Lateral Position

A modeling approach similar to the one that was followed for GSR was used to estimate the relationship between independent variables and participant's mean lateral position. Both fixed and random effects were included in the model.

The results of the bike lane and no bike lane models are shown in Table 4.4. The random effects were significant for both (Wald Z=4.62, $p < 0.001$, Wald Z=4.63, $p < 0.001$) respectively, which suggests that it was necessary to treat the participant as a random factor in the models.

Table 4.4: Summary of Estimated LMM Models of Lateral Position

Model	Variables	Levels	Estimate	DF	p-value
Lateral Position (Bike lane)	Subject random effect (SD)	-	0.14	-	<0.001
	Constant	-	5.23	47	<0.001
	ADT	High	0.04	333	0.002
		Low	Base Value	-	-
	Speed Limit	45 mph	0.00	333	0.95
		25 mph	Base Value	-	-
	ADT x Speed Limit	45 mph x Low	0.01	333	0.18
		25 mph x Low	Base Value	-	-
Summary Statistics					
R^2	0.76	Observations			384
-2Log Likelihood	-621.69	Subjects			48
AIC	-617.66	Observation/subject			8
Lateral Position (No bike lane)	Subject random effect (SD)	-	0.25	-	<0.001
	Constant	-	5.21	47	<0.001
	ADT	High	0.06	333	<0.001
		Low	Base Value	-	-
	Speed Limit	45 mph	-0.02	333	0.13
		25 mph	Base Value	-	-
	ADT x Speed Limit	45 mph x low	0.04	333	0.02
		25 mph x low	Base Value	-	-
Summary Statistics					
R^2	0.75	Observations			384
-2Log Likelihood	-173.15	Subjects			48
AIC	-169.12	Observation/subject			8

For the bike lane condition, LMM showed ADT was statistically significant (Table 4.4). Results showed that when the traffic volume is low, bicyclists tended to ride in the center of the bike lane; however, while riding with high traffic volume they veered closer to the adjacent parking lane (p-value = 0.002). In comparison, bicyclists' lateral position was not influenced by the vehicle speed. Additionally, the interaction term between vehicle speed and ADT was not significant (Figure 4.8). In Figure 4.8, the y-axis shows mean lateral position in meters. The x-axis shows the two levels of vehicle speed treatment at low and high ADT. Therefore, Figure 4.8 shows the interaction between the levels of vehicle speed (25 mph and 45 mph) and ADT (low traffic volume and high traffic volume). As is shown from the figure, at both speeds the higher the ADT is the higher lateral position became.

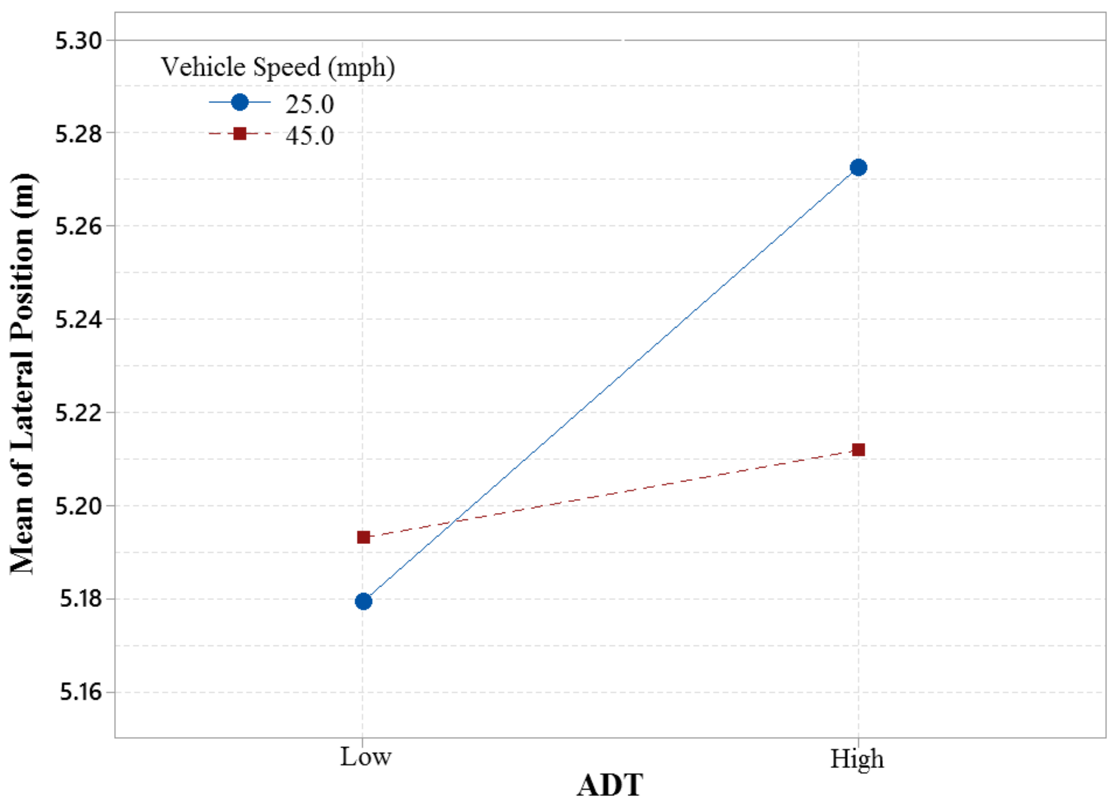

Figure 4.8 Two-way interactions on mean lateral position for bike lane condition

For the no bike lane condition, similar results to the one in the bike lane LMM showed ADT and its interaction with vehicle speed were statistically significant (Table 4.4). Results showed that when the traffic volume is low, bicyclists tended to keep their position to the right of the travel lane; however, while riding with high traffic volume they veered closer to the adjacent parking lane (p-value = 0.002). In comparison, bicyclists' lateral position was not influenced by the vehicle speed. The two-way treatment interaction was statistically significant (p-value = 0.02). Additionally, they were considered in the pairwise comparison for ADT, and vehicle speed variables. Figure 4.9 plots the mean lateral position at each level of ADT (low versus high traffic volume), and vehicle speed (25 mph versus 45 mph). For example, when participants encountering high traffic volume at 45 mph, they had a greater lateral position than when riding with low traffic volume at 25 mph ($p < 0.001$).

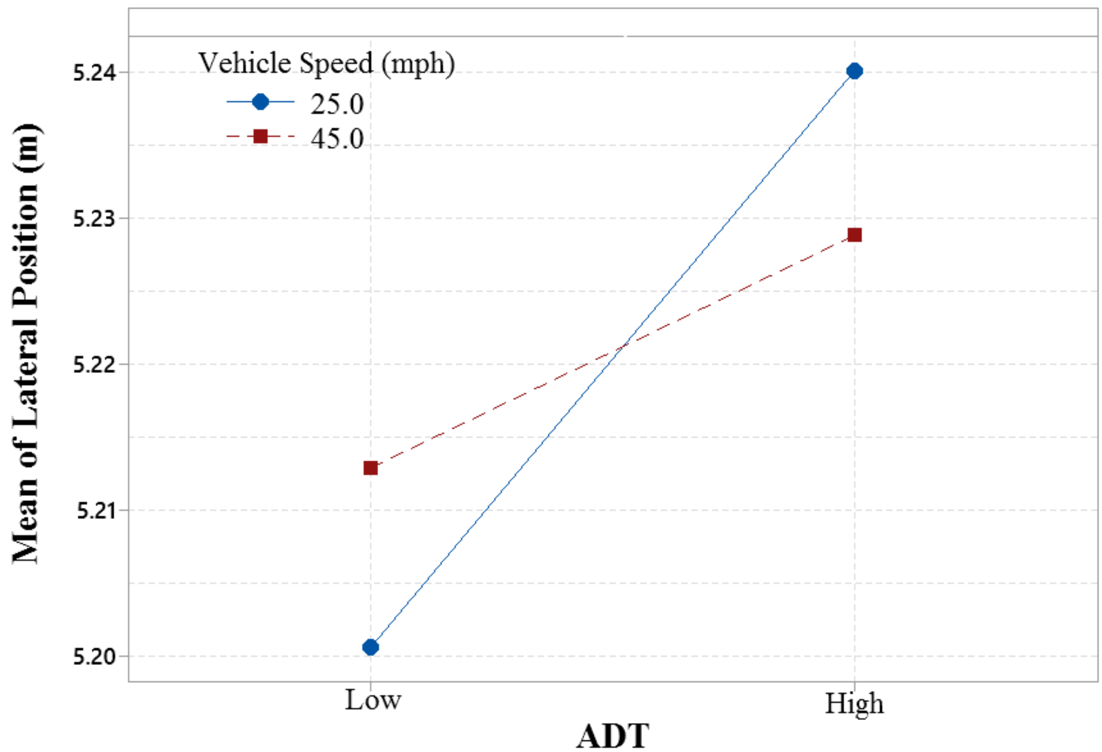

Figure 4.9 Two-way interactions on mean lateral position for no bike lane condition

4.5.2.3 Velocity

A modeling approach similar to the one that was followed for the lateral position was used to examine differences in mean velocity. The results of the model are shown in Table 4.5. The LMM for velocity in the bike lane and no bike lane conditions found both treatment factors (ADT and vehicle speed) were statistically insignificant and thus having no influence on bicyclists' velocity at the 95% confidence level.

Table 4.5: Summary of Estimated LMM Models of Velocity

Model	Variables	Levels	Estimate	DF	p-value
Velocity (Bike lane)	Subject random effect (SD)	-	0.83	-	<0.001
	Constant	-	5.40	47	<0.001
	ADT	High	0.01	333	0.78
		Low	Base Value	-	-
	Speed Limit	45 mph	0.03	333	0.45
		25 mph	Base Value	-	-
	ADT x Speed Limit	45 mph x Low	-0.06	333	0.11
		25 mph x Low	Base Value	-	-
Summary Statistics					
R^2	0.82	Observations			384
-2Log Likelihood	620.03	Subjects			48
AIC	624.06	Observation/subject			8
Velocity (No bike lane)	Subject random effect (SD)	-	0.84	-	<0.001
	Constant	-	5.33	47	<0.001
	ADT	High	-0.02	333	0.45
		Low	Base Value	-	-
	Speed Limit	45 mph	0.03	333	0.42
		25 mph	Base Value	-	-
	ADT x Speed Limit	45 mph x low	0.08	333	0.04
		25 mph x low	Base Value	-	-
Summary Statistics					
R^2	0.86	Observations			384
-2Log Likelihood	515.87	Subjects			48
AIC	519.91	Observation/subject			8

Additionally, the interaction term between vehicle speed and ADT was not significant for bike lane condition (P-value = 0.11). In Figure 4.10, the y-axis shows mean velocity in meters per second. The x-axis shows the two levels of vehicle speed treatment at low and high ADT. Therefore, Figure 4.10 shows the interaction between the levels of vehicle speed (25 mph and 45 mph) and ADT (low traffic volume and high traffic volume). As is shown from the figure, at 45 mph with high traffic volume, bicyclists' velocity is slightly higher than with low traffic volume at the same vehicle speed.

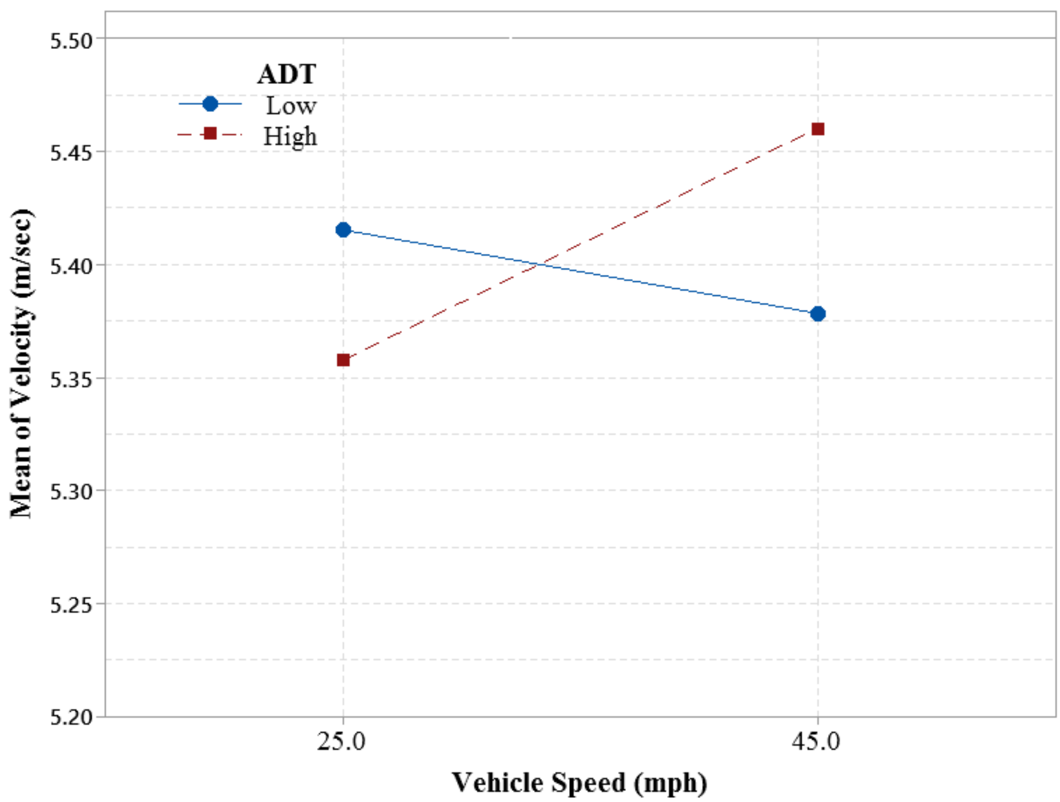

Figure 4.10 Two-way interactions on mean velocity for bike lane condition

The interaction term between vehicle speed and ADT for the no bike lane condition was statistically significant (P-value = 0.04). Figure 4.11 shows the interaction between the levels of vehicle speed (25 mph and 45 mph) and ADT (low traffic volume and high traffic volume). at 45 mph with high low traffic volume, bicyclists' velocity had the higher avearge velocity.

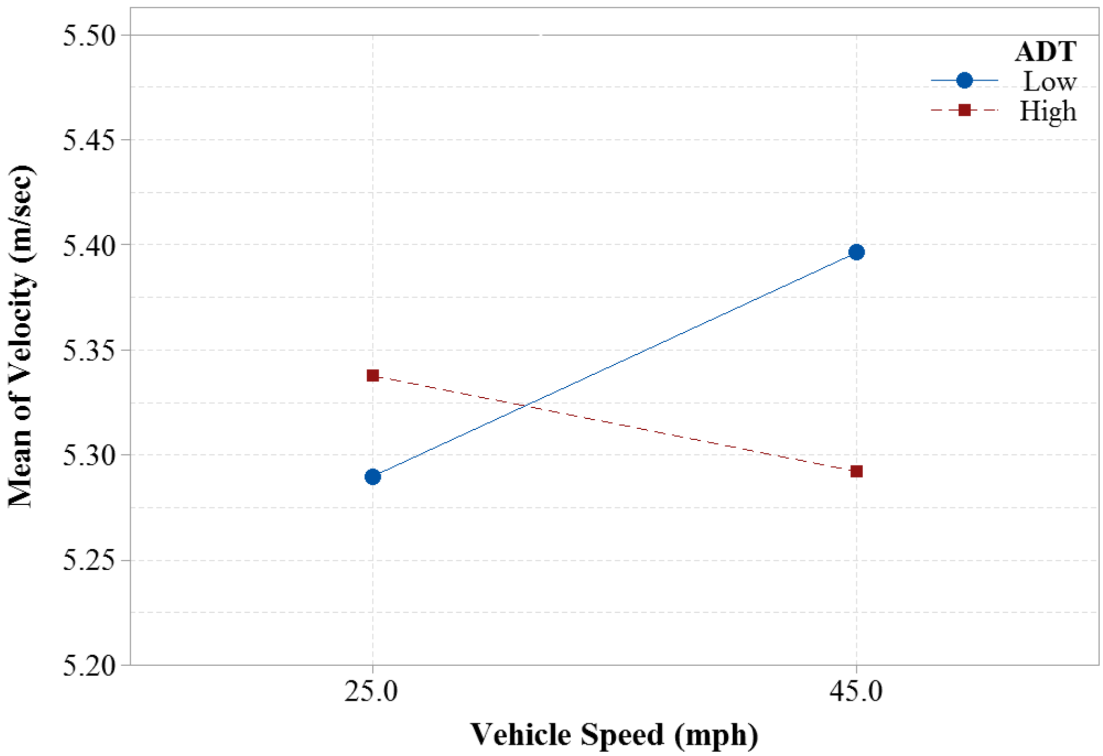

Figure 4.11 Two-way interactions on mean velocity for no bike lane condition

4.5.2.4 Mixing zone effect

Paired t-test results showed that average minimum bicyclist's velocity at the mixing zone in the presence of the conflict with a vehicle is less than when no conflict is present (p-value < 0.001).

4.6 Discussion and Conclusions

The results of this study demonstrate a consistent narrative related to how bicyclists' behavior and levels of stress was influenced by different traffic volumes, adjacent vehicle speed, and conflicts with right-turn vehicle while riding in both bike lane and without bike lane conditions. In terms of the GSR reading, our results showed that bicyclists showed a 1.25 average peaks per minute less when riding in bike lane versus no bike lane conditions. The variation of traffic volume had no influence on bicyclists' level of stress while riding in bike lane condition and this finding was congruent with the LTS methodology that states volume is not a factor that plays influence into stress if bicyclist are given a dedicated bicycle lane adjacent to on-street parking (Mekuria et al., 2012). Additionally, the results indicated that with an increase in vehicular volume in the no bike lane condition that bicyclists stress responses increased, which also follows the LTS methodology (Mekuria et al., 2012). In comparison, the research produced results that conflicted with the existing LTS methodology. Specifically, increasing the speed from 25 to 45 mph in both the no bike lane and bike lane conditions had no effect on bicyclist's stress responses; however, the LTS methodology states that the levels of LTS would increase with the increase of vehicular speed, as shown in Table 4.1. Table 4.6 summarizes the findings of this study.

Table 4.6: Stress Responses based on Varying Roadway Conditions

Mixed Traffic Condition (2-way street with centerline)		
ADT	**Speed**	
	25 mph	**45 mph**
Low (751-1500)	Low GSR	Low GSR
High (3000+)	High GSR	High GSR
Bike Lane Condition (alongside a parking lane)		
ADT	**Speed**	
	25 mph	**45 mph**
Low (751-1500)	Low GSR	Low GSR
High (3000+)	Low GSR	Low GSR

Based on these results, the LTS methodology had good validity for the first couple of measures including volume of vehicles and type of bicycle infrastructure playing significance into bicyclist stress; however, the measures of speed of vehicles adjacent to the bicyclist didn't play influence into bicyclists stress. Therefore, a working definition of the LTS methodology could be reconsidered.

In addition, when bicyclists rode in the bike lane, bicyclists velocity were not affected by the variations in vehicular volume or change in vehicular speed. However, the lateral position was affected by vehicular volume. In mixed traffic conditions, none of the variables influenced bicyclist's velocity. For the lateral position, only the vehicular volume had a significant affect. Finally, the average minimum bicyclist's velocity at the mixing zone in the presence of the conflict with a vehicle is less than when no conflict is present. This indicates that most participants responded to the conflicts and they either reduced their speed or came to complete stop before the conflict happens.

Therefore, recommendations for bicycle facilities should aim to provide striped bike lanes if possible or limit vehicular volumes on roadway. Reducing volumes on the roadway can be accomplished with traffic calming measures or roadway cross-section redesign that aims to prioritize vulnerable road users over vehicles. In addition, it is recommended to provide designs that mitigate this mixing zone conflict that occurs, as it not only makes bicyclists feel less comfortable but requires them to slow down or stop at a critical point of the intersection.

4.6.1 Limitation and Future Work

Although the within-subject design of the bicycling simulator provides the potential for increased statistical power, a potential limitation is fatigue effects, which can cause a participant's performance to degrade over the course of the experiment as they become tired or bored. The order of the scenarios was partially randomized, and riding times were minimized to limit the influence of fatigue effects. In addition, the study was conducted in a simulated environment, which is an abstraction of real-world conditions. Given the limitations, a next step in this research could be to conduct this evaluation in a real-world naturalistic experiment, where bicyclists behavior and stress-responses are measured while riding on the roadway.

5 – CONCLUSION

5.1 Synthesis

This dissertation presented three manuscripts that explored and evaluated factors that influence bicyclists' behaviors and comfort at intersections and on the roadway. The first manuscript (Chapter 2) used an online and intercept-based survey experiment to identify and analyze the comprehension and understanding of BLDF. The second manuscript (Chapter 3) expanded on the evaluation of user understanding and comprehension of novel bicycle technology, BSCT, with an online-based survey experiment. These two initial manuscripts were an effort to attempt to minimize bicyclists from prematurely entering an intersection during a circular red signal indication by developing innovative cycling technology and traffic control devices. The third manuscript (Chapter 4), explores bicyclists behaviors and physiological responses with respect to various roadway conditions and bicycle infrastructure. This work substantially advances the literature and state of knowledge and provides the groundwork for future research in factors that influences bicyclists' behaviors and comfort on the roadway.

5.2 Findings and Applications

The findings from these studies exploring factors that influence bicyclist's behaviors and comfort on the roadway can be categorized into two main areas: Evaluation and Improved Practice.

The three studies *evaluated* bicyclists' preference, comprehension, and comfort to innovative bicyclist's technology, signage, roadway conditions, and infrastructure. The BLDF was better understood, with supplemental signage, and users indicated that they would feel more comfortable about waiting at an intersection with supplemental signage. Users also indicated that they would be more willing to stop and wait at an intersection that provided a BSCT. In addition, the results showed that bicyclists in a bicycle lane had a GSR reading 1.25 peaks per minute less than when cycling in a mixed traffic condition. In addition, when bicyclists rode in the bike lane, GSR and velocity were not affected by variations in vehicular volume or changes in vehicular speed. However, bicyclist lateral position was affected by vehicular volume. When bicyclists were riding in mixed traffic conditions, the GSR reading was not affected by vehicle speed; however, it was affected by the vehicular volume. In mixed traffic conditions, none of the experimental variables influenced bicyclist's velocity. For the lateral position, only the vehicular volume had a statistically significant affect.

These studies provide support for *improved practice* related to cycling technology and infrastructure. The MUTCD dictates currently that BLDF can be used under FHWA requests to experiment (RTE), which includes blue light in backplate with supplemental signage. However, in the few places that the system has been used, signage is purely text based, with the blue light separate from the sign (e.g., either embedded into the black back plate of the signal head or as a supplemental light adjacent to the signal head). Furthermore, bicyclists continue to enter intersections prematurely on red indication due to lack of detection feedback, impatience, and perceptions of adequate gaps in cross traffic. However, the risk of these actions can be improved with improved traffic control devices. Initially, participants of the survey didn't understand the meaning of the BLDF; however, with the implementation of the supplemental signage, the comprehension of the system rose by 40 to 50%. Participants overwhelmingly indicated that that they preferred the sign option that included symbols, text, and the blue dot, in comparison to the sign options that only included symbol and text or text and blue dot. Additionally, participants indicated that they “Strongly Agree” that the supplemental signage helped with the understanding of the purpose of the BLDF, that they would support the system at intersections, and that it made them feel better about waiting at an intersection. It is recommended to use supplemental signage that includes the symbol, text, and blue light as supplemental information for the BLDF.

There is no policy on the use of BSCT; however, Portland has an experimental “Wacht” BSCT. Participants generally understood the purpose of the BSCT, with the highest correct responses associated with the numerical BSCT. Additionally, participants preferred the numerical BSCT, in comparison to the circular and vertical disappearing dot alternatives. While the numerical BSCT was preferred, the MUTCD does not allow for numerical countdown timers on vehicle or bicycle signal heads at signalized intersections; therefore, it is recommended to pursue a request to experiment with BSCT.

There are many policies and methodologies for implementing new bicycle infrastructure; however, often bicycle infrastructure is installed with little empirical evidence to support specific locations within a municipality. Based on the results of the bicycling simulator experiment, bicyclist’s stress response was not affected by the vehicular speed or volume, which indicates that bicyclists generally feel more comfortable while riding in a bicycle lane. Additionally, vehicular speed does not play significant influence into bicyclists’ stress response or behavior; therefore, limiting the amount of traffic provided on the roadway can reduce bicyclists stress levels, even if a bike lane is not present. Therefore, recommendations for bicycle facilities should provide striped bike lanes if possible or limit vehicular volumes on roadway where bicyclists are in mixed traffic conditions through traffic calming measures or implementing roadway cross-section redesign to prioritize vulnerable road users over vehicles.

5.3 Future Work

How bicyclists interact with the roadway is still a shallow topic of research. While the manuscripts in this dissertation contribute to the body of knowledge related to factors that influence bicyclist's behavior and comfort on the roadway, research could expand on this foundational work.

The results of these studies provide a basis for more research related to innovative traffic control devices for bicyclists at intersections and understanding factors that influence bicyclists psychological stress responses. The survey studies conducted were focused on stated preference responses, which limits the ability to see actual bicyclists' behaviors. Surveys are a good way to capture participant's preference and opinion on varying conditions; however, some responses may not directly correlate to actions taken in the field. Further research could evaluate bicyclist's behavior either in a simulated or real-world scenario.

The bicycling simulator study looked at the velocity, horizontal displacement, and physiological responses (i.e. GSR) of bicyclists to determine their comfort based on varying roadway conditions; however, simulated environments can lead to more controlled and tapered results. In an effort to complement this methodological approach, this research could be conducted in a real-world naturalistic experiment, where bicyclist's behavior and stress-responses are measured while riding on the roadway.

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