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An Accident Waiting to Happen: Cognitive Drivers of Unsafe Cycling Behavior

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AN ACCIDENT WAITING TO HAPPEN: COGNITIVE DRIVERS OF UNSAFE CYCLING BEHAVIOR

by

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For my parents and my brother. Thanks for all the love and support.

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ABSTRACT

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Bicycling is a popular method of transportation and recreational activity utilized ubiquitously around the world. In the United States alone thousands of active cycling clubs exist, in addition to the millions of riders who ride independently, and cycling has shown a continual steady increase for decades. As cycling becomes more and more popular, a commensurate increase in cycling accidents and fatalities has also occurred. Regardless of current safety interventions employed hundreds of cyclist fatalities and tens of thousands of cyclist injuries are recorded/reported annually. Cycling accidents are estimated to cost billions of dollars in damages, medical expenses, lost wages, and insurance. The current body of literature may not comprehensively take into account important factors associated with unsafe cycling behaviors and resulting cycling safety efforts may be predicated on this incomplete information. Thus, my doctoral research focuses on investigating cognitive drivers of unsafe cycling behaviors through multiple studies.

Study 1 was a systematic review of the current unsafe cycling behavior literature utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. Emergent themes from this review were incomplete representations of actual behaviors, shortcomings associated with the various methodological approaches employed, and scant understanding of why cyclists choose to ride unsafely. Study 2 utilized an observational approach to identify actual rates of unsafe cycling behaviors across different infrastructure design characteristics. Accident data in conjunction with laws governing cyclists drove the selection of behaviors observed (e.g., failing to stop at a stop light or making an illegal turn), and infrastructure design characteristics (e.g., enhanced pedestrian walkway or staggered t-intersection) were identified via established parameters according to the Department of Transportation. High rates of unsafe behaviors were consistently seen across locations including, for example, failing to stop at a stop light and failing to yield to traffic. Significant differences across locations were, for instance, making an illegal turn and riding in an unauthorized area. Study 3 employed questionnaires to quantitatively examine several cognitive drivers of unsafe cycling behaviors. Factors that impact cyclists' decisions to ride unsafely, as well as unsafe behavioral outcomes, were analyzed using Analytic Hierarchy Process and Policy Capturing methodologies. Results indicated which factors were significant (e.g., if the cyclist is running late or has ample time to reach their destination) and which were not (e.g., the presence or lack of a dedicated bicycle path) within the decision making process to ride unsafely. Finally, the overall results of the studies were synthesized into a policy statement outlining major findings and recommendations to inform future legal, civil, and academic endeavors associated with cycling safety interventions.

CHAPTER 1. INTRODUCTION

Motivation

Bicycling is a popular method of both transportation and recreation around the world. Due to its popularity and ubiquitousness many safety issues arise associated with protecting the cyclists and others with whom they may come into contact. According to the United States Census Bureau (2014) cycling is growing in popularity especially as a means of commuting to and from work. As a result of cycling's rise in popularity there has been a commensurate increase in the number of accidents and injuries. In the years between 1998 and 2013, cycling accidents and hospitalizations resulting from cycling accidents increased by 28% and 120%, respectively (Sanford, McCulloch, Callcut, Carroll, & Breyer, 2015). In 2014, according to the National Highway Traffic Safety Administration (NHTSA), 726 bicycle fatalities were reported. The number of fatalities rose to more than 1000 in 2015 according to the Centers for Disease Control and Prevention (CDC) (2017). Additionally, bicycling related injuries, insurance, damages, lost wages, etc., are estimated to be in the billions of dollars annually (Miller et al., 2004). In 2015 almost 467,000 bicycle-related injuries occurred resulting in non-fatal crash-related lifetime costs and productivity loss of $10 billion (CDC, 2017). Beck and colleagues (2007) suggest bicyclists, relative to passenger vehicle occupants, are 1.8 times as likely of being non-fatally injured and 2.3 times as likely of being fatally injured on a given trip. These statistics underscore both the danger bicyclists face and the importance of cycling safety research as a means of informing and facilitating safety interventions to protect these at risk road users.

The majority of cycling research to date falls into three main categories: (1) equipment usage, (2) environmental/infrastructure factors, and (3) cyclist interactions with other vehicles. Equipment usage typically involves the cycle itself or safety gear such as helmets, including usage, risk reduction, and injury trends (e.g., Attewell, Glase, & McFadden, 2001; Karkhaneh, Rowe, Saunders, Voaklander, & Hagel, 2013; Cossman et al., 2013; Jewett, Beck, Taylor, & Baldwin, 2016; Olivier & Creighton, 2016). Environmental factors may include routes cyclists ride, bike lane characteristics, or other infrastructure design issues associated with safety and risk (Dill & Gliebe, 2008; Ewing & Cervero, 2010; Fraser & Lock, 2011; DiGioia, Watkins, Xu, Rodgers, &

Guensler, 2017; Ng, Debnath, & Heesch, 2017). Interactions between cyclists and other vehicles, particularly motor vehicles, has had much attention as collisions often result in serious injury or death (e.g., Kim, Kim, Ulfarsson, & Porrello, 2007; Reynolds, Harris, Teschke, Cripton, & Winters, 2009). These main areas of cycling literature comprise the majority of safety and injury prevention research efforts. These focal areas tend to exclude the unsafe cycling behaviors of the cyclists themselves. Little is known about unsafe cycling behaviors and how they factor into cycling safety from a holistic perspective. The purpose of this dissertation research is to examine what is known about unsafe cycling behaviors, identify the gaps within the literature, address those gaps with multiple research methodologies, and synthesize the results into holistic recommendations for policy makers to improve cycling safety efforts. This purpose will be accomplished through three phases: (1) conducting a systematic review of the current literature on unsafe cycling behavior utilizing Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, (2) employing observational techniques to assess actual rates of a broad set of unsafe cycling behaviors across varying infrastructures, and (3) utilizing questionnaires to quantify why cyclists choose to ride unsafely as well as what factors influence these choices.

Existing evidence

As seen above, research has been conducted in the area of cycling safety, though little has focused on cyclists' unsafe behaviors. Specifically, few studies have focused on cyclists' decisions to ride unsafely. Those decisions are an important aspect of cycling safety as cyclist behaviors partially dictate how they interact with their environment, motor vehiclists, and pedestrians. In fact, cyclists' unsafe riding behaviors may contribute to the majority of accidents with motor vehicles (Gårder, 1994). Understanding why cyclists decide to break established laws, ride unsafely, or put themselves at risk is an integral component of cycling safety that has gone largely ignored. Researchers, infrastructure designers, and policy makers, intent on developing effective safety protocols and safety interventions, may benefit from a deeper understanding into why cyclists decide to ride unsafely and put themselves at risk. Thus, the first objective of this dissertation is:

Research Objective 1: To systematically examine the current research on bicycling safety involving cyclists' unsafe behaviors following the PRISMA methodology.

To accomplish this objective a systematic literature review was conducted following the PRISMA methodology. Research databases were selected and search criteria utilized to survey and extract articles examining bicycling safety from a behavioral perspective. This study is covered in Chapter 2.

Unsafe cycling behavior literature

The sparse research efforts examining cyclists' unsafe behaviors have employed three primary methodologies: (1) utilizing archival data such as hospital records or police reports to analyze accidents, injuries, or fatalities (e.g., Bíl, Bílová, & Müller, 2010; Yan, Ma, Huang, Abdel-Aty, & Wu, 2011), (2) employing observational methods to analyze unsafe cycling or rule-breaking behaviors (e.g., Huan, Yang, & Jia, 2012; Bai, Liu, Guo, & Yu, 2015), and (3) using questionnaires or interviews to assess perceptions about unsafe cycling behaviors (e.g., Johnson, Charlton, Oxley, & Newstead, 2013; Shaw, Poulos, Hatfield, & Rissel, 2014). All of these methods employed in isolation lack a full view of why cyclists choose to ride unsafely. Archival data, by far the most utilized approach of the three, may suffer from underreporting or reporting bias (DiGioia et al., 2017). Hospital or law enforcement records may not be comprehensive. Not all injuries require medical attention and thus no report would be filed. Similarly, a lack of cycling rule enforcement may dramatically reduce the number of police reports dealing with unsafe cycling behaviors (Beck, 2007). Thus, reported statistics and subsequent behavioral inferences may not accurately reflect the reality of unsafe cycling behavior.

Observational and naturalistic methods have an advantage over archival data in that unreported behaviors may be documented and direct observations allow for actual rates of behaviors whether they go unreported or not. Observational research may reach a large sample size at the cost of few observational locations while naturalistic studies leverage detailed behavioral information across many locations at the cost of a small number of cyclists observed.

Questionnaires and interviews allow for researchers to assess how cyclists and others perceive unsafe cycling rates and antecedents (e.g., Shaw et al., 2014), though outcomes may differ between perceived rates and actual rates when comparing questionnaire data to observational studies.

However, questionnaires and interviews can be advantageous in being able to assess large numbers of cyclists and garner their perceptions about why they choose to ride unsafely.

The above research methodologies fail to provide an accurate representation of how prevalent various unsafe cycling behaviors are. The result is a lack of knowledge about the actual rates of various unsafe cycling behaviors across multiple locations. Thus, the second objective of this dissertation is:

Research Objective 2: To examine the actual rates of multiple unsafe cycling behaviors across multiple locations with varying infrastructure design characteristics.

To accomplish this objective an observational study was conducted. The study utilized several locations with differing infrastructure design characteristics and multiple behaviors were selected to be observed. The observational study can be found in Chapter 3.

Behavioral antecedents

Unsafe riding behaviors contribute to accidents with motor vehicles. Indeed, Yan et al. (2011) found on roadway segments, cyclists were responsible for 62.6% of vehicle-cyclist accidents. Depending on the location (e.g., roadway vs intersection), cyclists' unsafe behaviors may contribute to up to 80% of vehicle-cyclist accidents (Gårder, 1994). Various casual unsafe behaviors have been identified including failure to yield, swerving, or violating traffic control mechanisms such as stop lights (Kim & Li, 1996; Wessels, 1996). Little is known however, about why cyclists choose to ride unsafely. Lavetti and McComb (2014) and Shaw et al. (2014) addressed this issue, via interviews and questionnaires respectively, to elucidate several risk factors explaining why cyclists may ride unsafely (e.g., infrastructure design, confusion about the rules, perceived personal benefit, excitement). Still missing from the literature is an understanding of how cyclists utilize these risk factors in their decision making processes. Moreover, the relative importance of the risk factors associated with choosing to ride unsafely have not been addressed. Thus, the third objective of this dissertation is as follows:

Research Objective 3: To examine risk factors associated with cyclists' decisions to ride unsafely.

Questionnaires were developed to assess what risk factors contribute to why cyclists choose to ride unsafely. The questionnaire consisted of a demographics section, an Analytic Hierarchy Process (AHP) section, and a Policy Capturing (PC) section. AHP is a tool developed by Saaty (1980; 1990) that utilizes pairwise comparisons to establish relative weights among alternatives. PC is a structured approach useful in eliciting respondent judgments when contextual information and corresponding decision options are presented (Cooksey, 1996). Risk factors examined with both methods were derived from findings in Lavetti and McComb (2014) and Shaw et al. (2014). Outcome measures assessed (i.e., the cyclists' judgments) were developed based on observational and archival data on unsafe behaviors (e.g., Yan et al., 2011; Bai et al., 2015). The questionnaire study can be found in Chapter 4.

Synthesis and the larger contribution

This research will contribute to the literature by synthesizing previously utilized methodologies, leveraging the advantages of each, and culminating with recommendations for policy makers based on a holistic view of unsafe cycling behavior. The systematic review of the literature (Chapter 2) contributes by providing concise metadata on unsafe cycling behavior research including trends and gaps. The observational study (Chapter 3) provides a view of the actual rates at which unsafe cycling behaviors occur as well as determining if infrastructure designs influence rates of specific behaviors. The questionnaire study (Chapter 4) assesses why cyclists choose to ride unsafely and quantifies how cyclists prioritize a set of risk factors associated with unsafe cycling behaviors. Finally, findings from these studies are synthesized into a policy statement (Chapter 5) consisting of a set of recommendations that may be utilized within the national Highway Safety Improvement Program (HSIP) and integrated into state level Strategic Highway Safety Plans (SHSP) to enhance programs developed to improve road safety.

CHAPTER 2. STRUCTURED LITERATURE REVIEW

Introduction

Bicycling is on the rise as a recreational activity, form of exercise, and eco-friendly method of transportation and as a result a commensurate increase in cycling accidents has occurred as well. For example, according to the US census, commuting to work via bicycling increased nationally from about 488,000 in 2000 to about 786,000 per year between 2008 – 2012 (United States Census, 2014); between 1998 and 2013 bicycle accidents increased 28% and hospitalizations from cycling accidents rose 120% (Sanford et al., 2015). In 2015, according to the Centers for Disease Control (CDC), over 1000 cyclists died and more than 467,000 bicycle-related injuries occurred resulting in non-fatal crash related lifetime costs and productivity losses of 10 billion dollars (CDC, 2017). Beck and colleagues (2007) suggest bicyclists, relative to passenger vehicle occupants, are 1.8 times as likely of being non-fatally injured and 2.3 times as likely of being fatally injured on a given trip. With the growing numbers of cyclists and commensurate increase in cycling accident rates, cycling safety is of paramount importance in the reduction and prevention of cycling injuries and fatalities.

Cyclist safety has been extensively researched for decades though many of those efforts have focused on equipment usage such as helmets (e.g., Attewell et al., 2001; Olivier & Creighton, 2016) or cyclists' interactions with their environments, such as infrastructure (e.g., Ewing & Cervero, 2010; Fraser & Lock, 2011). Additionally, many studies have examined cycling behavior (e.g., Dill & Gliebe, 2008; Dill & McNeil, 2013). The majority of those studies, however, do not specifically examine unsafe behaviors and instead evaluate non-safety related behaviors (e.g., route choice, riding patterns, and motivation for cycling).

Unsafe cycling behavior warrants further attention as an important component of the overall issue of road safety that contributes to annual injury rates as well as the subsequent costs. These types of inquiries have been few but provide insight into, for example, what rules cyclists choose to violate and their rationale behind those choices. The purpose of this literature review is to systematically examine bicycling safety research involving cyclists' unsafe behaviors following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology.

Methods

Due to the broad nature of the subject area (i.e., bicycling being broad and behavior having multiple interpretations), multiple databases were searched. The selected databases were: Compendex, Engineering Research Database, IEEE Xplore, Inspec, JSTOR, PsycARTICLES, PsycINFO, and PubMed. The following terms were utilized for the searches: (bicycling OR bike OR biking OR bicycle OR bicyclist OR cyclist) AND (safe* OR accident* OR behavior OR crash) AND (traffic OR pedestrian OR risk OR path OR lane OR decision). Additional filters for each database were as follows: Compendex – subject, title, and abstract; Engineering Research Database – Peer reviewed, scholarly journals; IEEE Xplore – none; Inspec – subject, title, and abstract; JSTOR – journals; PsycARTICLES – academic journals; PsycINFO – academic journals; Pubmed – species: human, English. A total of 7678 articles resulted from the search once duplicates were removed with one additional article found through other sources.

Studies were included if they focused on cyclists' unsafe riding behaviors, were not equipment oriented (e.g., helmets or cycle model), had sufficient detail about the unsafe behaviors (e.g., information about the circumstances, fault, or specific behaviors), and utilized quantitative data for analyses. Exclusion criteria included any research focusing on children or adolescent cyclists, any behaviors that were not specifically unsafe behaviors (e.g., equipment usage, route selection, or throughput behaviors), studies focusing on attention instead of the choice to ride unsafely (e.g., visual search and reaction times to road obstacles), studies focusing on weather or visibility instead of cyclist decisions, purely qualitative data analyses, studies focusing on cyclist maneuvers to avoid a collision that did not initiate from the cyclist's fault, and traffic conflicts resulting in normal behaviors due to infrastructure. No date ranges were utilized for the literature search.

The flow diagram for article selection can be seen in Figure 1. Two researchers completed each step independently and then combined their results prior to completing subsequent steps. An initial review of titles resulted in retaining 341 articles; the remaining 7338 were excluded due to being irrelevant to the research purpose, not meeting the inclusion criteria, or meeting exclusion criteria.

The second pass involved evaluation of the 341 article abstracts and resulted in the exclusion of 247 articles based on the inclusion and exclusion criteria. The full text of the 94 remaining articles was reviewed and resulted in 24 articles being retained for the evaluation (including the one additional article found through legacy searches). The extracted data from the 24 selected articles are summarized in Table 1.

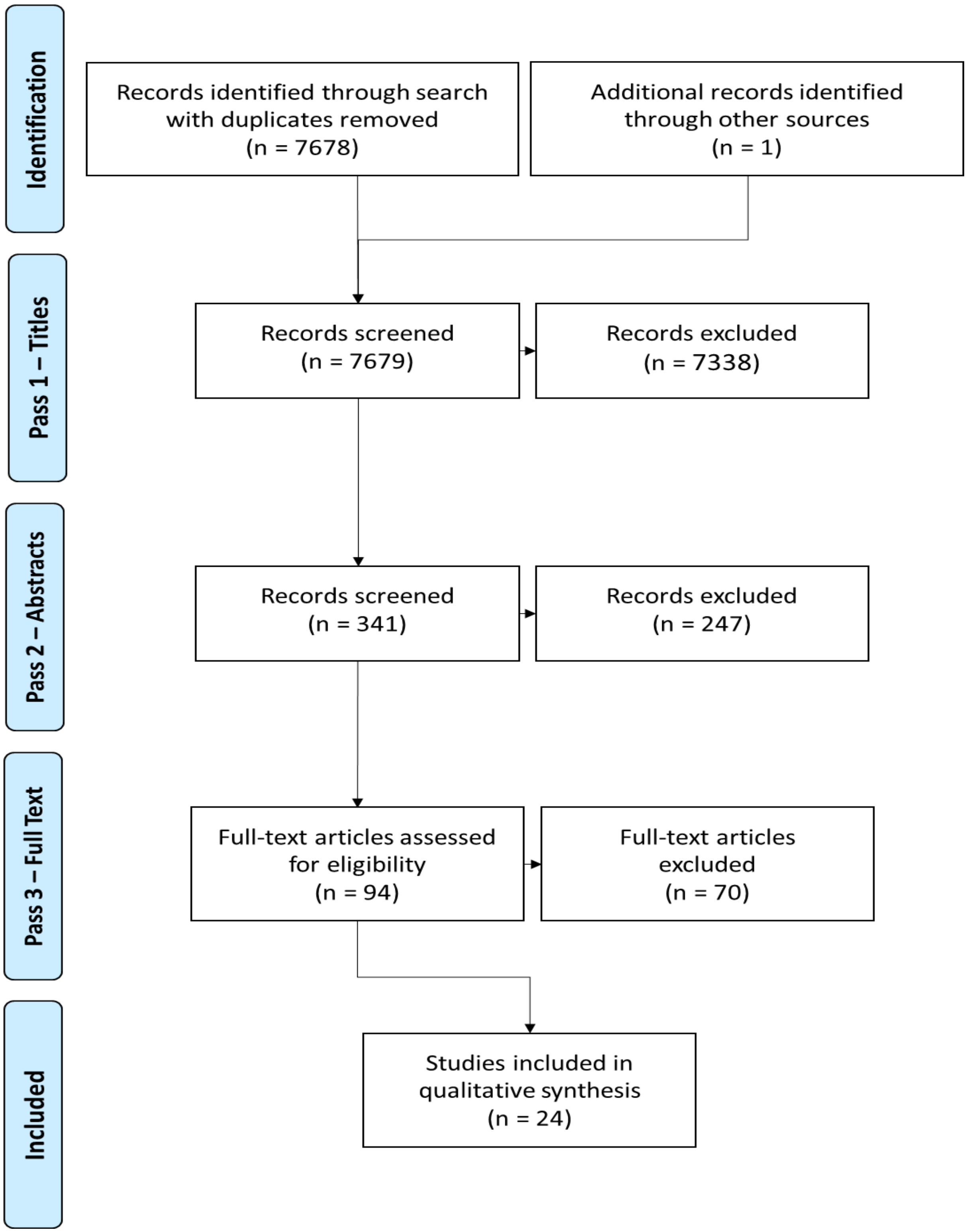

Figure 1. PRISMA flowchart for article selection

Table 1. Description of selected articles

Author(s)	Publication Date	Method Archival	 Observational / Naturalistic	 Questionnaire / Interview	Country	Data Source(s)	Sample	Study Design	Outcomes
Agent, K. R., Zegeer, C. V., & Deen, R. C	1980	✓			USA	Bicycle related motor vehicle accidents from police records	762 bicycle related, motor vehicle accidents	Data was summarized and analyzed for relationships using a Severity Index (SI)	Cyclist characteristics, motorist characteristics, accident characteristics, behavioral characteristics
Bacchieri, G., Barros, A. J., Dos Santos, J. V., & Gigante, D. P.	2010			✓	Brazil	Interviews based on census tracts	43 census tracks, 1133 commuters	Descriptive analyses of cyclists, equipment, and behavioral characteristics	Cyclist characteristics, risky behaviors and safety related variables
Bai, L., Liu, P., Guo, Y., & Yu, H.	2015		✓		China	Observational, video cameras	13 intersections, 6169 individuals (632 e-bikes, 3,990 e-scooters, 1,547 bicycles)	Chi-square tests for comparisons, binary logit models and odds ratios utilized to evaluate explanatory variables on risky behaviors	E-bike, e-scooter, and cyclist characteristics and their associations with risky behaviors
Bernhoft, I. M., & Carstensen, G.	2008			✓	Denmark	Questionnaire	1017 "older" people, 888 people aged 40-49	Chi-square tests for comparisons between younger and older respondents as pedestrians and cyclists, regression analysis on whole data set	Important factors for behavior and route for cyclists and pedestrians, behaviors both groups engage in both pooled and across age and gender
Bíl, M., Bílová, M., & Müller, I.	2010	✓			Czech Republic	Cyclist related accident in police reports	5428 profiles met their criteria	Multivariate logistic regression	Accident demographics including cyclist faults and behaviors
Billot-Grasset, A., Amoros, E., & Hours, M.	2016	✓		✓	France	Rhone Registry medical database	1078 cyclists that had been injured	Accident typology construction and Multiple Correspondence Analysis	17 recurring accident configurations and analyses of the factors involved
Gårder, P.	1994	✓			USA	Police-reported accidents between cyclists and motor vehicles, hospital records	2059 accident reports	Descriptive statistics	Accident and behavioral characteristics of the cyclists and motor vehicles
Huan, M., & Yang, X.	2015		✓		China	Observational, video cameras	619 intersection crossing events	Hazard models were utilized to analyze red light running behavior	Predictive models of red-light crossing covariates
Huan, M., Yang, X., & Jia, B.	2012		✓		China	Observational, video cameras	516 intersection crossing events	Proportional hazard-based duration models utilized	Red light violation behaviors based on waiting times
Johnson, M., Charlton, J., Oxley, J., & Newstead, S.	2010		✓		Australia	Naturalistic, helmet mounted video cameras	13 participants, 127:38 hours analyzed	Descriptive statistics of riding and events	Key variables for 54 observed events (collision and near collision) and descriptions
Johnson, M., Charlton, J., Oxley, J., & Newstead, S.	2013			✓	Australia	Online survey through University and other websites	2061 cyclists	Descriptive statistics and relative odds of characteristics	Reasons why cyclists ran red lights and cyclist characteristics
Johnson, M., Newstead, S., Charlton, J., & Oxley, J.	2011		✓		Australia	Observational, video cameras	4225 cyclists	Descriptive statistics and binary logistic regression	Relative odds of infringement and factors related to the model
Kim, K., & Li, L.	1996	✓			USA	Department of Transportation, Hawaii, crash reports (police collected)	2204 cyclists-motor vehicle collisions	Descriptive statistics and logistic regression	Characteristics of cyclists and drivers as well as collisions
Langford, B. C., Chen, J., & Cherry, C. R.	2015		✓		USA	GPS data bike mounted units	6 bikes, 7 e-bikes	Descriptive statistics and proportions	Cyclist and e-cyclist behaviors at intersections, speeding, and wrong way
Pai, C. W., & Jou, R. C.	2014		✓		Taiwan	Observational, video cameras	12,447 observations: 859 risk-taking, 1170 opportunistic, 10,418 law abiding	Descriptive statistics, and mixed logit model	Estimation results for cyclist intersection crossing behavior
Rowe, B. H., Rowe, A. M., & Bota, G. W.	1995	✓			Canada	Coroner's reports in Ontario	212 coroner's reports	Descriptive statistics	Characterizations of deaths involving cyclists and descriptive statistics broken down across demographics

Table 1 continued

Shaw, L., Poulos, R. G., Hatfield, J., & Rissel, C.	2014			✓	Australia	Questionnaire in NSW Australia	770 transport cyclists	Descriptive statistics, themes for contributing factors examined	Unsafe behaviors and rationale
Terzano, K.	2013		✓		Netherlands	Observational	1360 cyclists	Descriptions of secondary activities, Chi-square tests	Unsafe behaviors and comparisons across groups of secondary tasks and non-secondary task cyclists
Wessels, R.	1996	✓			USA	Washington State Patrol (WSP) collision data base	8540 collision records	Descriptive statistics, Cross/Fisher bicycle-collision classification method	Classifications of accident by location and other variables including behavioral
Williams, A. F.	1976	✓			USA	Police reports on 888 injury-producing bicycle-motor vehicle collisions	888 collision records	Descriptive statistics	Collision characteristics and probable responsibility
Wu, C., Yao, L., & Zhang, K.	2012		✓		China	Observational, video cameras	451 observations (222 e-bike, 229 cyclist)	Descriptive statistics, logistic regression, in depth look at crossing behaviors, time distributions, odds ratio	Red light violation behaviors and predictors, crossing behaviors, time distribution characteristics
Yan, F., Li, B., Zhang, W., & Hu, G.	2016		✓		China	Observational, video cameras	162,124 vehicles, 31,649 pedestrians	Descriptive statistics, poisson regression, adjusted violation rate ratio (VRR)	Red light violation behaviors by road user
Yan, X., Ma, M., Huang, H., Abdel-Aty, M., & Wu, C.	2011	✓			China	Police reports from the traffic accident database in Beijing Traffic Management Bureau	1914 crash records	Multinominal and binary model logit models, crash pattern propensity analysis	Crash characteristics, irregular maneuvers to accidents, roadway characteristics
Yang, X., Huan, M., Si, B., Gao, L., & Guo, H.	2012		✓		China	Observational, video cameras	459 observations	Descriptive statistics, relative hazard ratios, duration model	Model covariate coefficients, survival probabilities vs waiting times

Results

As seen in Table 1, results from the 24 studies reviewed are organized based on differences in data sources. Specifically they fall into three distinct categories: (1) analyzing accidents, injuries, or fatalities using archival data such as hospital records or police reports, (2) analyzing violations or illegal maneuvers using observational or naturalistic methods, and (3) analyzing behaviors using questionnaires or interviews. Eight studies were based on archival data, 11 were observational or naturalistic, and five utilized questionnaires. These differences in foci and methodologies preclude conducting any meta-analyses.

As documented in Table 2, 71.0% of the studies included were conducted in three countries; China, comprising 29.2%, the United States of America (USA) with 25.0% of the studies, and Australia with 16.7%. The studies that took place in China were all observational except one, which was archival. Studies conducted in the USA were all archival except one that was naturalistic. Australian studies were split between questionnaires and observational / naturalistic methods. The remaining 29.2% were distributed among Brazil, Canada, the Czech Republic, Denmark, France, the Netherlands, and Taiwan and across the three research methods relatively evenly.

Table 2. Numbers of articles by country.

Country	Total Number (%)	Method		
		Archival	Observational / Naturalistic	Questionnaire / Interview
China	7 (29.2%)	1	6	
USA	6 (25.0%)	5	1	
Australia	4 (16.7%)		2	2
Brazil	1 (4.2%)			1
Canada	1 (4.2%)	1		
Czech Republic	1 (4.2%)	1		
Denmark	1 (4.2%)			1
France	1 (4.2%)	1		1
Netherlands	1 (4.2%)		1	
Taiwan	1 (4.2%)		1	

Accidents, injuries, or fatalities using archival data

As summarized above, eight of the retained studies examined accidents, injuries, or fatalities documented in archival data such as police reports, hospital records, or some manner of registry available from their countries. These articles covered a broad range of behavioral antecedents resulting in collisions, however, varied greatly with reported percentages of each behavior taking place. Included studies focused on the cyclists' unsafe behaviors (not equipment), had sufficient detail about those behaviors, and contained quantitative data about the behaviors. In the case of archival data, all the identified studies included accident data. Table 3 shows the percentages of accidents, based on archival data, where the cyclists were engaging in behaviors that resulted in or contributed to accidents.

Table 3. Behavioral findings of identified articles based on archival data.

Authors	Date	Violating stop lights, stop signs, or riding through intersection	Riding the wrong way	Swerving, weaving, or turning into path of motor vehicles	Failure to yield, improper turn	Riding where shouldn't be	Speeding	Faulty overtaking	Inattention	Cyclist at fault (all)
Accidents / injuries with archival data										
Rowe, B. H., Rowe, A. M., & Bota, G. W.	1995	11% (fatal accidents)		21% (fatal accidents)		12% (fatal accidents)		1% (fatal accidents)		
Yan, X., Ma, M., Huang, H., Abdel-Aty, M., & Wu, C.	2011	29% (accidents, signal intersection)	5.4% (accidents, road segments)		5.7% (accidents, signal intersections) 12.7% (accidents, non-signal intersections)					35.1% (accidents, signal intersections) 37.5% (accidents, non-signal intersections) 62.6% (accidents, road segments)
Bíl, M., Bílová, M., & Müller, I.	2010				24.4% (accidents)		1.2% (accidents)	1.2% (accidents)		16.0% (accidents)
Agent, K. R., Zegeer, C. V., & Deen, R. C	1980	21.7% (accidents)	9.1% (accidents)	16.3% (accidents, driveway to path of vehicle)	21.7% (accidents, at intersection) 12.4% (accidents, improper left turn)					70% (accidents)
Gårder, P.	1994	4% (accidents)	3% (accidents)		18% (accidents, failure to yield) 3% (accidents, improper turn)				29% (accidents)	80% (accidents, contributed)
Williams, A. F.	1976	22% (accidents)	15% (accidents)	27% (accidents, entering traffic)	1% (accidents, left turn)					78% (accidents)
Kim, K., & Li, L.	1996	2.9% (accidents)	2.2% (accidents)		9.1% (accidents, failure to yield) 1.2% (accidents, improper turn)		1.6% (accidents)	.82% (accidents)		16.5% (accidents)
Wessels, R.	1996	7.7% (accidents)	14.5% (accidents)	5% (accidents, entering or exiting traffic)	7.2% (accidents, failure to yield) 2.9% (accidents, improper turn)					

Violating stop lights or signs was a prevalent cause, cited in seven of the eight articles. Accident rates varied, however, ranging from 2.9% (Kim & Li, 1996) to 29.0% (Yan, et al., 2011) of accidents reported. Failing to yield was another ubiquitous cause of accidents where cyclists were at fault, ranging from a combined total (signalized and non-signalized intersections) ranging from 10.3% (Kim & Li, 1996) to 34.1% (Agent, Zegeer, & Deen, 1980). One study by Williams (1986) reported 1.0% of accidents resulting from a failure to yield but that statistic only included left hand turns. Riding the wrong way or against traffic was cited in fewer studies and with lower percentages, ranging from 2.2% (Kim & Li, 1996) to 15.0% (Williams, 1986). Swerving was cited in only four studies and ranged from a low of 5.0% (Wessels, 1996) to a high of 27.0% (Williams, 1976), though three of the four were above 16.0% (Agent et al., 1980; Rowe, Rowe, & Bota, 1995; Williams, 1976) and one included fatal accidents (Rowe et al., 1995).

The remaining behaviors were sparsely cited, being mentioned in only a few studies. Cyclists riding where they should not be riding resulted in 12.0% of fatal accidents (Rowe et al., 1995). Speeding was accounted for in two studies with accident causal rates of 1.2% (Bíl et al., 2010) and 1.6% (Kim & Li, 1996). Faulty over taking of another cyclist or motor vehiclist was cited in three studies with accident rates ranging from 0.8% (Kim & Li, 1996) to 1.2% (Bíl et al., 2010), as well as accounting for 1.0% of fatal accidents (Rowe et al., 1995). Lastly, cyclist inattention was cited as the cause for cyclist-at-fault accidents 29.0% of the time (Gårder, 1994).

Several studies reported accidents by which party (e.g., cyclist or motor vehicle) was responsible or at fault. Two articles found that cyclists were at fault for all reported accidents involving a cyclist around 16.0% of the time, with 16% of the time and 16.5% of the time being cited (Bíl et al., 2010; Kim & Li, 1996). Three studies found cyclists to be at fault the majority of the time (e.g., more than 50.0%) in accidents involving a cyclist, accounting for 70.0% (Agent et al., 1980), 78.0% (Williams, 1976), and 80.0% (at least contributing as opposed to full fault) (Gårder, 1994). The final study citing cyclists being at fault overall broke it down by type of location; with 35.1% for accidents occurring at signalized intersections, 37.5% at non-signalized intersections, and 62.6% on roadway segments (Yan et al., 2011).

Violations using observational or naturalistic methods

Eleven studies focused on violations of rules utilizing observational or naturalistic methods, typically using video recording or Global Positioning System (GPS) tracking technology. These studies fell into two groups; three focused on overall behaviors and eight focused on red-light running behaviors, and are summarized in Table 4. The observational or naturalistic studies that focused on overall behaviors accounted for them very differently. Johnson, Charlton, Oxley, & Newstead (2010) conducted a naturalistic study that examined overall behavior and cited when cyclists were at fault for collisions or near-collisions observed. In these studies, cyclists accounted for 9.2% of all incidents observed (with an additional 3.7% being of unknown fault and 87.0% being motor vehiclist fault). The pre-event (e.g., collision or near-collision) behaviors for the cyclists were found to be unsafe and illegal in 3.7%, safe but illegal in 1.8%, unsafe but legal in 7.4% of incidents, and safe and legal 87.0% of the time.

Table 4. Behavioral findings of identified articles based on observational or naturalistic data.

Authors	Date	Violating stop lights, stop signs, or riding through intersection	Cyclist at fault (all)	Other
Violations with observational / naturalistic data				
Johnson, M., Charlton, J., Oxley, J., & Newstead, S.	2010		9.2% (all incidents) 3.7% (unknown fault, all incidents) Pre-event behavior Unsafe and illegal 3.7% Safe but illegal 1.8% Unsafe and legal 7.4%	
Langford, B. C., Chen, J., & Cherry, C. R.	2015	80% (slow speeds, 6kph) 20%-30% (high speeds, 12kph)		
Johnson, M., Newstead, S., Charlton, J., & Oxley, J.	2011	6.9% of cyclists infringed (ranging from 3.9% to 13% across 10 sites) Left turn was most common infringement (57.3% of violators)		
Huan, M., Yang, X., & Jia, B.	2012	79.07% of cyclists ran the red light Average waiting time of violator was 10.8 seconds Average waiting time of non-violator was 15.5 seconds Waiting time increases violation inclination 55% of cyclists at right of violation 5% can obey the rules after waiting 51 seconds		
Bai, L., Liu, P., Guo, Y., & Yu, H.	2015	18.7% cyclists stopped beyond the line (lower than e-bikes and e-scooters)	19.9% all risky behaviors (cyclists, lower than e-bikes or e-scooters)	0.2% cyclists riding the wrong way (lower than e-bikes or e-scooters)
Wu, C., Yao, L., & Zhang, K.	2012	55.9% total violated red light (46%-61% across sites) E-bikes 62% vs 50% cyclists Number of riders waiting upon arrival and at light across significantly affected red light running behavior ($p<.01$ and $p<.001$ respectively) Cyclist crossing behavior: 28% risk taking, 23% opportunistic		
Yan, F., Li, B., Zhang, W., & Hu, G.	2016	18.74% cyclist violation (highest for total across all categories but similar to motorcycles 18.64 and pedestrians 18.54)		

Table 4 continued

Yang, X., Huan, M., Si, B., Gao, L., & Guo, H.	2012	64.27% of cyclists violated the red light Average waiting time 25.16 seconds Average waiting time of violators 15.71 Average waiting time for normal crossing 43.14 Covariates significant at p<.001, waiting number, crossing number, twice crossing		
Huan, M., & Yang, X.	2015	51.70% of cyclists ran the red light Average waiting time of violator was 28.06 seconds Average waiting time of non-violator was 54.53 seconds Predictive models estimated: Gender Waiting position Traffic volume		
Terzano, K.	2013		Percent unsafe behavior: 20.8% No secondary behavior 42.9% Smoking 46.0% Music 50.0% Other 50.5% Talking 51.1% Cell phone	19.4% distracted hesitated before entering, 14.2% non-distracted did Performing secondary task increased overall unsafe behavior (48.9% total, 43%-51% depending on task) vs non-secondary behavior (20.8%) Performing a secondary task related to cyclist behavior forcing others to avoid them (18% non-secondary vs 48.1% secondary)
Pai, C. W., & Jou, R. C.	2014	6.9% of cyclists took risks crossing 9.4% were opportunistic		

Terzano (2014) examined distracting secondary behaviors and how they contributed to overall unsafe behaviors. A secondary task could include smoking, listening to music, talking, or using a cell phone. According to the study, of the people not performing a secondary task only 20.8% engaged in unsafe behavior while 48.9% of the people engaged in a secondary task did engage in unsafe behavior. Bai et al. (2015) conducted a behavioral comparison across traditional bicycles, electronic bikes (e-bikes), and electronic scooters (e-scooters). With regard to red-light stopping behavior they found 18.7% of cyclists stopped beyond the line (which was lower than the other two conditions). They also found cyclists rode the wrong way at a lower rate than the other two vehicle types at only 0.2%. For overall risky behaviors, cyclists were found to be the lowest of the three groups, at 19.9%.

The remaining eight observational studies focused primarily on red-light running behaviors and they reported a large range of violations. The lowest rates reported were 6.9% (Johnson, Newstead, Charlton, & Oxley, 2011), 16.3% (6.9% risk-taking crossing and 9.4% opportunistic crossing) and 18.7% (Pai & Jou, 2014; Yan, Li, Zhang, & Hu, 2016). The remaining six studies ranged from 51.7% (Huan & Yang, 2015) to as high as 80.0% (Langford, Chen, & Cherry, 2015). Two groups of researchers went further to examine the average waiting time before violating a red-light (10.3 seconds and 15.7 seconds) vs not violating (15.5 seconds and 43.1 seconds) (Huan, et al., 2012; Yang, Huan, Si, Gao, & Guo, 2012). Additionally, several researchers identified variables that may increase the likelihood someone would violate a red-light, including number of people waiting and crossing volume (Huan et al., 2012; Yang et al., 2012; Huan & Yang, 2015).

Behaviors using questionnaires or interviews

Five studies used questionnaires or interviews as their primary methods and centered around overall cycling behavior (summarized in Table 5). All behavioral rates reported within the questionnaire and interview studies were self-reported. Red-light or stop sign running behavior were cited in three studies. Two of the three studies found similar violation rates, with 37.3% and 38% (Johnson et al., 2013; Bacchieri, Barros, Dos Santos, & Gigante, 2010) and the third found varying rates depending on demographics ranging from 1.0% for older females to 31% for younger males (Bernhoft & Carstensen, 2008). The behavior of riding the wrong way was found in one study to range from 25.5% (wrong side of the road) to 38.4% (wrong way on a one way) (Bacchieri et al., 2010), and in another study to range from 18.0% for older females to 36.0% for younger males (Bernhoft & Carstensen, 2008). Riding where the cyclists should not be (e.g., a sidewalk) was much higher with one study citing 33.5% (Bacchieri et al., 2010) and another ranging from 31.0% for older males to 53.0% for younger females (Bernhoft & Carstensen, 2008). Speeding was examined in two studies resulting in 14.0% (Bacchieri et al., 2010) and 25.1% of accidents according to questionnaire respondents (Billot-Grasset, Amoros, & Hours, 2016). Finally, Shaw et al. (2014) examined the frequency of violating any rules and reported the top reasons for these violations. Specifically, 5.0% of respondents said they never violate any rules, 40.0% said rarely, 41.0% said sometimes, and 13.0% said often. The self-reported top reasons for violating the rules were infrastructure design, the behavior of other road users, speeds of the motorized traffic, perceived personal benefit to the cyclists, and excitement.

Table 5. Behavioral findings of identified articles based on questionnaires or interviews.

Authors	Date	Violating stop lights, stop signs, or riding through intersection	Riding the wrong way	Riding where shouldn't be	Speeding	Cyclist at fault (all)	Other
Behavior with questionnaires / interviews							
Billot-Grasset, A., Amoros, E., & Hours, M.	2016				25.1% (accidents)		3.9% no light or reflectors at night (accidents)
Johnson, M., Charlton, J., Oxley, J., & Newstead, S.	2013	62.7% of respondents said they did not infringe on red lights 32% because they turned left (Australia but still an infringement) 24.2% because light did not detect them 16.6% infringed because no other traffic or pedestrians 10.7% pedestrians crossing 16.5% for other reasons					
Shaw, L., Poulos, R. G., Hatfield, J., & Rissel, C.	2014					Frequency of breaking rules: Never ~5% Rarely ~40% Sometimes ~41% Often ~13%	Top reasons: Infrastructure design Behavior of other road users Speed of motorized traffic Perceived personal benefit Excitement
Bernhoft, I. M., & Carstensen, G.	2008	~99% older females never do ~95% older males never do ~75% younger females never do ~69% younger males never do	~82% older females never do ~78% older males never do ~66% younger females never do ~64% younger males never do	~66% older females never do ~69% older males never do ~47% younger females never do ~55% younger males never do			Stop before turning Left: ~71% older females never do ~44% older males never do ~43% younger females never do ~21% younger males never do
Bacchieri, G., Barros, A. J., Dos Santos, J. V., & Gigante, D. P.	2010	38%	38.4% (wrong way one way) 25.5% (wrong side of road)	33.5% (sidewalk)	14%		7% swerving 14% failure to yield

Discussion

The purpose of this literature review was to systematically examine the existing research on unsafe bicycling behaviors utilizing the PRISMA methodology. Results of the identified articles yielded several findings. First, people elect to ride unsafely as demonstrated across all articles analyzed. Second, few of the identified studies assess why cyclists ride unsafely, which may be an important component of future mitigations or interventions. Third, the examination of unsafe cycling behaviors has employed three distinctive methodologies and approach each with pros and cons. Finally, cycling unsafe behavior research is mostly prevalent across three locations; USA, China, and Australia, each with a specific methodology that is utilized more than others in each country. This research is the first systematic literature review of unsafe cycling behaviors following the PRISMA methodology and may provide a platform for further investigatory endeavors aimed at making the roads a safer place for the cyclists and others who share them.

Overall behaviors

Many unsafe behaviors were reported across the articles. The most prevalent were violating traffic control devices (e.g., stop lights and stop signs), riding the wrong way, and failing to yield. Interestingly, rates varied across studies. Two reasons for this eventuality may be plausible: (1) subjectivity of characterizing behaviors and (2) methodology used which will be discussed extensively in a subsequent section. Characterizing behaviors has a degree of subjectivity involved as some behaviors are clearer than others such as running a traffic light vs failing to yield. Running a traffic light is a very clear behavior and researchers may experience little, if any, confusion regarding what constitutes a violation. Failing to yield, conversely, may be more difficult to assess because meeting the requirement of “failure” may be contingent on the perspective of the data gatherer or a result (i.e., accident). That is, if a cyclist could have yielded but did not and no accident ensued then a degree of subjectivity may exist in determining if, for instance, the behavior was a failure to yield or if no yield was required. Regardless of the reasons, the existing data strongly indicated that cyclists engage in a slew of unsafe behaviors. Yet, the magnitude of the potentially problematic behaviors cannot be captured.

Drivers of unsafe cycling behaviors

Assessing the rationale for riding unsafely may be an important component of overall cycling safety. Cyclists ride unsafely causing accidents, injuries, and fatalities as seen within the archival data. Cyclists engage in unsafe behaviors very frequently as demonstrated by observational research. Understanding their rationale for doing so may factor into designing more effective safety interventions including the design of infrastructure or writing cycling policy or laws. Interviews and questionnaires do allow researchers to assess the perceived reasons why cyclists chose to ride safely. Indeed, two of the studies reviewed demonstrate the utility of understanding cyclists' rationales. First, Shaw et al. (2014) asked the respondents to list their top reasons for breaking rules and riding unsafely. The reasons included infrastructure design, other road users' behaviors, speed of traffic, perceived personal benefit, and excitement.

In the second study, Johnson et al. (2010) took a naturalistic approach to analyze cycling behavior and broke down pre-event (e.g., accident or near accident) cyclist behaviors into three categories; unsafe and illegal, safe but illegal, and unsafe but legal. This categorization is interesting because a cyclist may be forced to violate a rule to protect themselves from harm (e.g., make an illegal turn to avoid a collision with a motor vehicle). Alternatively, a cyclist may violate a rule and be completely safe (e.g., riding on a sidewalk without any pedestrian traffic). They both may be considered safe violations but the former is a necessity to avoid harm while the latter may be due to convenience or, in that specific instance, a lack of knowledge about rules prohibiting cycling on sidewalks. These distinctions may be useful regarding cycling safety research by delineating the differences between actual and perceived safety. The distinctions may also be integral to rule design and behavioral interventions (e.g., education) by providing insight into possible legal language or rule enforcement (e.g., when a violation is necessary for the safety of the cyclist).

In summary, few of the examined studies evaluated why cyclists chose to ride unsafely. Nevertheless, this line of inquiry is extremely important for enhancing both education and safety mitigation policies. First, some of the unsafe behaviors may be attributable to a lack of cyclists' knowledge about what constitutes unsafe practices or self-awareness about their own behaviors. Self-awareness may be particularly problematic because the results from the questionnaire/interview studies suggest that cyclists do not believe they are riding unsafely, whereas, the rates identified through the archival and observational/naturalistic studies suggest they are. Examining this disconnect may identify opportunities for helping cyclists become more aware of their behaviors and educating them about the potential consequences associated with their actions. Second, efforts are in place in many locales to enhance cycling safety (e.g., constructing cycling lanes, informing cyclists about safe practices), yet the rates of occurrence are still very high. These efforts, however, may fall short because those designing them may not incorporate a comprehensive view of cyclists and their actions. Thus, an understanding about what drives unsafe behaviors is needed to devise meaningful safety measures.

Methodology

The methodologies employed fall into three main categories: (1) the examination of cyclist accident, injury, or fatality data using archival sources, (2) the identification of cyclist behaviors in real world situations using observational or naturalistic methods, and (3) the collection of cyclists' perspectives collected through interviews or questionnaires. These approaches are summarized in Table 6. Archival data (e.g., accident reports and hospital records) are plentiful and provide access to very detailed demographic information and potential event antecedents if recorded. Archival data are also relatively easy to get and can make gathering large data sets less cumbersome than other methods (e.g., sending out many questionnaires). The main issues with archival data are that it only captures accidents or injuries being reported and may not be accurate and/or complete. Moreover, variability exists across municipalities as to when a police report is to be filed. For example, a minimum amount of property damage (e.g., $500.00 damage to car if a collision takes place) may be required before a police report is filed in one city, but these thresholds may differ across municipalities. In both cases the report will not be generated if the thresholds are not met meaning the accident will not be documented at all. This approach causes three issues with the data: (1) some accident data may be missing because thresholds were not met, (2) comparisons across datasets may be inaccurate because of differences in reporting rules, and (3) subjectivity of the report writer may lead to inconsistencies across reports. Additionally, police reports capturing rule violations or unsafe acts are only generated if the rules are enforced by police. According to Beck (2007) a lack of bicycle rule enforcement is a very large problem that is quite common. If rules are not being enforced then records cannot exist, ergo any unsafe behaviors not resulting in reports are not included in the data sets. Thus, while archival data may be detailed, it is likely incomplete, inconsistent across organizations, and may not reflect actual rates of unsafe cycling behaviors.

Table 6. Pros and cons of different data collection methods for bicycling.

	Pros	Data Collection	Cons
Archival	Large number of data points	Hospital reports (injuries)	Reliant on injury or accident being reported or meeting criteria (e.g., more than $300.00 damages)
	Very easy to get large data sets	Police reports (accidents)	May be lacking behavioral pre-event data
	Demographic information may be detailed	Local or regional governmental agencies (combination)	Subjectivity on the part of the report generators
Observational / Naturalistic	Very large numbers of observations possible	Observations or video recordings of specific locations	Observation locations typically limited to only a few or small data sets for naturalistic studies
	Very detailed GPS or video data possible	GPS bike mounted devices	GPS data may not provide environmental variable information
	Allows for potentially detailed behavioral information	Video recording bike mounted devices	Observers may subjectively determine if some behaviors took place or not
Questionnaire / Interview	Allows for potentially wide breadth of data and/or behaviors	Town registry or snowball sampling for distribution and/or recruitment	Data points based on self-report
	Very detailed demographic information possible	Distribution and/or recruitment from archival accident data	Response rates may be low
	Opportunities to expand upon responses or clarify		Relies on perception of respondents which are subjective

Observational study designs allow for large data sets with detailed behavioral information, typically using a video recording device mounted in a specific location such as an intersection (e.g., Bacchieri et al., 2010; Yang et al., 2012). However, the number of locations tends to be small, which may impact generalizability. For example, many of the studies reviewed herein that focused on a specific type of violation (e.g., red-light running behaviors) and utilized a small number of intersections and intersection configurations, which makes generalizing behaviors observed at a specific subset of configurations to all configurations difficult. Additionally, there is a degree of subjectivity by the observers as to what may or may not constitute a behavior (e.g., yielding vs failing to yield if there was no resulting conflict). Finally, very little, if any, reliable demographic information can be collected through observations alone. The observers may attempt to gauge the gender and approximate age of the cyclists but accuracy would certainly be an issue. Other demographic data (e.g., economic status) would be infeasible to glean from video. Naturalistic studies (e.g., Johnson et al., 2010; Wu, Yao, & Zhang, 2012) utilizing GPS devices or bike mounted cameras allow the researchers to observe myriad cyclist behaviors. The researchers could also record demographic information about the cyclists when data collection equipment is distributed. This approach allows for a broader range of locations and behaviors, limited only by where and how the cyclist chooses to ride. The tradeoff is that these samples are typically small in number and the devices must be attached to a single cyclist for an amount of time sufficient to gather meaningful observations. The data then needs to be extracted from the devices, coded, and analyzed requiring large time investments. The result is that the number of cyclists included in the research studies are far fewer than in observational studies conducted at static locations such as intersections, but the data collected would be much more comprehensive.

Questionnaires and interviews allow for collecting information spanning the entire gamut of behaviors, expanding upon or seeking clarification regarding cycling behaviors, and facilitate the collection of meaningful demographic information. Unfortunately this approach does not measure what the cyclists actually do but their perceptions of what they do, and thus are subjective. The cyclists may inaccurately gauge how often they ride unsafely or may not even consider some behaviors or violations to be unsafe. Moreover, these rationales may differ across cyclists. These incongruities may be alluded to by rule infringement rates in questionnaire and observation studies. Whereas questionnaire data suggests most cyclists do not break rules and if they do it is not often, observational data suggests rates of rule infringement can be extremely high depending on the violation. For example, Shaw and colleagues (Shaw et al., 2014) found that 45% of respondents said they rarely or never violate rules while Bernhoft and Carstensen (2008) found between 69% and 99% of respondents (depending on age and gender) said they never violate a stop light or stop sign. These findings contradict the observational findings that estimate much higher levels of unsafe behaviors. For example, Wu and colleagues (Wu et al., 2012) and Yang et al. found that 55.9% and 64.3% of observed cyclists violated stop lights, respectively.

As demonstrated above, the various methodological approaches have advantages and disadvantages, yielding differing types of information (e.g., reported accident statistics, actual rates of unsafe behaviors, perceptions of behaviors) and in some cases contradictory findings (e.g., perceived low rates of occurrences reported in questionnaires vs actual high rates documented in observational studies). Disparate results from the various methods make comparisons difficult and do not facilitate a holistic view of unsafe cycling behavior.

Article country of origin

The country in which the research was conducted and the types of studies follow a trend. China, the United States, and Australia comprised nearly 71% of the total studies examined in this review. Researchers in each country tended to utilize a single methodology for the majority of the research. Specifically, the Chinese studies were 86% observational, the US studies were 83% archival, and Australian studies were 50% questionnaire based. It is not inconceivable that rules, violations, enforcement, and even unsafe cycling trends differ from country to country; however, no unsafe cycling multi-country comparative analysis was identified through the search conducted for this review. Moreover, differences in methodological foci make cross-country comparisons difficult.

Limitations

As with the examined cycling literature, some limitations exist within this review. First, the search strategy was designed to be fully encompassing, however, it is possible terminology was used or articles exist that were not included. For example, the search terms only used American English and did not take into account different spellings of words (e.g., behavior vs behaviour). While it is possible articles were missed, the researchers did cast a wide net, including a title only review of 7678 articles. Second, the inclusion and exclusion criteria could have precluded the addition of some articles that provided insights into behavior or behavioral rationale. A degree of subjectivity exists when applying the inclusion and exclusion criteria though the researchers attempted to be comprehensive with regard to unsafe cycling behavior terminology. These limitations do not detract from the utility of the findings reported in this systematic review, particularly as a basis for further investigation into the area.

Conclusion

Bicycling is a popular recreational activity, form of exercise, and means of travel and has seen an increase in popularity in recent years. The increase in cycling has resulted in an increase in both bicycling related injuries and the costs associated with them. The costs incurred by unsafe cycling demonstrate why further attention to cycling safety research, specifically unsafe cycling behaviors, is needed to increase road safety. Few studies, however, have focused on cycling safety from the perspective of bicyclists' unsafe riding behaviors. Those behaviors have been identified in this systematic review as contributing factors to cycling injuries and economic costs associated with accidents. Nevertheless, more research is necessary to (1) accurately represent how frequently cyclists engage in unsafe acts, (2) understand what drives cyclists to commit unsafe acts, and (3) conduct multimethod, multicountry studies that will provide more comprehensive views of cyclists' behaviors. Findings from such investigations have the potential to better inform cyclists, policy makers, and infrastructure designers as they work to make cycling safe for cyclists and those around them.

CHAPTER 3. OBSERVATIONAL STUDY

Introduction

Bicycling is a popular method of transportation and recreational activity utilized ubiquitously around the world. In the United States alone thousands of active cycling clubs exist, in addition to the millions of riders who ride independently. Cyclists range from small children to the elderly and everything in between. To govern these cyclists and protect their wellbeing, laws are in place at the local and state levels. These rules are meant to protect not only the cyclists themselves but pedestrians and motor vehicle operators who share the environment with the cyclists (Bush, 2012). Examples of these rules may include requiring cyclists to adhere to the same traffic signals as motor vehicles or ride in designated areas to protect nearby pedestrians. Even with established regulations and recommendations in place to protect cyclists, safety remains a grave concern. The National Highway Traffic Safety Administration (NHTSA) estimates that in 2014, 726 cyclist fatalities and 50,000 injuries occurred (www.pedbikeinfo.org). The total annual cost of cycling injury and death is estimated to be in the billions and is comprised of damages, medical expenses, lost wages, insurance, etc. (Miller et al., 2004). These statistics are used to indicate the prevalence and costs of cycling injuries and deaths. Yet, simply looking around while in any major city or on a college campus may lead one to conclude that these statistics do not adequately represent the actual rates of unsafe cycling behavior or opportunities for collisions.

The current body of literature focusing on cycling safety mainly targets equipment design and usage as well as interactions between cyclists and their environments. Common themes are helmet safety (e.g., Cossman et al., 2013; Jewett et al., 2016), the impact of helmets on injuries (e.g., Attewell et al., 2001), environmental factors (e.g., Dill & Gliebe, 2008), and interactions with motor vehicles (e.g., Pradhan et al., 2005). These areas of study, while important, do not focus on the behavior of the cyclists as they engage in normal daily activities. The purpose of this study is to examine the occurrences of multiple unsafe cycling behaviors and how they manifest across different infrastructure designs. For the purposes of this research unsafe cycling practices are any behaviors that violate a rule, regulation, or recommended safe practice, and may put the cyclists, pedestrians, and/or motor vehicle drivers in harm’s way. These rules may include, but are not limited to, state level statutes, city ordinances, campus regulations, and Department/Bureau of Motor Vehicles established safety protocols. Infrastructure design refers to those components that comprise the cycling environment based on principles and definitions within the Department of Transportation Design Manual.

Unsafe cycling behaviors

Cycling safety, specifically examining unsafe cycling behaviors, has been examined by researchers across three categories, observing cyclists' unsafe acts or rule violations (e.g., Terzano, 2013), cyclist accident or injury statistics utilizing archival data (e.g., Bíl et al., 2010), and assessing perceived behaviors with questionnaires (e.g., Shaw et al., 2014). The unsafe cycling behavior studies using observational or naturalistic methods provide a glimpse into the magnitude of cyclists' behaviors but suffers from several limitations. Specifically, the majority of these studies focus on red light running behaviors such as failing to stop at stop lights or not waiting until the light changes to green (e.g., Johnson et al., 2011; Langford et al., 2015). While some studies included a wider breadth of unsafe acts beyond red light running behavior (e.g., Johnson et al., 2010), they often suffer the limitation of small sample sizes. Thus, more research may be needed to assess the myriad unsafe riding behaviors cyclists engage in aside from red light running.

Studies based on accident data, provide limited information about unsafe cycling behaviors when accidents do not occur, but allow researchers to gain insight into accidents resulting in injury or death and the circumstances that contributed. Unsafe cycling behavior studies using questionnaires generally focus on cyclist self-reports about their perceived behaviors and rule adherence. According to results of these studies cyclists do not believe they often violate rules (e.g., Bernhoft & Carstensen, 2008), in contradiction to findings reported in observational studies (e.g., Yang et al., 2012). For example, Bernhoft and Carstensen (2008) found that 69.0% to 99.0% of respondents, depending on demographic group, stated they never violated traffic control devices while Yang et al. (2012) observed 64.29% of cyclists did. The above methods used for unsafe cycling behavior research may fail to capture actual rates of unsafe behaviors due to including only small sets of behaviors, not utilizing multiple locations, relying on archival reports, or measuring only perception. Thus, more research is needed to determine the actual prevalence and breadth of unsafe cycling behaviors that may or may not result in reportable events.

Infrastructure design

An additional focus of researchers is the impact of infrastructure design on accident rates (e.g., Reynolds et al., 2009). Examples of these studies include how specific aspects of the environment affect the number of accidents in a given area, including roundabouts (e.g., Daniels, Nuyts, & Wets, 2008), intersections (e.g., Wang & Nihan, 2004), railroad crossings (e.g., Ling, Cherry, & Dhakal, 2017), and other road design characteristics (e.g., Klop & Khattak, 1999) or variables that may put cyclists at a high risk of injury (e.g., Madsen & Lahrmann, 2017). These studies rely on archival accident data to make inferences about the infrastructure (e.g., number of turning lanes), interaction with the environment (e.g., throughput of right turning vehicles through a bike lane), and non-behavioral cycling factors (e.g., high bike volume) that impact the risk of an accident occurring. However, few examine cycling behaviors themselves and none, utilizing archival data, provide insights into unsafe cycling behaviors when an accident did not occur. Thus, more research is needed examining the effect of infrastructure design on unsafe cycling behaviors without utilizing archival data that may omit myriad behaviors not resulting in an accident.

Study objectives

The above research elucidates rates of specific unsafe behaviors as well as links between injury and environment. It does not, however, provide much insight into the breadth of unsafe behaviors in which cyclists engage, the corresponding rates at which these behaviors are occurring, nor linkage between infrastructure design and unsafe cycling behaviors. The objectives of this study, therefore, are two-fold to: (1) assess the actual rates of unsafe behaviors in a real-world setting, and (2) examine the linkage between infrastructure design and cyclists' behaviors. Observational approaches have an advantage to researchers by allowing them to study behaviors on the road in their natural environments (Ortiz, Ramnarayan, & Mizenko, 2017). Thus, we conducted an observational study to achieve these objectives. This study differs from other observational studies by incorporating multiple behaviors across several observational locations with differing infrastructure design characteristics.

Method

Subjects

This study was conducted on the campus of a large University in Indiana. Subjects consisted of all cyclists within three designated observation areas during observation times. A total of 1168 cyclists were observed across the observation locations. A subject was only counted once per behavior regardless of how many times they repeated the behavior. An example is if a subject failed to notify many pedestrians of their approach (which was one of the behaviors being observed), this behavior would only be captured once even though it occurred multiple times by the same cyclist. The same subject could be recorded multiple times across the behaviors observed (e.g., if a cyclist failed to notify multiple pedestrians while riding in an unauthorized area (also a behavior being observed), then two behaviors were recorded).

Observation behavior selection

Rules governing cyclists are based on statues or codes in place for all vehicle traffic with additional or modified rules specifically for cyclists (e.g., Indiana state code title 9 article 21 chapter 11 details traffic regulations specifically for bicyclists and motorized bicyclists). These rules, in addition to recommendations for conduct within official documentation (e.g., signaling a turn is noted in the official Bureau of Motor Vehicles handbook, https://www.in.gov/bmv/2557.htm) have been written to mitigate the number of collisions and guide safe cycling practices. The list of behaviors observed for this research is based on three criteria: (1) the behavior is specifically identified in the aforementioned rules or guidelines, (2) evidence exists suggesting an increased potential for collision, and (3) all included behaviors are observable from a distance without specialized equipment. For example, helmet usage does not mitigate collisions and cyclist speed could result in a collision but requires specialized equipment to capture, therefore neither are observed in this study.

Table 7 shows the observed behaviors, evidence supporting increased potential for collision, source supporting the selection evidence, and any relevant statutes or official government documentation related to the behaviors. For example, the behavior of failing to yield contributed to 24.4% of accidents with motor vehicles according to Bil et al. (2010). Indiana code statues 9-

21-11-2 and 9-21-11-11 state all cyclists must follow the same rules and regulations as motor vehicles except for where specifically denoted. For example, the statute describing motor vehicles yielding, 9-21-8-33, states "A person who drives a vehicle approaching a yield sign shall slow down to a speed reasonable for the existing conditions or stop if necessary. The person shall yield the right-of-way to a pedestrian legally crossing the roadway and to a vehicle in the intersection or approaching on another highway so closely as to present an immediate hazard. After yielding, the person may proceed, and all other vehicles approaching the intersection shall yield to the vehicle proceeding" (Indiana code 9-21-8-33). Thus, based on the above statute as well as 9-21-11-2 and 9-21-11-11, cyclists must also yield. The complete set of behaviors observed were: not stopping at a stop light or stop sign, making an illegal turn, not signaling during a turn, failing to yield, not audibly notifying a pedestrian of approach, and riding in an unauthorized area or manner.

Table 7. Selected behaviors, evidence supporting increased the potential for collision, and relevant laws.

Behavior	Statutes supporting rationale	Evidence supporting increased the potential for collision	Source of evidence
Failed to Yield	9-21-11-2, 9-21-11-11, 9-21-8-33	24.4% of accidents	Bil et al., 2010
Did Not Stop at Stop Sign or Light	9-21-11-2, 9-21-11-11	29% of accidents	Yan et al., 2011
Illegal Turn	9-21-11-2, 9-21-11-11	21% of fatalities (turns or swerves into path of motor vehicle)	Rowe et al., 1995
Did Not Signal Turn	9-21-8-28	Use hand signals when "Operating a bicycle or other vehicle that doesn't have turn signals."	Indiana Driver's Manual
Did Not Audibly Notify	9-21-11-8	A person may not ride a bike unless equipped with device to notify audibly by 100 feet	9-21-11-8 Bells or other audible signal devices
Riding in Unauthorized Area	9-21-11-2, 9-21-11-11	5.4% of accidents (wrong way), 12% fatalities (riding onto street mid-block)	Yan et al., 2011; Rowe et al., 1995

Observation sites

Three observations locations were selected to collect data. The locations varied in design characteristics based on the current Indiana Department of Transportation Design Manual (2013). All locations abutted campus on one side and the city proper on the other. All three locations were adjacent to parking garages to provide a vantage point by which to conduct observations. Some distinct differences existed across the locations. Table 8 summarizes the observation locations and key characteristic differences based on design characteristics.

Table 8. Observation location characteristics.

Characteristics	Observation Location 1 (Figure 1)	Observation Location 2 (Figure 2)	Observation Location 3 (Figure 3)
Type	Staggered intersection	Enhanced crossing intersection	Four-way intersection
Intersection details	One-way main street with two staggered t-intersections	Two-way single road separated by median one exit/entrance into parking garage	Four-way intersection with one-way street intersecting a two-way street
Traffic control mechanism(s)	Multiple stop signs	Single stop light	Single stop light
Pedestrian walkway	Sidewalks	Sidewalks and pedestrian area adjacent to sidewalks	Sidewalks
Pedestrian crosswalk	Two crosswalks	One enhanced pedestrian crossing	Four crosswalks
Bicycle path	Single type A with traffic on main street and single type B two-way on sidewalk adjacent to main street	None	Single type A on one-way street

Note: Type A bike paths refer to a portion of the road designated for cyclists by paint, strip, or curb. Type B bike paths refer to a separate trail or path where motor vehicles are prohibited.

Figure 2 depicts the first location, which consists of a staggered intersection, one main two-lane one-way street running south to north with a bike lane on the right-hand side (also running south to north). Another two-way bike lane on the left of the one-way street is located within a pedestrian area. Two roads are perpendicular to the main street with stop signs, one of which has a pedestrian crosswalk. The main road also has a pedestrian crosswalk prior to the intersecting roads. Ample pedestrian walkway space is available on all sides of each road. This location does not conform to a typical intersection layout and has ample sidewalk area where a cyclist could ride, which has been associated with greater risk than riding on the road (Wachtel & Lewiston, 1994). Additionally, the direction of travel is one way providing cyclists with the opportunity to travel against traffic, which has been associated with greatly increased risk (Wachtel & Lewiston, 1994; Yan et al., 2011).

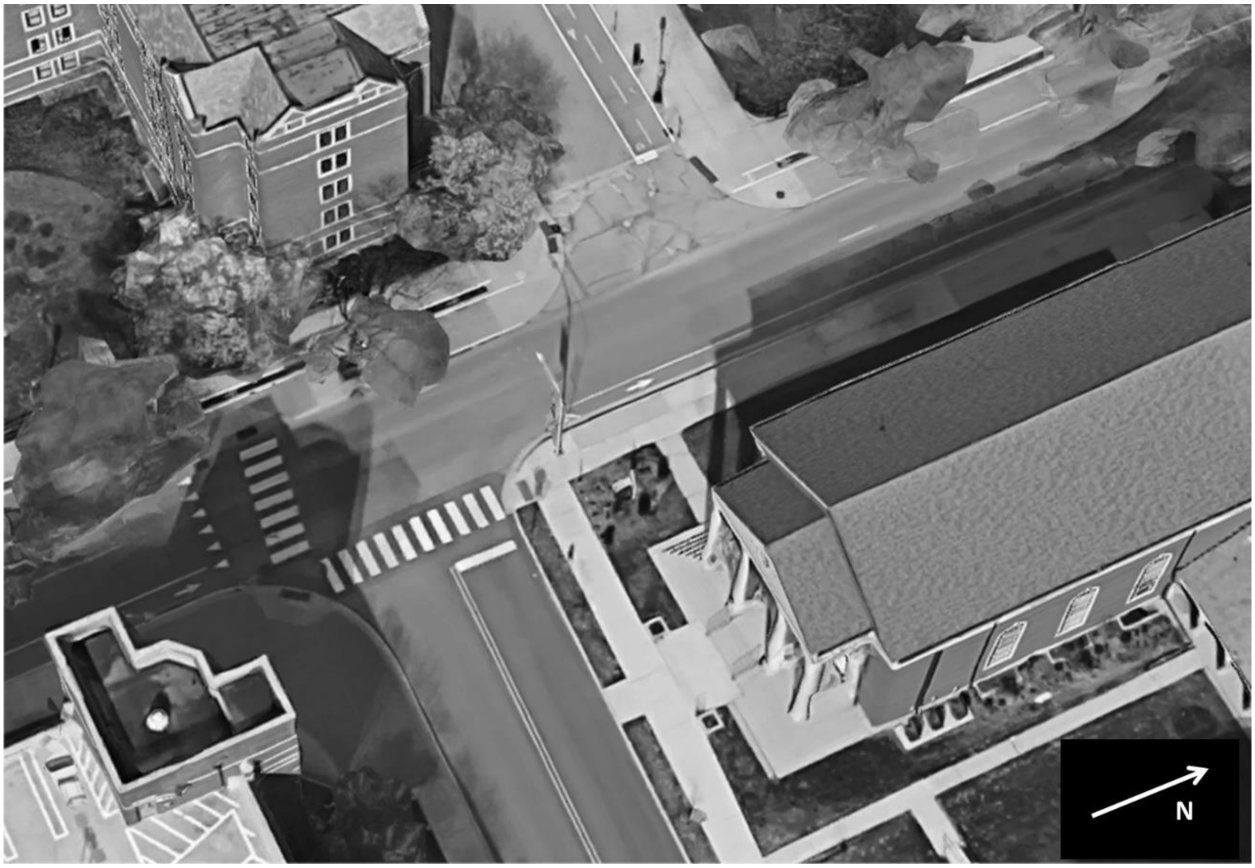

Figure 2. Observation Location 1. Source: Google Earth coordinates 40°25’32”N 86°54’37”W.

Figure 3 illustrates the second location selected. This location consists of two two-lane one-way streets separated by a large median. Neither street has a designated bicycle lane. Pedestrian walkways are located on both sides of the streets. One traffic signal governs both streets. The light alternates between allowing traffic to flow in both directions and stopping traffic to allow pedestrians to cross the roads in the crosswalk. Traffic flowing east to west (left to right in the picture) can turn right into a parking garage, and opposing traffic can turn left into the same parking garage when the traffic signal is green. This location was selected due to its unique design and large pedestrian area adjacent to the road. No dedicated bike path exists at this location forcing cyclists to ride on the sidewalk or ride on the roadway with the motor vehicles. Additionally, an enhanced pedestrian crosswalk across the median provides opportunities for cyclists to cycle in unauthorized areas, ride against traffic, and swerve in front of vehicles, which have been associated with increased risk and contributing to accidents (Wachtel & Lewiston, 1994; Williams, 1976).

Figure 3. Observation Location 2. Source: Google Earth coordinates 40°25’46”N 86°54’43”W.

The third observation area, pictured in Figure 4, is a four-way intersection with one-way traffic running south to north (bottom to top in the picture) and two-way traffic running west to east and east to west (left and right in the picture). The intersection has one set of traffic lights that alternate between the one-way street and the two-way street, no bicycle lanes, and a pedestrian crosswalk across all streets. Pedestrian walkways are located on both sides of each street. The layout allowed for both left and right turning vehicles, which have been linked to increased likelihood of collision (Madsen & Lahrmann, 2017) and a non-designated bike path sidewalk area, which increases risk of accidents (Wachtel & Lewiston, 1994).

Figure 4. Observation Location 3. Source: Google Earth coordinates 40°25’38”N 86°55’00”W.

Data analysis

Data were stratified and a contingency table was populated containing all behaviors and locations. Chi-squared tests of independence were conducted to determine if differences existed across the three observation locations. In cases where significant differences were found, the Marascuilo (1966) procedure was conducted to determine which locations significantly varied from one another. A significance level of $p < .05$ was utilized for all statistical testing.

Observation procedure

Data collection was similar to previously utilized methods for observing traffic behavior (e.g., Huth et al., 2015). Three observation locations were selected and time sampling took place for two 60 minute sessions in the morning and two 60 minute sessions in the afternoon on different days totaling four hours per location. Weather was clear for all days that observations took place. The observer utilized a pencil and paper to record observations on a sheet designed for previous observational research (Lavetti & McComb, 2014) as well as a device to indicate when one hour had concluded. The number of violations committed were recorded with paper and pencil as well as the number of chances for a behavior to occur (e.g., number of times a cyclist ran a red light and number of times a cyclist approached a red light).

Results

Results addressing the first research objective about the prevalence of unsafe cycling behaviors are summarized in Figure 5. The figure illustrates the total numbers of cyclists who could have behaved unsafely, and breaks those acts down into those who did behave safely and those who did not. For example, 513 cyclists had the opportunity to stop at a stop sign or stop light. Of those, 461 (89.9%) cyclists did not stop and 52 did. As seen in the figure, some behaviors, such as failing to signal during a turn and riding in an unauthorized area, were far more prevalent than other behaviors, such as failing to yield or not stopping at a sign or light. None of the violations recorded in this study were cited by law enforcement. Thus, as the figure suggests, the potentially unsafe behaviors we observed were pervasive.

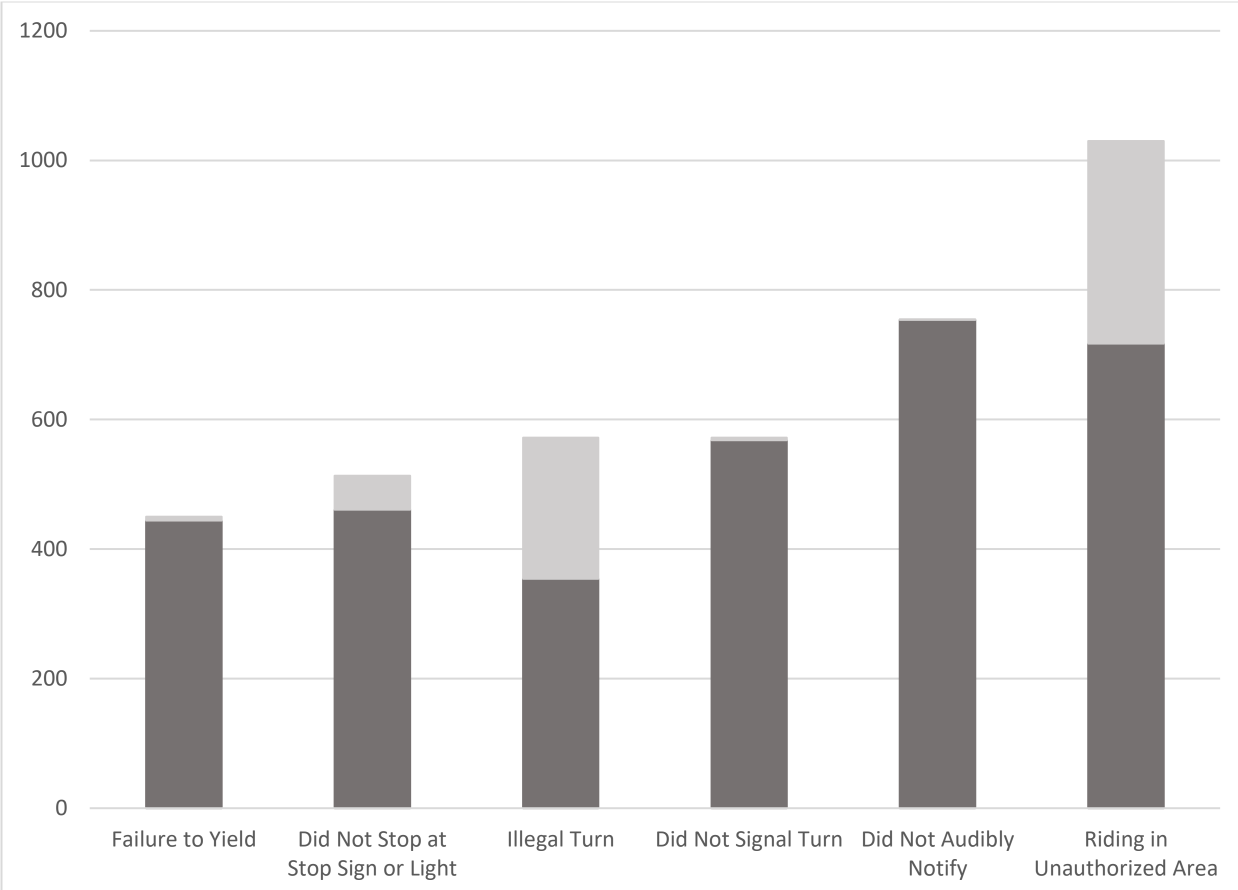

Figure 5. Number of unsafe behaviors and total observed behaviors.

The second objective focused on the role of infrastructure design in cycling behavior, which requires the data to be separated by location. The raw numbers of behaviors observed (both unsafe and unsafe) and the percentages of times unsafe behaviors took place when the cyclists had the opportunity to commit them by location are documented in Table 9. For example, 355 cyclists were observed at Location 1. Of those 355, 313 (i.e., 287/.9169=313) had the opportunity to stop at a stop sign but only 26 (i.e., 313-287=26) stopped. The remaining 287, or 91.7% (i.e., 287/313=.9169), failed to stop. The only behaviors that were observed occurring less than 90.0% of the time in at least one location were failing to stop at a light or stop sign (Location 3), making an illegal turn (Locations 1 and 3), and riding in an unauthorized area (Locations 1 and 3). Many of the observed unsafe behaviors occurred very frequently, and in some cases 100.0% of the time, particularly at Location 2.

Table 9. Number of Unsafe Behaviors, Percentage of Violations, and Results from Chi-Squared Analyses

	Location 1 n=355		Location 2 n=252		Location 3 n=561			
	Unsafe/Not-Unsafe Behaviors	Percent Unsafe Behaviors*	Unsafe/Not-Unsafe Behaviors	Percent Unsafe Behaviors*	Unsafe/Not-Unsafe Behaviors	Percent Unsafe Behaviors*	Chi-Square	p-value
Failed to Yield	164/1	99.39%	115/0	100.00%	165/5	97.06%	5.56	.06
Did Not Stop at Stop Sign or Light	287/26	91.69%	21/2	91.30%	153/24	86.44%	3.48	.18
Illegal Turn	167/67	71.37%	132/0	100.00%	55/151	26.70%	198.35	<.0001*
Did Not Signal Turn	232/2	99.15%	132/0	100.00%	204/2	99.03%	1.23	.54
Did Not Audibly Notify	336/0	100.00%	236/0	100.00%	182/1	99.45%	3.13	.21
Riding in Unauthorized Area	313/42	88.17%	248/4	98.41%	156/267	36.88%	370.85	<.0001*

Note: Percent is calculated by dividing the number of unsafe behaviors observed by the number of cyclists who had the opportunity to commit the behavior.

To test for significant differences in the proportions of unsafe behaviors across locations, a Chi-squared test was conducted, also reported in Table 9. Failure to stop at a sign or light and riding in an unauthorized area were the only two behaviors with significant differences. Pairwise comparisons of the three locations indicated that all three pairs of locations were significantly different with regard to both behaviors. Failure to yield was not significant at the .05 threshold according to the Chi-squared test but does have a p-value <0.01. Therefore, it was included in the subsequent pairwise comparisons to determine if significant differences between pairs of locations existed; none were found.

One additional behavior seen during the observation period, but not included in the study design, is worth mentioning. Specifically, we report here the numbers of cyclists who chose to stop at a stop sign or traffic signal when no immediate threats from traffic were present (i.e., the cyclist would not be hit by a vehicle if they failed to stop). Of the 26 cyclists who did come to a stop at Location 1, only four (15.4%) did so when no immediate danger of being in a collision was present. At Location 2, the two cyclists (100.0%) observed stopping did so without an imminent threat of collision. When traffic was present, cyclists were observed shifting into pedestrian walkways to avoid having to stop. At Location 3, 39 cyclists came to a complete stop regardless of the current traffic situation. Of those 39, 24 cyclists (61.5%) stopped even though no traffic was present and remained stopped until the signal changed. The remaining 15 cyclists stopped because of a potential threat and resumed cycling once the threat had moved out of their path; these cyclists were recorded as having committed the violation of not stopping at a stop sign or traffic signal. Interestingly, the opposite behavior (i.e., not stopping when a potential threat is present) only occurred once during the observation period and resulted in the only near-collision observed.

Discussion

The results of this observational study demonstrate that unsafe cycling behaviors occur at very high rates (e.g., 91.7% cyclists did not stop at stop signs at Location 1) and in some cases the behaviors occurred 100.0% of the time (e.g., 100.0% of cyclists failed to yield at Location 2). Additionally, none of the observed behaviors resulted in accidents or citations meaning, with the exception of the observation notes, no record exists of any of the unsafe acts. These direct observations indicate that previous attempts at encapsulating cyclists' behaviors via archival statistics may dramatically underestimate actual rates of unsafe actions. Rates of unsafe behaviors were high across all three observational locations though significant differences did exist.

The theory of fast and frugal heuristics provides a framework by which to explain some of these findings. The theory states that humans make decisions based on limited information within their environment with limited cognitive capabilities (Gigerenzer & Goldstein, 1996; Goldstein & Gigerenzer, 2002; Forster, 1999). Specifically, cyclists may synthesize the information in the environment (e.g., traffic density), evaluate the risks and benefits of riding unsafely very quickly, and choose whether or not to violate rules. Self-preservation may be a driving force in the selection of whether or not to violate rules as noted by the vast majority of cyclists stopping at stop signs or lights only doing so when it directly prevented a collision. Thus, educational activities that help cyclists modify their heuristics with realistic information (i.e., ecologically valid) about potential consequences useful.

Behaviors that had non-significant differences across observation locations included failing to yield, failing to stop at a stop light or sign, failing to signal during a turn, and failing to audibly notify pedestrians of approach. All the above behaviors had high rates with the lowest being 86.4% and many being 100.0%. Several reasons could exist for these findings. First, cyclists may not be aware of some rules, including the use of hand signals when making a turn and needing to audibly notify pedestrians of approach. If a lack of knowledge is responsible then it is expected that differences would not exist. For rules that are better known, such as yielding and stopping, cyclists may decide that the extra effort required to follow the rules is not worth it especially when they are reasonably certain disobeying the rules carries little to no risk to them (e.g., a lack of consequences such as rule enforcement). Indeed, none of the violations resulted in harm to the cyclist nor consequences by law enforcement. An increase in rule enforcement or some other consequences may aid to reduce this risk taking behavior. While it is possible more data would indicate statistically significant differences for practical purposes it is plausible cyclists simply do not often yield given the structural characteristics examined. Future research is needed to delineate which specific design characteristics contribute to the reduction of unsafe behaviors.

Significant differences across locations existed for the behaviors of turning illegally and riding in an unauthorized area. Specifically, Location 3 had lower rates of these behaviors. We posit two plausible explanations for this finding. First, the more traditional intersection design (i.e., four-way with a traffic light and small pedestrian sidewalks) provides fewer ways to make illegal turns and limited opportunities to ride in unauthorized areas than the other intersection designs. Second, the more compact size of the intersection, compared to the sizes of the other two intersections, combined with structural characteristics (e.g., curbs between the roads and small sidewalks), may also have restricted cyclist, pedestrian, and automobile traffic flow. The resulting increased density of activity due to structural characteristics, which by itself is not a design characteristic, may have mitigated unsafe cycling behaviors. Together, these reasons may suggest that the cyclists incurred fewer opportunities to ride unsafely and the risks associated with unsafe behaviors increased with this infrastructure design.

Several limitations exist with this study. While the observation locations selected did exhibit infrastructural design differences, there were only three sites. A more formalized experimental design in future studies may be beneficial taking into account structural differences across additional observation locations. This step is warranted as significant differences in rates of unsafe cycling behaviors were identified utilizing high-level similarities and differences in this design. Additionally, this research was limited in the selection of unsafe behaviors being observed. The behaviors utilized in this study were important and their selection was grounded in the literature but a more comprehensive collection of behaviors may be useful in examining overall unsafe cycling behavior. Finally, generalizability beyond the college town in which the study was conducted may be limited. But, given the high rates of occurrence observed. Expanding this study to include additional college towns or urbanized areas that are more densely populated may help to better understand unsafe cycling behaviors and how they may be impacted by infrastructure design characteristics.

Conclusions

Bicycling is a popular method of exercise, recreation, and transportation that is increasing in popularity. This increase has led to a commensurate rise in accidents involving cyclists necessitating additional cycling safety efforts. While accident data links unsafe cycling behaviors to collisions and injuries, it may underestimate the rates of these behaviors. This study is a critical step towards a more comprehensive depiction of the actual rates of unsafe cycling behaviors. Additionally, the findings provide a good first step in identifying how those rates may be similar or different across infrastructure design characteristics. Together these steps contribute to a vital process of holistically understanding unsafe cycling behavior and enhance cycling safety.

CHAPTER 4. POLICY CAPTURING STUDY

Introduction

Bicycling is a popular method of both transportation and recreation around the world. Due to its popularity and ubiquitousness many safety issues arise associated with protecting the cyclists and others with whom they may interact. Cyclists make decisions about how they are going to ride every time they get on a bike, including the decisions to ride unsafely. Lawmakers have rules place governing cycling behaviors to protect cyclists and the populace. Regardless of these rules, cyclists sometimes elect to violate them and ride unsafely. To date, little is known about what actually drives the decisions cyclists make to ride unsafely.

When cyclists decide to ride unsafely, accidents may happen, resulting in injuries, loss of life, and vast financial consequences. In 2014, according to the National Highway Traffic Safety Administration (NHTSA), 726 bicycle fatalities were reported, as well as more than 50,000 injuries (www.pedbikeinfo.org). The number of fatalities rose to more than 1000 in 2015 according to the CDC (2017). Additionally, bicycling related injuries, insurance, damages, lost wages, etc., are estimated to be in the billions of dollars annually (Miller et al., 2004). These statistics underscore the importance of understanding the decision making processes of cyclists. Such understanding can inform and facilitate safety interventions for the protection of these at risk road users.

The purpose of this research is to further unsafe cycling behavior research by examining cyclists' decisions to ride unsafely. Specifically, we (1) quantify how cyclists prioritize factors associated with breaking traffic laws or vehicle operation recommendations and (2) examine how circumstances influence their decisions to put themselves, and potentially others, in danger.

Background

One theoretical foundation that that may help elucidate why cyclists decide to ride unsafely is the theory of fast and frugal heuristics (Gigerenzer & Goldstein, 1996). Models of rational inference have historically treated the decision making process as though there is boundless knowledge, unrestricted time, and limitless computational might (Gigerenzer & Goldstein, 1996). However, human beings make decisions about the world around them with limited knowledge, under time constraints, and with finite cognitive ability. The theory of fast and frugal heuristics (Gigerenzer & Goldstein, 1996; Gigerenzer, 1999) was developed to more accurately reflect how human beings make decisions about the world around them. Heuristics are simple and efficient rules used to make decisions or judgments often when the decision maker is faced with complex problems. The theory of fast and frugal heuristics holds several axioms by which humans make rational decisions. These axioms parallel the contexts in which bicyclists may find themselves and may help explain why cyclists choose to ride unsafely.

The first axiom states that the decision rules should be bound within the decision maker's rationality (Gigerenzer & Goldstein, 1996; Goldstein & Gigerenzer, 2002; Forster, 1999). The decision rules are frugal with what information is taken into account and fast enough to operate efficiently. Cyclists are often faced with a changing environment (e.g., traffic or motor vehiclist behavior) and must make decisions very quickly with limited information (e.g., future motor vehiclist behavior or traffic occluded by a structure). Cyclists may not be able to access all information beyond what they can gather with their senses and take as long as they need to thoroughly explore all options and arrive at an optimal conclusion. An example may be coming to a stop light that turns red and deciding, based on the specific environmental factors at that moment, whether or not to stop at the light or violate the rule and ride through. This decision must be made quickly and with only the information immediately available to the cyclists (e.g., what they can see and hear).

The second axiom states that the rules are ecologically valid and fit the world around them (Gigerenzer & Goldstein, 1996; Goldstein & Gigerenzer, 2002; Forster, 1999). This axiom applies to cyclists and their decision making because they must make decisions utilizing information within their environment to make decisions about their environment. They do not need to make decisions in one environment and extrapolate to a different environment thus lowering the ecological validity. An example of this would be when cyclists come to stop lights, they use the information around them (e.g., other vehicle behaviors, what they know about stop lights, presence of authority figures) to assess the pros and cons of stopping vs not stopping and come to decisions about how to behave.

The third axiom states that rules are grounded within established cognitive capabilities such as memory and perception (Gigerenzer & Goldstein, 1996; Goldstein & Gigerenzer, 2002; Forster, 1999). Cyclists can only gather and process finite amounts of information. They utilize their senses to gather information (e.g., visually, audibly) and process that information within the bounds of their mental abilities. Cyclists do not have access to unlimited processing power to evaluate all alternatives through to their outcomes. Continuing the example of cyclists approaching stop lights and deciding whether or not to stop, they only have a finite amount of information they can perceive (e.g., they do not have access to other vehiclists' mental processes) and only limited cognitive capacity to process all possible outcomes of stopping or not through to fruition (such as a simulation with unlimited processing). They must make their decisions based on their own perceptions and cognitive abilities.

To apply the fast and frugal framework to the examination of cyclists' decision making processes with respect to how they choose to ride, we turn to what is currently known about cyclists' unsafe riding behaviors. Unsafe cycling behavior research coalesces into several categories; examining accident and injury statistics using archival data to make inferences about unsafe riding behavior (e.g., Rowe et al., 1995; Bil et al., 2010; Yan et al., 2011), directly observing unsafe or rule violating behaviors using observational or naturalistic methods (e.g., Johnson et al., 2010; Yang et al., 2012; Pai & Jou, 2014), and eliciting cyclists' perceived unsafe riding behaviors using questionnaires or interviews (e.g., Bernhoft & Carstensen, 2008; Johnson et al., 2013; Lavetti & McComb, 2014; Shaw et al., 2014). The first two approaches provide insight into how pervasive unsafe riding practices are. The third approach has the potential to provide insight into the reasons why.

Lavetti and McComb (2014) begin to address how cyclists choose to ride unsafely. Though the use of observational techniques a pilot study was conducted to assess how frequently cyclists engage in various unsafe behaviors. The identified behaviors and associated rates can be found in Table 10.

Table 10. Observed unsafe behaviors (Lavetti & McComb, 2014).

	Occurrences / total opportunities	Percent occurrences
Failure to Yield	112/112	100%
Failure to Stop	108/112	96%
Illegal Turn	79/112	71%
Failure to Signal	79/79	100%
Failure to Notify	112/112	100%
Riding in Unauthorized Area	112/112	100%

Research conducted by Lavetti and McComb (2014) as well as Shaw et al. (2014) also start to address why cyclists choose to ride unsafely. The identified reasons from those studies are summarized in Table 11. Shaw et al. (2014) utilized a questionnaire to assess cyclists' perceptions of how often they broke rules and produced a list of the top reasons including infrastructure design, other road users' behaviors, traffic speed, perceived personal benefit, and excitement. Lavetti and McComb (2014) utilized interviews to assess the top reasons as well, including perceived awareness, infrastructure, role confusion, convenience, urgency of travel, and competitiveness.

Table 11. Reasons cyclists choose to ride unsafely (Lavetti & McComb, 2014; Shaw et al., 2014).

	Lavetti & McComb	Shaw et al.
Disagreement or disregard of rules	89%	
Perceived Awareness	44%	
Physical Infrastructure	44%	Y
Visibility	33%	
Cyclist Role Confusion	22%	
Convenience	22%	Y
Urgency of travel	22%	
Behavior of road users		Y
Speed of road users		Y
Excitement		Y

These results provide evidence suggesting why cyclists choose to ride unsafely. However, missing from the literature is how cyclists utilize these reasons in the decision making processes. Additionally, the relative importance of these reasons associated with choosing to ride unsafely have not been addressed. Thus, the research objectives for this study are:

Research Objective 1: To determine how cyclists prioritize reasons for riding unsafely.

Research Objective 2: To examine under what circumstances cyclists decide to ride unsafely.

Two methods that may be appropriate for achieving these objectives are the Analytic Hierarchy Process (AHP) and Policy Capturing (PC) methodologies, respectively. AHP is a tool that utilizes pairwise comparisons to assess relative weights between alternatives (Saaty, 1980; Saaty, 1990). PC is a statistical method used to assess and describe the relationships between outcome measures predicated on information presented to the participant making judgments (Cooksey, 1996). Both methods tap into the judgments cyclists make about whether or not to ride unsafely and provide a means by which to achieve the objectives of this research.

Methods

A questionnaire was utilized to address the research objectives and consisted of three parts: a demographics section, an AHP section, and a PC section. The AHP is a tool by which to evaluate alternatives and rank them based on some goal (Saaty, 1980; Saaty, 1990). The AHP tool is especially useful when evaluating complex decisions where no clear best choice is apparent. The AHP tool is utilized within this questionnaire to evaluate alternative factors that may lead to unsafe cycling behaviors. PC is a statistical method used to describe how individuals reach decisions based on information presented to them (Cooksey, 1996). PC approaches have been applied to myriad complex contexts to assist in understanding how complicated decisions are made, for example how supervisors reach decisions about salary increases for their employees and what factors are most important for those increases (e.g., Sherer, Schwab, & Heneman, 1987). We utilize the PC method to determine under what circumstances cyclists elect to ride unsafely. Moreover, this approach aligns with the axioms of the theory of fast and frugal heuristics. Table 12 enumerates each axiom of the fast and frugal heuristics theory, how they apply to cycling in general, and how they facilitate meaningful use of the PC methodology.

Table 12. Fast and Frugal axioms mapped to cyclists and questionnaire.

Axiom	Application to cycling	Application to PC methodology
Rules are bound within the decision maker's rationality, frugal with information, and fast enough to operate efficiently.	Cyclists must make decisions quickly and based on limited information in a constantly changing environment.	Cycling decision scenarios do not include excessive amounts of information that may be superfluous to the cyclist or take a great deal of time to process.
Rules are ecologically valid and fit the world around them.	Cyclists must make decisions about their environment based on information within their environments and do not need to extrapolate beyond where they cycle.	Cycling decision scenarios are constructed within a cycling context and utilizing real-world situations.
Rules are grounded within established cognitive capabilities such as memory and perception.	Cyclists must make decisions based on finite information that they can gather through their senses and process with their finite cognitive abilities.	Cycling decision scenarios do not include information outside the bounds of human perception (e.g., thoughts of other road users) or assume infinite memory capacity.

Outcome measures and cue development

The outcome measures for this research are judgments about unsafe behaviors. The unsafe behaviors were drawn from observations by Lavetti and McComb (2014) and identified as hazardous behaviors in previous research (e.g., Bil et al., 2010; Yan et al., 2010). For this research, the outcome measures were stopping at a stop sign, riding on an unauthorized area (e.g., sidewalk), riding against traffic, and weaving among vehicles and pedestrians. Not stopping at a stop sign was observed at a rate of 96.0% for cyclists that approached a stop sign (Lavetti & McComb, 2014). Riding in an unauthorized area (e.g., sidewalk) was observed in 100.0% of cyclists (Lavetti & McComb, 2014). Weaving has been identified in previous research as leading to accidents and accounting for as much as 21.0% of fatal accidents with motor vehicles (Rowe et al., 1995). The behavior of weaving among pedestrians was included as the result could lead to an accident or injury, though little data exists about pedestrian collisions and they may be underreported. Failing to signal a turn was excluded due to the behavior being contingent on another behavior (i.e., making a turn). Failing to audibly notify pedestrians of approach was excluded because not all scenarios developed for the questionnaire afforded the ability to do so.

Both the AHP and PC methods require the development and incorporation of cues. Cues are independent variables, which in these cases are factors that affect cyclists' decisions to ride unsafely. Cues were developed by selecting factors identified in the interview portion of Lavetti and McComb (2014) and the questionnaire responses in Shaw et al. (2014) in Table 11. The selected cues included directness of route (e.g., convenience), time available to get to destination (urgency of travel), availability of a designated bike bath (physical infrastructure), and likelihood of a collision (perceived awareness of cyclists and behavior of other road users). The remainder of identified cues were excluded. Disagreement or disregard of rules was omitted because that was an outcome measure for this research. Visibility was omitted because weather is beyond the cyclists' control. Cyclist role confusion was controlled for by utilizing clearly articulated rules within the questionnaire design (e.g., stopping at a stop sign vs a more complicated scenario). Speed of road users was not incorporated into the design as intersections where all vehicles must come to a stop was used. Finally, excitement was not included as a factor because only one respondent identified it in Lavetti and McComb's interviews and Shaw et al. (2014) describe it as being rarely reported as a contributory cause.

Sample

Potential participants included anyone above the age of 18 who has cycling experience and speaks English. A combined approach of snowball sampling through personal networks and contacts within the USA cycling group was utilized. USA cycling was asked to send out an email about the research with a link to the questionnaire. Those contacts then relayed the message to their subgroup members. USA cycling is a nationwide consortium of cycling clubs consisting of more than 60,000 members, 2,700 clubs, and 67,000 licenses. USA cycling has a strong body of followers on social media as well, with more than 130,000 Facebook followers.

Contacts at USA cycling sent the invitation to participate in the survey to all club contact points who presumably sent them out to all club members. Response rates were incalculable due to no information about how many potential respondents received the survey invitation. In total, 472 responses were collected. Only complete responses (e.g., 100% of the AHP and/or PC portions) were included for analysis. Applying these criteria, the resulting sample sizes were 178 (37.7%) complete responses for the AHP portion and 192 (40.7%) complete responses for the PC portion. Cyclists reported living in multiple states across the US. Ages ranged from 18 – 69 (mean age

26.7, standard deviation 10.6), 71.0% of respondents were male (29.0% female), and years cycling ranged from 0 – 60 (mean 10.6, standard deviation 10.5).

Procedure

Analytic Hierarchy Process

The AHP utilizes a set of evaluation criteria or cues, a scale by which to compare each alternative directly (e.g., a pairwise comparison), and once analyzed weights are generated for each criterion predicated on the decision makers' judgments of preferences between each pair of criteria.

Participants were presented the four cues: time available to destination, directness of route, availability of a bike path, and likelihood of a collision. Participants were then presented each pair of cues and asked which would be more likely to influence their decision to exhibit unsafe cycling behavior. Each of the four cues were paired with the other cues making six total pairs per respondent. Table 13 shows the actual comparisons and scale used.

Analyses were then conducted in accordance with Saaty (2008) resulting in overall priorities the participants utilized when deciding how the factors of interest influenced their decisions to ride unsafely. Specifically, the six pairwise comparisons were evaluated based on each set of subjects' responses (e.g., which item in each pair was more or less influential). For example, a respondent may find likelihood of a running late much more influential on their decision to ride unsafely when compared to the presence of a bike path but much less influential when paired with a higher chance of a collision. The geometric mean was calculated using the sum of responses for each pair and a matrix was constructed. Responses were normalized by dividing the mean scores for each pair by the sum of mean scores for all pairs to allow for meaningful comparisons across cues.

Table 13. Pairwise comparison portion of AHP.

Which of the following factors would be more likely to influence your decision to exhibit unsafe bicycling behavior?						
	Much more influential	More influential	Equally influential	More influential	Much more influential	
Time available to arrive at destination						Directness of route to destination
Time available to arrive at destination						Availability of an official bike path
Time available to arrive at destination						Likelihood of collision with car/pedestrian
Directness of route to destination						Availability of an official bike path
Directness of route to destination						Likelihood of collision with car/pedestrian
Availability of an official bike path						Likelihood of collision with car/pedestrian

Policy Capturing

Policy Capturing involves the presentation of cues (e.g., running late) to each respondent making judgments (e.g., running a stop sign). Following the guidance by Cooksey (1996), participants were presented with a series of scenarios that incorporated the cues developed from the information in Table 12. Each of these cues were dichotomous: amount of time the rider has (running late or plenty of time), directness of route (direct or indirect), presence of a bike lane (yes or no), and amount of traffic (heavy or light) making a collision more or less likely. Scenarios were constructed by combining each dichotomous cue for a total of 2x2x2x2=16 combinations. Participants were then asked to make five judgments based on the scenarios. The judgments were setup using a five-point Likert scale ranging from Very Unlikely to Very Likely. Table 14 shows an example scenario presented and the five judgments participants were asked to make.

Table 14. Example scenario.

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic. Officials have designated a different path that: Is a reasonably direct route to your destination, has clearly marked bicycle lanes on the side of the road, and has light traffic on the road and few pedestrians on the sidewalk making a collision less likely. You have plenty of time.					
Given the above scenario:	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?					
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?					
How likely is it that you would take your normal route against traffic?					
How likely are you to weave between cars on the road?					
How likely are you to weave between pedestrians?					

The design was orthogonal and each subject was presented with all 16 combinations of cues (e.g., the scenarios) for each judgment. The 16 scenarios were randomly presented to the participants to eliminate respondent fatigue. There were five judgments (dependent variables) for each of the 16 scenarios presented to subjects. Judgments were treated as interval data as opposed to ordinal data in accordance with Likert scale response analysis practices (e.g., Boone & Boone, 2012). Blocks were utilized for each subject (e.g., the 16 responses for a single subject created a block). ANOVAs were used to evaluate the differences among the means of the responses for each independent variable (e.g., cues) for each dependent variable (e.g., judgments).

Results

Analytic Hierarchy Process

Results from the AHP are depicted in in Figure 6 and indicate that the likelihood of a collision influences the decision to ride unsafely highest of the four cues (34.0%). Time available (i.e., running late) was second most influential (27.4%). Directness of route was third (20.4%) followed by availability of a dedicated bike lane as least influential (18.2%). The Consistency Ratio (CR) is a measure of how consistent the responses were in the evaluation matrix developed when compared to a random matrix. A CR of 0.1 or less is considered acceptable and means the responses are consistent. The consistency for the AHP was 0.0001, meaning the responses were very consistent across subjects.

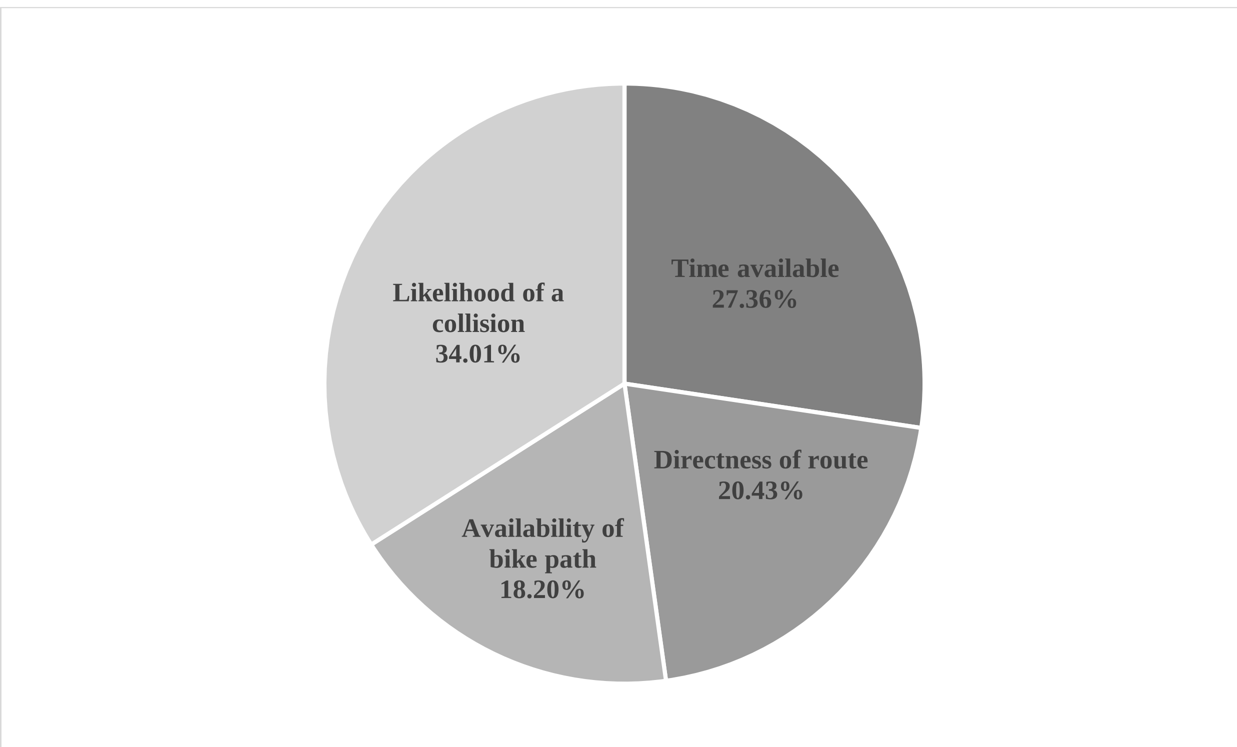

Figure 6. Priorities across variables.

Policy Capturing

To analyze the PC portion of the questionnaire ANOVAs were employed. This methodological approach is appropriate because we were interested in results across all participants (i.e., nomothetic) as opposed to individual policies (i.e., idiographic) and all responses were orthogonal (e.g., Slovic, 1969; Billings & Marcus, 1983). ANOVAs were conducted for each judgment; detailed tables of these results and histograms of the responses are located in Appendices C and D. Table 15 provides a summary of these results. Specifically, the p-values are reported depicting which cues explained a significant amount of the variance for unsafe cycling for all five judgments. For a conservative measure of the results, a Bonferroni adjustment was conducted modifying the required p-value for significance to be $\alpha = \frac{.05}{5} = .01$ (e.g., Bland & Altman, 1995).

Table 15. Summary of p-values across variables and cues.

	Stop Signs	Sidewalk	Against Traffic	Cars	Pedestrians
Direct	.2200	< .0001***	< .0001***	< .0001***	.0220
Lanes	.4760	.1600	.5370	< .0001***	.0110
Traffic	< .0001***	.0120	.0400	.1260	.1390
Time	< .0001***	< .0001***	< .0001***	< .0001***	< .0001***
Direct*Lanes	.2200	.6080	< .0001***	< .0001***	.2840
Direct*Traffic	.3180	.5180	.3040	.6380	.7600
Direct*Time	.9320	.0530	.4720	1.0000	.8380
Lanes*Traffic	.8420	.4620	.3820	.4440	.8780
Lanes*Time	.7970	.0070**	.5040	.7690	.0170
Traffic*Time	.1040	< .0001***	.9590	.7690	.1030

For stopping at stop signs or stop lights, traffic and time are the only significant influences on the decision to stop at a stop light or stop sign, both significant at the $p < .0001$ level. No interactions were found to be significant. For riding in an unauthorized area, directness of route and time were significant at the $p < .0001$. Additionally, two interactions were found to be significant; bike lanes x time ($p = .007$) and traffic x time ($p < .0001$). For riding against traffic, directness ($p < .0001$) and time ($p < .0001$) were found to be significant. One interaction, directness x lanes, was also found to be significant ($p < .0001$). For weaving between cars, directness of route, presence of bike lanes, amount of time, and directness x lanes were all found to be significant at the $p < .0001$ level. For weaving between pedestrians time was found to be significant at the $p < .0001$ level.

Discussion

The results of the AHP analyses indicate that cyclists prioritize factors associated with electing to ride unsafely by avoiding collisions first, then saving time, followed by riding in a direct route, and finally using a bike path. Results from the PC study show that running late may be the most important factor when choosing to ride unsafely. Density of traffic, directness of route, and availability of a bike path were significant for some outcome measures. The theory of fast and frugal heuristics provides some insight into the results of this research. Specifically, when cyclists traverse their environment and utilize the information within to arrive at their decisions to ride unsafely they may weigh the risk of electing to violate rules against the likelihood of consequences. Avoiding a collision, according to the AHP and some of the PC results, factors heavily into their heuristic evaluations. For instance, avoiding a collision was the highest prioritized cue among alternatives in the AHP. The consequence of being late also appears to factor heavily into their decisions according to both the AHP and PC results.

As stated above, the results from both analyses suggest running late is an important factor in cyclists' decisions to ride unsafely. Interestingly, running late has nothing to do with environmental information the cyclist collects and processes to make decisions. All other cues utilized within this research could be directly observed by the cyclist when constructing fast and frugal heuristics (e.g., traffic density, how direct the route is, and whether or not a bike path was available). This finding suggests that the fast and frugal heuristics model of decision making may be mediated by other contextual factors. Additional research is needed to investigate the impact of external variables on the decision making processes according to the model.

According to the AHP results the presence of a bike lane was prioritized lowest among the alternatives when deciding to ride unsafely. Results from the PC indicated that the presence of a bike lane was not significant when deciding to stop at a stop sign, riding in an unauthorized area, and riding against traffic. These findings may be important to road safety efforts because they suggest cyclists consider other variables more important when developing their heuristic evaluations of their environments and using these heuristics when deciding to put themselves and others at risk of injury by riding unsafely. It is possible that cyclists view bike paths as simply an extension of the road and do not differentiate between using them or not. This could explain why the presence or lack thereof is not weighed heavily in the decision making process. Further examining how cyclists interpret bike paths and how they fit into heuristic evaluations is needed to ascertain whether alternative cycling safety efforts (e.g., rule enforcement or deterrence methods) would increase road safety more effectively than the development of bike paths alone.

The results also suggest that environments within the fast and frugal heuristics framework may need to be redefined to include situational constructs unique to each individual. As seen in the results, running late was significantly associated with the decision to exhibit each behavior examined and was also ranked second highest in cue priority. This variable is not accounted for but may mediate the way humans make decisions or utilize the information about the world around them. Another example could be environmental familiarity. If a cyclist has made the same journey many times they may not process information or even assess environmental cues the same way a cyclist unfamiliar with the area or novice cyclist would.

Several limitations exist in this research. While the cues utilized in this study were derived from interviews and questionnaire literature (Lavetti & McComb, 2014; Shaw et al., 2014), the development of additional cues may facilitate a deeper understanding about how cyclists weigh factors associated with unsafe cycling decisions. Additionally, the behavioral outcome measures used in this research were selected based on observational (Lavetti & McComb, 2014; Chapter 3) and archival data (e.g., Bil et al., 2010; Yan et al., 2011) though additional outcome measures may be examined (e.g., speeding).

Conclusions

Bicycling is a widespread recreational activity and method of transportation that is increasing in popularity. The increase in popularity has been accompanied by a commensurate increase in cycling accidents. While unsafe cycling behaviors have been linked to causing accidents and rationale for riding unsafely has been identified, little research has been conducted examining how factors affecting unsafe riding influence how cyclists make decisions to ride unsafely. Specifically, no research has been conducted examining how cyclists prioritize factors that influence their decisions to ride unsafely. Results of this study provide a first step in understanding the cognitive antecedents involved in cyclists' decisions to ride unsafely by quantitatively describing how cyclists assign weights to factors that affect their decisions to ride unsafely. This research contributes to the holistic understanding of unsafe cycling behavior and provides quantitative results that may enable future endeavors to protect cyclists and improve road safety.

CHAPTER 5. POLICY STATEMENT

Introduction

Bicycling is a popular method of transportation and recreation with profound safety issues contributing to hundreds of thousands of injuries annually, hundreds of fatalities annually, and billions of dollars in accident related costs over the lifetime of the victims. Though the importance and impact of cycling safety cannot be denied, the factors contributing to unsafe bicycling behaviors have largely been ignored. This dissertation addresses this gap in three ways: (1) examining the current body of literature focusing on unsafe cycling behavior using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, (2) employing observational techniques to assess the actual rates of unsafe cycling behaviors across different infrastructural designs, and (3) utilizing quantitative methods to measure what risk factors contribute to cyclists' decisions to ride unsafely. The results of the studies can be synthesized into policy recommendations to aid in the facilitation of traffic safety efforts at the national, state, and local levels (see Appendix D for the consolidated policy statement).

The first contributions were the results from a systematic review of unsafe cycling behavior literature utilizing the PRISMA method (Chapter 2). Themes that emerged as a result of the review included incomplete accounts of actual cycling behaviors, methodological trends and the subsequent shortcoming associated with them, and a poor understanding about why cyclists choose to ride unsafely. The second contribution was derived from an observational approach aimed at identifying actual rates of unsafe cycling behaviors and how they differed across infrastructure design characteristics (Chapter 3). The selection of behaviors observed (e.g., failing to stop at a stop light) was developed based on accident data and cycling rules. Infrastructure design characteristics (e.g., enhanced pedestrian walkway) were identified based on Department of Transportation guidelines. High rates of unsafe behaviors were recorded across all observation locations with some significant differences (e.g., making an illegal turn and riding in an unauthorized area). The third contribution is insights about why cyclists decide to ride unsafely identified using the Analytic Hierarchy Process and Policy Capturing methodologies (Chapter 4). The risk factors examined were identified from existing interviews and questionnaires (Lavetti &

McComb, 2014; Shaw et al., 2014). Outcome measures were selected based on observational data in Chapter 3 and accident data identified in Chapter 2. The results indicate several risk factors were significantly associated with specific unsafe behaviors (e.g., if the cyclist is running late or has ample time to reach their destination they were more likely to ride through stop signs). Together these three contributions provide a holistic view of unsafe cycling behavior and can be synthesized into a set of policy recommendations.

The contributions in this dissertation can be synthesized to provide a more comprehensive perspective of the overall cognitive behavioral aspects of cycling safety. This perspective may be invaluable for informing road safety efforts by facilitating the incorporation of new unsafe cycling areas of research into safety improvement programs. The contributions may be incorporated at the national and state level plans which may in turn be adopted by smaller municipalities.

Federal and state level guidance

Designing and implementing road safety improvements, including cycling safety improvements, is mandated by the US government (23 U.S. Code § 148). The United States Department of Transportation's Federal Highway Administration employs a Highway Safety Improvement Program (HSIP) in accordance with United States Code, Title 23, Chapter 1, Section 148, which encapsulates all projects, activities, plans, and reports defined within the code. The purpose of the HSIP is to help each state plan road safety improvement projects, implement those projects, evaluate project performance, and report on the ongoing efforts for roadway safety. A major component of the HSIP is the requirement for a Strategic Highway Safety Plan (SHSP). According to the Federal Highway Administration, a SHSP is a "statewide-coordinated safety plan that provides a comprehensive framework for reducing highway fatalities and serious injuries on all public roads" (https://safety.fhwa.dot.gov/shsp/). These initiatives identify specific safety needs of a state and helps to guide strategies and countermeasures to improve safety as well as reduce injuries and fatalities. Each state is responsible for the development and implementation of their respective SHSPs.

The Indiana SHSP's mission, vision, and goal is to "ensure safe travel for all users of Indiana's streets, roads, and highways," "reduce human suffering and economic loss from traffic crashes," and "eliminate traffic crash deaths and incapacitating injuries" (Indiana Strategic Highway Safety Plan, 2010, p.4). According to the Indiana SHSP, one dilemma safety practitioners face is developing measures that allow for accurate evaluation of safety outcomes. The Indiana SHSP has thus incorporated two benchmarks by which to measure the success of safety efforts: reducing highway deaths and limiting severe crashes. One facet of the SHSP is bicycle safety, reducing bicycle related deaths, and limiting severe bicycle related crashes. To this end, Indiana's SHSP recommends utilizing the National Cooperative Highway Research Program's (NCHRP) 500 series reports as guidance. Volume 18 of those reports is entitled Guidance for Implementation of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan: A Guide for Reducing Collisions Involving Bicycles. This report suggests objectives and strategies by which to increase cycling safety on roadways. The guidance within the report, as well as guidelines within the Indiana SHSP, are entirely based on crash statistics and do not consider the behavior of the cyclists in the development of safety interventions or planning new safety efforts. Thus, the findings from this dissertation research may be useful in augmenting the current SHSP as described in the next section.

Specific policy recommendations

The purpose of this policy statement is to synthesize the research conducted within this dissertation and incorporate the findings into recommendations to be included within statewide Strategic Highway Safety Plans. The consolidated policy statement can be found in Appendix E. The following policy recommendations are made based on the studies within this dissertation along with examples of how a local governing body, in this case Purdue University, may employ them on their campus:

1. <u>Enforcement of established rules should be prioritized.</u> As demonstrated in this work, (a) development of rules and regulations aimed towards cycling safety does not deter unsafe behaviors and (b) little enforcement currently occurs. For example, in the observational study no enforcement stops were observed regardless of violation rates above 97% for three behaviors across all observation locations. Enforcement of violations may provide incentive to obey traffic rules by providing consequences for riding unsafely thus improving adherence.

Purdue University has previously launched an effort to improve cycling rule compliance via police outreach with encouraging results according to a local news article (Vizza, 2014). A combination of police outreach to educate and enforcement of rules through citations or warnings may result in improved rule compliance. The beginning of each semester is an ideal time to engage the students and educate them about the rules governing proper bicycling behavior as many on-campus organizations use this time to disseminate information. Police may then choose to select historically problematic intersections to monitor and issue warnings or citations, increasing both the visibility of law enforcement and expectation of consequences resulting from unsafe cycling behaviors.

2. Incorporate cyclist behavior considerations into selection of safety intervention. Current guidance for the development and implementation of safety interventions do not take into account cyclists' behaviors. The NCHRP series 500 guide volume 18, which provides guidance for states to implement their respective SHSPs, offers strategies to reduce bicycling crashes based on archival data and crash statistics. The guidance fails to include behavioral data on cyclists' unsafe riding practices that may be an integral component of prospective interventions. Incorporating behavioral data collection and findings into the development of a program may modify the guidance for improving safety based on behavioral outcomes.

   Purdue University could utilize the inclusion of behavioral findings in the development of cycling safety interventions and future projects. One potentially relevant finding from this dissertation research is that cyclists tend not to stop at traffic control devices (e.g., stop lights or stop signs) unless traffic precludes them from safely riding through. Purdue could leverage this information by developing a method to track when cyclists fail to stop (e.g., RFID tags when bicycles are registered). Purdue could then employ an incentive program for safe cycling behaviors such as a modest reduction in tuition or reward program for continued safe cycling. To facilitate the RFID concept, Purdue could institute a registration campaign and issue citations to cyclists who are found with unregistered bicycles.

3. Incorporate cyclist behavior considerations into infrastructure design. This research has demonstrated cyclists behave differently based on infrastructure design characteristics. Cycling behavior should be taken into account when developing the roadway infrastructure, which may require using behavioral data to determine if alterations or modifications of the existing designs are necessary to maximize cycling safety and reduce unsafe cycling behaviors. For example, cyclists' utilization of bike paths differed depending on location, with those on the sides of roads being more frequently utilized than those adjacent to sidewalks.

   Purdue University may utilize this recommendation by including behavioral research in the process of designing campus bike paths. Currently, studies are conducted by the University regarding traffic flow and preferred routes of cyclists. In fact, the University reaches out to the cyclists and gets their feedback about where bike paths would be most helpful. Collecting empirical data about cyclists' actual behaviors during this phase combined with typical route choices elicited during cyclist feedback may result in a better understanding of where bike paths would be most appropriate to maximize road safety.

Conclusions

The above policy recommendations and action strategies may serve to increase the overall cycling safety, not only on the campus of Purdue University, but any municipality that incorporates them into their SHSPs. Implementing these evidence-based recommendations may serve to increase safety and improve the required evaluation phase of each governing body's safety plans. States evaluate the success of their SHSPs based on outcome measures and benchmarks they have developed (e.g., reduction in deaths). New metrics could be developed and incorporated into the evaluation criteria for each project. In particular, metrics designed to capture cyclists' behaviors are needed. The inclusion of the above recommendations may improve SHSPs by enhancing the guidance they follow and improve the evaluation criteria resulting in an increase in overall cycling safety and, ultimately, saving lives.

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APPENDIX A. OBSERVATION DATA COLLECTION SHEET

Date Time Location			
	Violation did not occur	Violation did occur	Notes
Total bikes observed			
Failure to yield			
Failure to stop at sign			
Failure to stop at light			
Illegal turn			
Failure to signal			
Failure to audibly notify			
Riding in unauthorized area/manner			

APPENDIX B. POLICY CAPTURING QUESTIONNAIRE

Age:

____

Gender:

○ Male

○ Female

Academic level:

○ Freshman

○ Sophomore

○ Junior

○ Senior

○ Graduate Student

○ Faculty

○ Staff

○ Other

What University are you affiliated with:

____

Major (if applicable):

____

What country did you grow up in:

____

Do you own a bicycle:

- ○ Yes
- ○ No

What type of bicycle(s) do you own:

- ○ Road Bike
- ○ Mountain Bike
- ○ Hybrid Bike
- ○ Other

How many years have you been cycling:

____

How many times per week do you ride your bicycle:

____

Please describe the main reason(s) you bicycle:

____

Where do you most frequently ride your bicycle:

____

Are you a member of any bicycle club or organization:

○ Yes

○ No

If so, which one(s)?

____

Have you ever been involved in a bicycle accident in which you were riding a bicycle:

○ Yes

○ No

If yes, please briefly describe what happened:

____

____

____

____

____

Have you ever been involved in a bicycle accident in which you were not riding a bicycle:

- ○ Yes
- ○ No

If yes, please briefly describe what happened:

____

____

____

____

____

Thank you for participating in this study of bicycle safety. Your participation is voluntary and your personal identity will be kept strictly confidential. By your participation you are giving your consent to the researchers to use this data for study purposes; you will not be personally identified. There are no right or wrong answers to the questions, so please answer them honestly. We estimate that it will take you approximately 20 minutes to complete the survey. The following pages contain scenarios one may encounter while bicycling. Each scenario is followed by 5 questions. Your answers should capture how you would behave if you were in the each scenario.

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has clearly marked bicycle lanes on the side of the road, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has clearly marked bicycle lanes on the side of the road, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has clearly marked bicycle lanes on the side of the road, and
has heavy traffic on the road and many pedestrians on the sidewalk making a collision more likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has clearly marked bicycle lanes on the side of the road, and
has heavy traffic on the road and many pedestrians on the sidewalk making a collision more likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has no bicycle lanes but you may ride on the road with traffic, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has no bicycle lanes but you may ride on the road with traffic, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has no bicycle lanes but you may ride on the road with traffic, and
has heavy traffic on the road and many pedestrians on the sidewalk making a collision more likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is a reasonably direct route to your destination,
has no bicycle lanes but you may ride on the road with traffic, and
has heavy traffic on the road and many pedestrians on the sidewalk making a collision more likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is an inconvenient route that takes your out of your way to the destination,
has clearly marked bicycle lanes on the side of the road, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is an inconvenient route that takes your out of your way to the destination,
has clearly marked bicycle lanes on the side of the road, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

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has heavy traffic on the road and many pedestrians on the sidewalk making a collision more likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

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Is an inconvenient route that takes your out of your way to the destination,
has clearly marked bicycle lanes on the side of the road, and
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You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is an inconvenient route that takes your out of your way to the destination,
has no bicycle lanes but you may ride on the road with traffic, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

Officials have designated a different path that:
Is an inconvenient route that takes your out of your way to the destination,
has no bicycle lanes but you may ride on the road with traffic, and
has light traffic on the road and few pedestrians on the sidewalk making a collision less likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

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You have plenty of time.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Your normal biking route is on a road with a bike path where you ride with traffic. You arrive at a stop sign one morning and find the bike path blocked in your direction but available against traffic.

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Is an inconvenient route that takes your out of your way to the destination,
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has heavy traffic on the road and many pedestrians on the sidewalk making a collision more likely.
You are running late.

	Very Unlikely	Unlikely	Equally Likely and Unlikely	Likely	Very Likely
How likely are you to come to a complete stop at the stop sign?	○	○	○	○	○
How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?	○	○	○	○	○
How likely is it that you would take your normal route against traffic?	○	○	○	○	○
How likely are you to weave between cars on the road?	○	○	○	○	○
How likely are you to weave between pedestrians?	○	○	○	○	○

Which of the following factors would be more likely to influence your decision to exhibit ***unsafe*** bicycling behavior?

	Much more influential	More influential	Equally influential	More influential	Much more influential	
	1	2	3	4	5	
Time available to arrive at destination	○	○	○	○	○	Directness of route to destination
Time available to arrive at destination	○	○	○	○	○	Availability of an official bike path
Time available to arrive at destination	○	○	○	○	○	Likelihood of collision with car/pedestrian
Directness of route to destination	○	○	○	○	○	Availability of an official bike path
Directness of route to destination	○	○	○	○	○	Likelihood of collision with car/pedestrian
Availability of an official bike path	○	○	○	○	○	Likelihood of collision with car/pedestrian

APPENDIX C. RESULTS FROM THE POLICY CAPTURING ANALYSES

ANOVA results for all cues and judgment for stopping at a stop sign or light.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	201	3876.40	19.2856	48.24	0.000
Blocks	191	3826.33	20.0331	50.11	0.000
Linear	4	47.97	11.9925	30.00	0.000
Direct	1	0.60	0.6019	1.51	0.220
Lanes	1	0.20	0.2035	0.51	0.476
Traffic	1	17.67	17.6722	44.20	0.000
Time	1	29.49	29.4925	73.77	0.000
2-Way Interactions	6	2.10	0.3506	0.88	0.511
Direct*Lanes	1	0.60	0.6019	1.51	0.220
Direct*Traffic	1	0.40	0.3988	1.00	0.318
Direct*Time	1	0.00	0.0029	0.01	0.932
Lanes*Traffic	1	0.02	0.0160	0.04	0.842
Lanes*Time	1	0.03	0.0264	0.07	0.797
Traffic*Time	1	1.06	1.0576	2.65	0.104
Error	2870	1147.36	0.3998		
Total	3071	5023.76			

ANOVA results for all cues and judgment for riding on the sidewalk.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	201	3675.82	18.2877	27.91	0.000
Blocks	191	3606.79	18.8837	28.82	0.000
Linear	4	52.56	13.1403	20.06	0.000
Direct	1	13.15	13.1514	20.07	0.000
Lanes	1	1.29	1.2920	1.97	0.160
Traffic	1	4.16	4.1566	6.34	0.012
Time	1	33.96	33.9613	51.84	0.000
2-Way Interactions	6	16.47	2.7447	4.19	0.000
Direct*Lanes	1	0.17	0.1722	0.26	0.608
Direct*Traffic	1	0.27	0.2738	0.42	0.518
Direct*Time	1	2.46	2.4639	3.76	0.053
Lanes*Traffic	1	0.35	0.3545	0.54	0.462
Lanes*Time	1	4.77	4.7660	7.27	0.007
Traffic*Time	1	8.44	8.4378	12.88	0.000
Error	2870	1880.28	0.6552		
Total	3071	5556.10			

ANOVA results for all cues and judgment for riding against traffic.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	201	2905.99	14.4577	29.36	0.000
Blocks	191	2835.59	14.8460	30.15	0.000
Linear	4	61.10	15.2751	31.02	0.000
Direct	1	35.45	35.4492	72.00	0.000
Lanes	1	0.19	0.1875	0.38	0.537
Traffic	1	2.08	2.0833	4.23	0.040
Time	1	23.38	23.3802	47.48	0.000
2-Way Interactions	6	9.30	1.5493	3.15	0.004
Direct*Lanes	1	7.92	7.9219	16.09	0.000
Direct*Traffic	1	0.52	0.5208	1.06	0.304
Direct*Time	1	0.26	0.2552	0.52	0.472
Lanes*Traffic	1	0.38	0.3763	0.76	0.382
Lanes*Time	1	0.22	0.2201	0.45	0.504
Traffic*Time	1	0.00	0.0013	0.00	0.959
Error	2870	1413.10	0.4924		
Total	3071	4319.09			

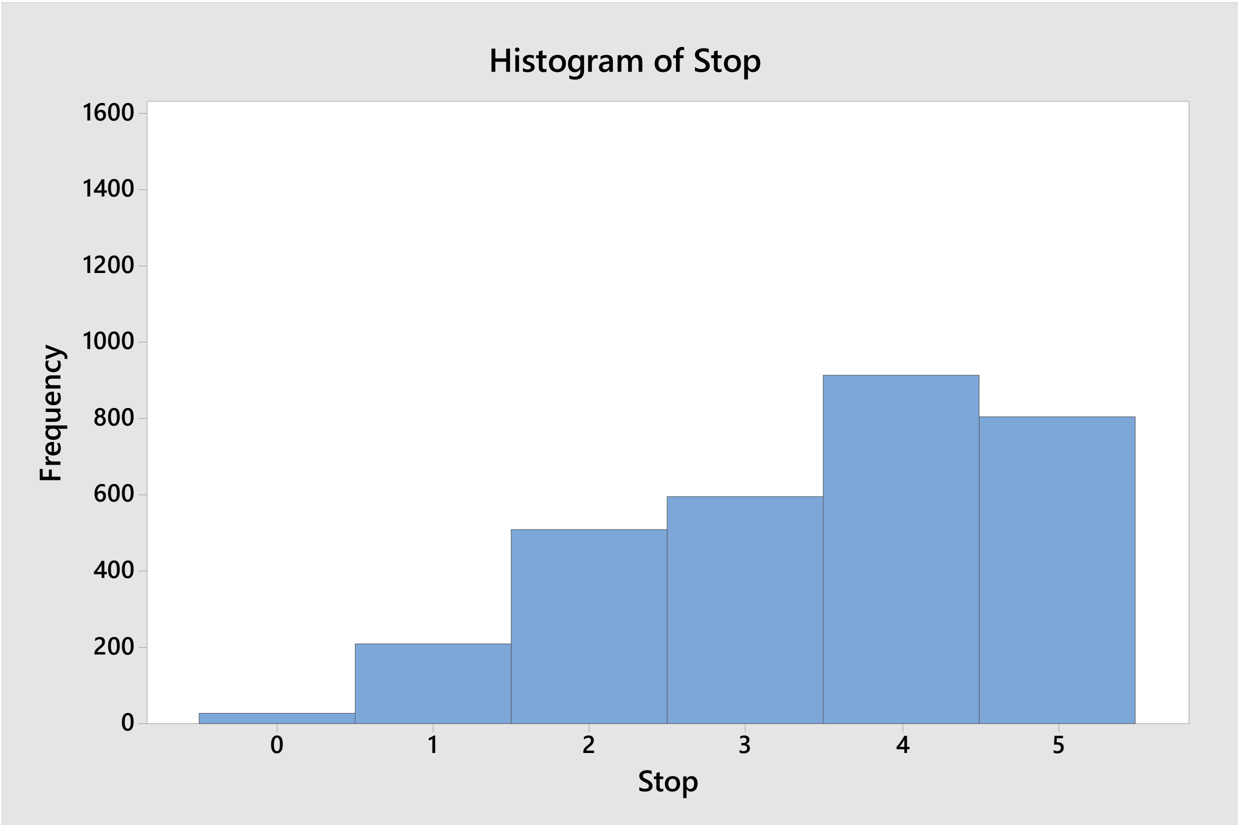
ANOVA results for all cues and judgment for weaving between cars.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	201	3620.61	18.0130	47.90	0.000
Blocks	191	3591.94	18.8059	50.01	0.000
Linear	4	23.30	5.8245	15.49	0.000
Direct	1	6.20	6.1992	16.49	0.000
Lanes	1	5.67	5.6719	15.08	0.000
Traffic	1	0.88	0.8802	2.34	0.126
Time	1	10.55	10.5469	28.05	0.000
2-Way Interactions	6	5.37	0.8956	2.38	0.027
Direct*Lanes	1	5.01	5.0052	13.31	0.000
Direct*Traffic	1	0.08	0.0833	0.22	0.638
Direct*Time	1	0.00	0.0000	0.00	1.000
Lanes*Traffic	1	0.22	0.2201	0.59	0.444
Lanes*Time	1	0.03	0.0326	0.09	0.769
Traffic*Time	1	0.03	0.0326	0.09	0.769
Error	2870	1079.20	0.3760		
Total	3071	4699.81			

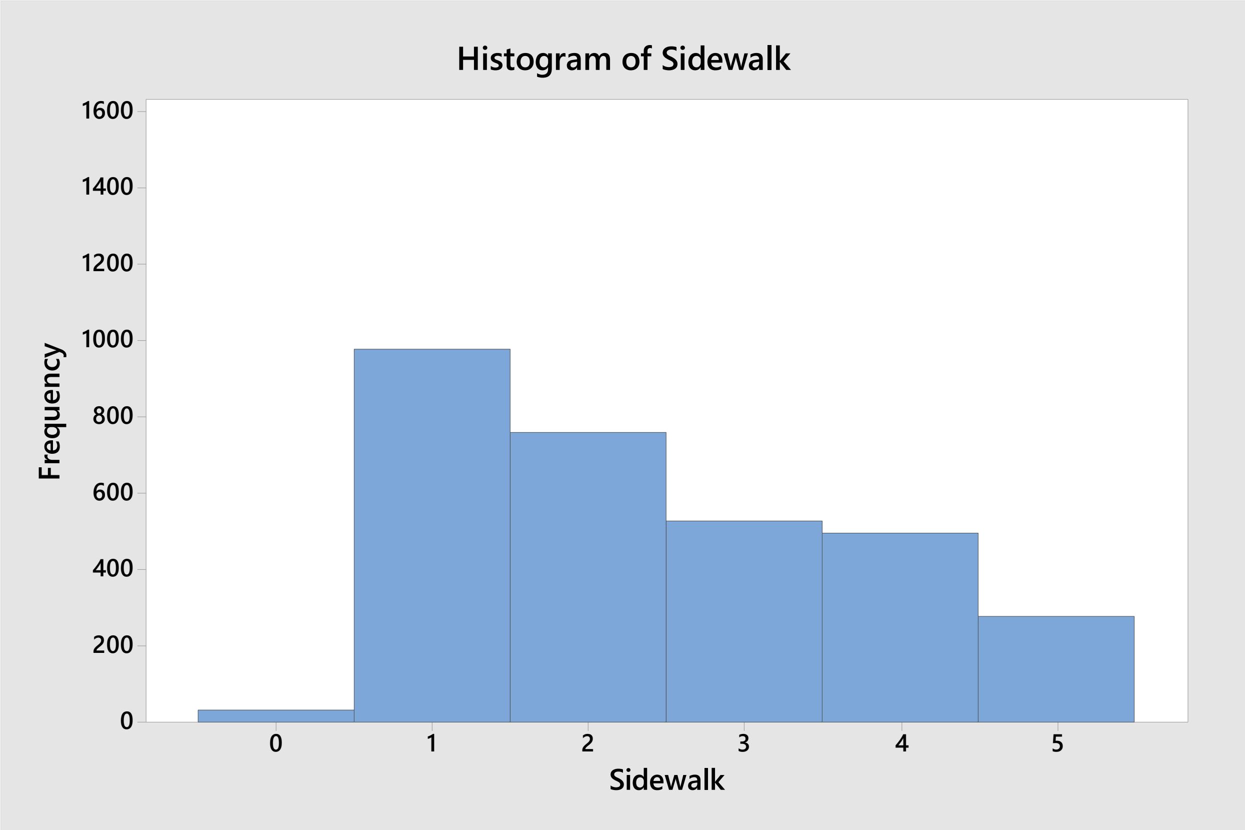
ANOVA results for all cues and judgment for weaving between pedestrians.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	201	3846.98	19.1392	38.27	0.000
Blocks	191	3809.24	19.9437	39.88	0.000
Linear	4	32.87	8.2184	16.43	0.000
Direct	1	2.64	2.6367	5.27	0.022
Lanes	1	3.26	3.2552	6.51	0.011
Traffic	1	1.10	1.0951	2.19	0.139
Time	1	25.89	25.8867	51.76	0.000
2-Way Interactions	6	4.86	0.8105	1.62	0.137
Direct*Lanes	1	0.57	0.5742	1.15	0.284
Direct*Traffic	1	0.05	0.0469	0.09	0.760
Direct*Time	1	0.02	0.0208	0.04	0.838
Lanes*Traffic	1	0.01	0.0117	0.02	0.878
Lanes*Time	1	2.88	2.8763	5.75	0.017
Traffic*Time	1	1.33	1.3333	2.67	0.103
Error	2870	1435.26	0.5001		
Total	3071	5282.24			

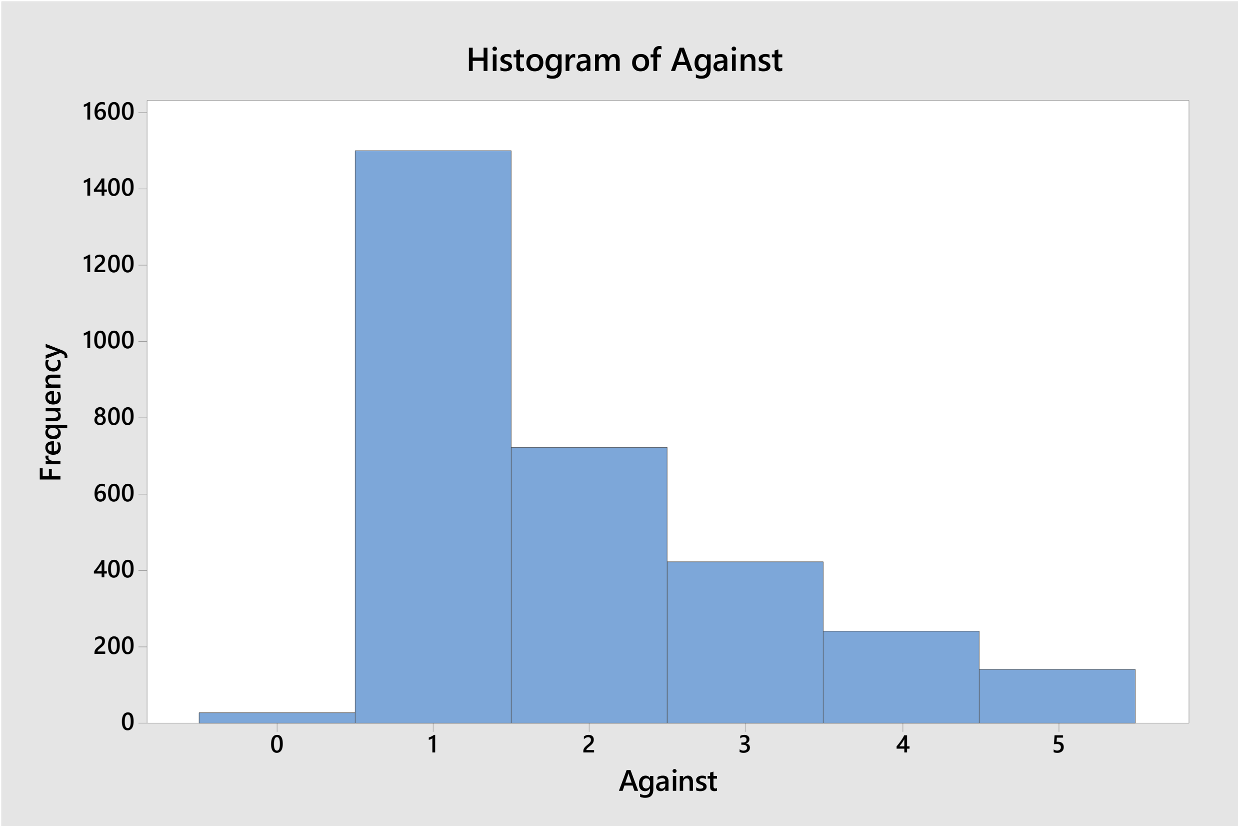
APPENDIX D. HISTOGRAMS OF THE POLICY CAPTURING DATA



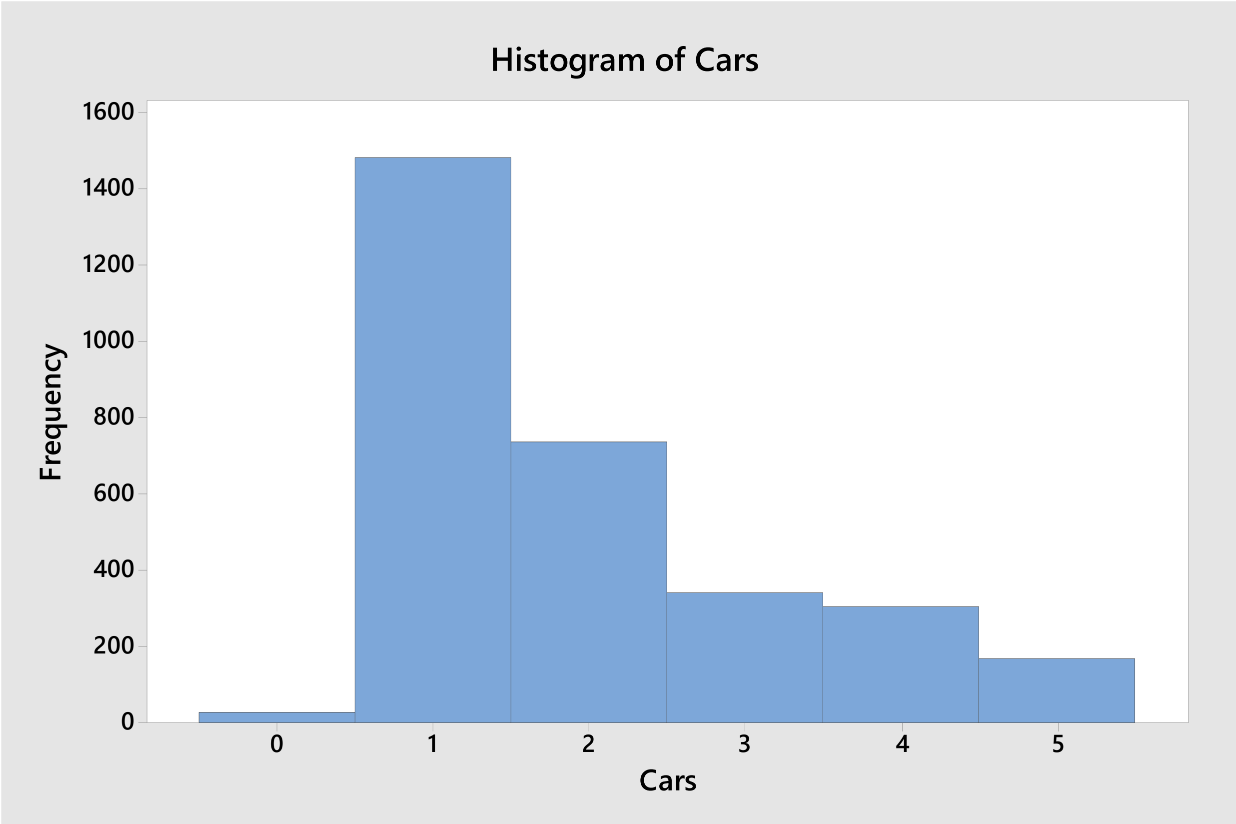
Histogram of responses for judgment: How likely are you to come to a complete stop at the stop sign?



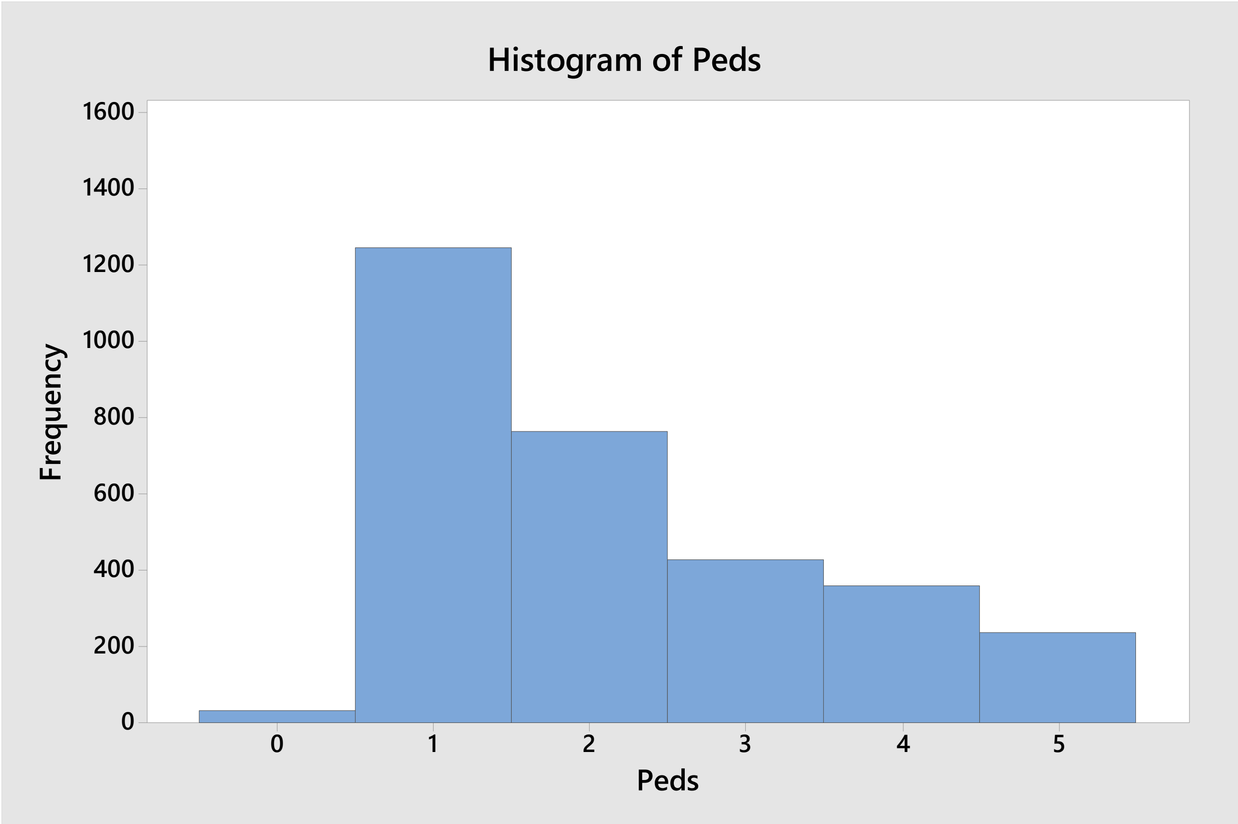
Histogram of responses for judgment: How likely is it that you would cycle on a non-bicycle designated area such as a sidewalk?



Histogram of responses for judgment: How likely is it that you would take your normal route against traffic?



Histogram of responses for judgment: How likely are you to weave between cars on the road?



Histogram of responses for judgment: How likely are you to weave between pedestrians?

APPENDIX E. POLICY RECOMMENDATIONS SUMMARY

The following policy recommendations are made based on the studies within this dissertation along with examples of how a local governing body, in this case Purdue University, may employ them on their campus:

1. Enforcement of established rules should be prioritized. As demonstrated in this work, (a) development of rules and regulations aimed towards cycling safety does not deter unsafe behaviors and (b) little enforcement currently occurs. For example, in the observational study no enforcement stops were observed regardless of violation rates above 97% for three behaviors across all observation locations. Enforcement of violations may provide incentive to obey traffic rules by providing consequences for riding unsafely thus improving adherence.
2. Incorporate cyclist behavior considerations into selection of safety intervention. Current guidance for the development and implementation of safety interventions do not take into account cyclists' behaviors. The NCHRP series 500 guide volume 18, which provides guidance for states to implement their respective SHSPs, offers strategies to reduce bicycling crashes based on archival data and crash statistics. The guidance fails to include behavioral data on cyclists' unsafe riding practices that may be an integral component of prospective interventions. Incorporating behavioral data collection and findings into the development of a program may modify the guidance for improving safety based on behavioral outcomes.
3. Incorporate cyclist behavior considerations into infrastructure design. This research has demonstrated cyclists behave differently based on infrastructure design characteristics. Cycling behavior should be taken into account when developing the roadway infrastructure, which may require using behavioral data to determine if alterations or modifications of the existing designs are necessary to maximize cycling safety and reduce unsafe cycling behaviors. For example, cyclists' utilization of bike paths differed depending on location, with those on the sides of roads being more frequently utilized than those adjacent to sidewalks.