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RISK AND BURDEN OF BICYCLE CRASH INJURIES IN IOWA AND NATIONWIDE

by

Cara Jo Hamann

An Abstract

Of a thesis submitted in partial fulfillment of the
requirements for the Doctor of
Philosophy degree in Epidemiology
in the Graduate College of
The University of Iowa

December 2012

Thesis Supervisor: Professor Corinne Peek-Asa

ABSTRACT

Increases in bicycling in the United States result in increased exposure to crashes and injuries. This research focuses on the factors involved in bicycle crashes in the United States and the state of Iowa. Data from the U.S. Nationwide Inpatient Sample and the Iowa Department of Transportation were used to address three aims: 1) estimate the burden and examine the outcomes of bicycle crashes resulting in hospitalizations nationwide by motor vehicle involvement, 2) describe how bicycle motor vehicle (BMV) crashes vary by intersection and non-intersection in Iowa, and 3) identify the impact of on-road bicycle facilities on BMV crashes in Iowa.

Using the U.S. Nationwide Inpatient Sample, years 2002-2009, the estimated annual burden of injury from bicycle-related hospitalizations equated to a billion dollars in hospital charges, over 100,000 days in the hospital, and over 34,000 non-routine discharges. We found that bicycling crashes involving motor vehicles had more hospital charges, longer stays, and greater odds of non-routine discharge.

We also used the Iowa Department of Transportation crash database, 2001 to 2010, to examine risk factors for BMV crash locations. We found that BMV crashes involve risk factors at person-, crash-, environment-, and population-levels that vary by intersection and non-intersection. Compared to intersections, non-intersection crashes were more likely to involve young bicyclists (0-9 years), locations outside city limits, with driver vision obscured, reduced lighting on the roadway and less likely involve failure to yield right of way.

Finally, we conducted a case site-control site study in Iowa, using crash data from 2007 to 2010 to investigate the impact of pavement markings (bicycle lanes and shared

lane arrows) and bicycle-specific signage on crash risk. Our results suggest that bicycle facilities are protective against crashes, with the most protective being the combination of both pavement markings and signage, followed by pavement markings alone, and then signage alone.

This project shows that bicycling carries a large burden of injury in the United States and that there are many contributing factors to bicycle crashes. It also provides evidence suggesting that infrastructure changes can decrease crash occurrence. There are also opportunities to intervene at other levels (e.g., person factors) to have an even greater impact in reducing the burden of bicycle injury.

Abstract Approved: _____

Thesis Supervisor

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Title and Department

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Date

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Graduate College
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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

Cara Jo Hamann

has been approved by the Examining Committee for the thesis requirement for the Doctor of Philosophy degree in Epidemiology at the December 2012 graduation.

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TABLE OF CONTENTS

LIST OF TABLES…… iv

LIST OF FIGURES…… v

LIST OF ABBREVIATIONS.....vi

CHAPTER

1. INTRODUCTION……..... 1
Prevention efforts and previous research..... 2
Current project..... 6

2. MOTOR VEHICLE INVOLVEMENT AND HOSPITALIZATIONS FOR BICYCLING INJURIES: UNITED STATES, ALL AGES, 2002-2009……..... 8
Abstract……..... 8
Introduction……..... 9
Methods……..... 11
Results……..... 15
Discussion……..... 17
Conclusions……..... 20

3. PERSON, CRASH, ENVIRONMENT, AND POPULATION CHARACTERISTICS OF BICYCLE-MOTOR VEHICLE CRASHES IN IOWA BY INTERSECTION AND NON-INTERSECTION, 2001-2010…..... 25
Abstract……..... 25
Introduction……..... 26
Methods……..... 27
Results……..... 31
Discussion……..... 35
Conclusions……..... 38

4. ON-ROAD BICYCLE FACILITIES AND BICYCLE CRASHES IN IOWA, 2007-2010……..... 47
Abstract…….. 47
Introduction……..... 48
Methods……..... 50
Results……..... 56
Discussion……..... 58
Conclusions..... 61

5. CONCLUSIONS……..... 67
Current study..... 67
Future directions..... 69

REFERENCES……..72

LIST OF TABLES

Table 2.1 Characteristics of bicycling injury hospitalizations by motor vehicle traffic involvement, Nationwide Inpatient Sample, 2002-2009, United States (N=41 469)……...22

Table 2.2 Injury characteristics for bicycle-related injury hospitalizations by motor vehicle collision involvement, Nationwide Inpatient Sample, 2002-2009….....……. 24

Table 2.3 Regression models predicting hospital length of stay, hospital charges, and non-routine discharge for bicyclists involved in motor vehicle traffic and non-motor vehicle traffic crashes, Nationwide Inpatient Sample, 2002-2009…..... 25

Table 3.1 Population characteristics of bicycle-motor vehicle crashes based on 2010 census in Iowa, 2001-2010……..... 41

Table 3.2 Person characteristics of bicycle-motor vehicle crashes in Iowa, 2001-2010 ……..... 42

Table 3.3 Crash and environmental characteristics of bicycle-motor vehicle crashes in Iowa, 2001-2010……... 43

Table 3.4 Predictors of bicycle-motor vehicle crashes occurring at non-intersections compared to intersections, Iowa, 2001-2010…… 45

Table 4.1 Characteristics of case and control intersections, Iowa, 2007-2010……. 66

Table 4.2 Unadjusted conditional logistic regression models predicting bicycle crashes at intersections, Iowa, 2007-2010, N=294……..... 67

Table 4.3 Predictors of bicycle crashes, multivariable conditional logistic regression, Iowa, 2007-2010, N=294……..... 68

LIST OF FIGURES

Figure 3.1 Annual average crash rate by zip code tabulation area, per 10 000 population, Iowa, 2001-2010…….. 47

Figure 3.2 Bicycle-motor vehicle crash distribution at intersections and non-intersections, selected counties, Iowa, 2001-2010……. 48

Figure 4.1 On-road bicycle facilities photographed during study data collection, Iowa, June-October, 2012……..... 65

LIST OF ABBREVIATIONS

BMV	Bicycle-motor vehicle
DOT	Department of Transportation
MVC	Motor vehicle crash
NIS	Nationwide Inpatient Sample
US	United States

CHAPTER 1

INTRODUCTION

Bicycling in the United States is increasing (Pucher, Buehler, & Seinen, 2011). There has been a 57% increase in the number of bicycle commuters between 2000 and 2009 (Alliance for Biking & Walking, 2012). These increases have also been seen in bicycling for recreation and exercise and in the use of bicycles in the occupational setting (e.g., bicycle police; IPMBA, 2012; Pucher, Buehler, & Seinen, 2011). Additionally, there was a 29% increase between 2010 and 2012 in the number of bicycle facilities (e.g., bicycle lanes, shared lane arrows, and bicycle-specific signage), which now stands at an average of 1.8 facilities per square mile in the United States (Alliance for Biking & Walking, 2012).

The body of literature related to bicycling and health indicates that increases in bicycling come with many benefits to both individuals and communities including: decreased obesity, cardiovascular disease, air pollution, noise, greenhouse gases and improved mental health (Transportation Research Board, 2012). Despite the positive impact of increased cycling on health and the environment, the inherent risk of cycling and the vulnerability of cyclists in traffic remain.

Annually, there are an average of 500 000 emergency department visits, 27 000 hospitalizations, and 800 deaths resulting from bicycle-related injuries in the United States (Centers for Disease Control and Prevention, 2010b; HCUP, 2012). Bicyclists are more vulnerable to injury and fatality than other road users, including passenger cars and trucks due to the lack of physical protection like that of the body of a car and differences in speed and mass compared to motor vehicles (Beck, Dellinger, & O'Neil, 2007; Elvik, Hoye, Vaa, & Sorensen, 2009). The risk associated with bicycling has also been found to

be higher in the United States in comparison to Canada and many European countries (Pucher & Buehler, 2006, 2008). One study found cyclist fatality rates at 5.8 per one billion kilometers in North America, versus 1.1 to 3.5 per billion kilometers in Europe (Pucher & Buehler, 2008). The disparity between countries suggests that changes can be made in the United States to make cycling safer and supports continued research on the causes of crashes and the evaluation of prevention methods (Pucher & Buehler, 2006; Pucher & Dijkstra, 2003). For these reasons, prevention of bicycle crashes and injuries should a public health priority.

Prevention Efforts and Previous Research

On multiple levels non-motorized transportation has become a priority in the United States over the past decade. Federal funding for non-motorized transportation increased significantly in the United States in the 1990s and as of 2010 the U.S. Department of Transportation declared the use of "complete streets" principles to design roadways to accommodate all modes of transportation, including bicycles (LaHood, 2010; Transportation Research Board, 2012). The League of American Bicyclists renewed and revamped their Bicycle Friendly Community program in 2002, which aims to improve conditions for bicycling through engineering, education, encouragement, enforcement, and evaluation (League of American Bicyclists, 2012). Additionally, the U.S. Centers for Disease Control and Prevention has recommended efforts related to policy to encourage physical activity by increasing "active transportation" infrastructure (e.g., bicycle lanes) and reducing injuries that result from collisions with motor vehicles (Centers for Disease Control and Prevention, 2010a).

Despite the prioritization, to date, efforts to make bicycling safer in the United States are minimal in scope. Historically, a large focus has been on helmet use policy and education among children via media campaigns and bicycle rodeos providing skills training. More recently, there has been a surge to incorporate bicycle facilities (paths, lanes, signage, etc.) into new or existing roadway and community plans. Research regarding bicycling crashes and injuries in the United States has mirrored these prevention efforts by focusing on children, helmets, and infrastructure and there has often been a focus on injury severity, as opposed to crash risk (Reynolds, Harris, Teschke, Cripton, & Winters, 2009; M. J. Thompson & Rivara, 2001).

A review of a priori research on bicycling crashes, injuries, and fatalities reveals several trends and established risk factors, but also many gaps in knowledge. At the person-level, we have learned that bicycle helmets decrease head injuries by 74 to 85% and reduce injury severity, but they do not help to prevent crash occurrence and are only effective if worn properly (Depreitere et al., 2004; Maimaris, Summers, Browning, & Palmer, 1994; O'Rourke, Costello, Yelland, & Stuart, 1987; Powell & Tanz, 2000; Puranik, Long, & Coffman, 1999; Rivara, Astley, Clarren, Thompson, & Thompson, 1999; Rivara, Thompson, Patterson, & Thompson, 1998; Schulman, Sacks, & Provenzano, 2002; D. C. Thompson, Rivara, & Thompson, 2000; D. C. Thompson, Rivara, & Thompson, 1996; M. J. Thompson & Rivara, 2001). We also know that males have higher crash risk. Previously children made up the largest proportion of injuries and fatalities from bicycle crashes, but that has changed to adults over the last two decades with the highest rates among the 45 to 54 age group (Insurance Institute for Highway Safety, 2012; National Highway Traffic Safety Administration, 2011; Rosenkranz &

Sheridan, 2003; M. J. Thompson & Rivara, 2001). In terms of injury type resulting from bicycle crashes, past research has shown that extremity and soft tissue injuries are the most common, but that head injuries have the poorest outcomes (HCUP, 2012; Heesch, Garrard, & Sahlqvist, 2011; Maimaris et al., 1994; Powell & Tanz, 2000; Puranik et al., 1999; M. J. Thompson & Rivara, 2001). Alcohol intoxication of the bicyclist has also been found to increase injury severity and one-third of fatal bicycle-motor vehicle (BMV) crashes involve an intoxicated bicyclist or motorist (Li, Baker, Smialek, & Soderstrom, 2001; Li et al., 1996; National Highway Traffic Safety Administration, 2011; Rivara, Thompson, & Thompson, 1997).

At the crash-level, motor vehicle involvement is also a risk factor for more serious injuries and death (Rivara et al., 1997; Siman-Tov, Jaffe, Peleg, & Grp, 2012; M. J. Thompson & Rivara, 2001), but we do not know the extent of the burden of these injuries in terms of economic impact and hospitalization outcomes over the past decade. Injury severity studies have also shown many environmental variables are risk factors for poorer outcomes including: unlit roadways, wide roads, perceptible road grades, and one-way streets (M. J. Thompson & Rivara, 2001). However, injury severity studies do not examine factors as they relate to crash occurrence, so the results may not be useful in efforts to prevent crashes from happening.

At the environmental-level we know that traffic-related fatal bicycle crashes most commonly occur in urban areas (70%), at non-intersections (67%), and between 4 and 8 p.m. (29%) (National Highway Traffic Safety Administration, 2011), but the factors contributing to these trends are unclear. The literature has mainly focused on bicycle-specific infrastructure. Overall, this research area is particularly sparse, but growing,

which is likely due to increases in the prevalence of the bicycle facilities in the United States. Infrastructure changes are considered a good investment as a prevention approach for several reasons: they are population-based, so wide reaching; 2) they do not require active participation from users, unlike helmets; and 3) they do not require repetition as do educational campaigns and enforcement of laws (Reynolds et al., 2009).

Existing research on bicycle-specific infrastructure is made up of a large proportion of European studies, which are often focused on intersections, while North American studies have had a larger focus on non-intersections (Reynolds et al., 2009). The non-intersection focus within North America may be part of the emphasis on bicycle crashes involving children, which happen more often in non-intersection locations among young children (Table 3.2, Chapter III; D. N. Moore, W. H. Schneider, P. T. Savolainen, & M. Farzaneh, 2011a). Lessons learned from existing literature indicate the following: roundabouts can decrease conflicts between cars and bicycles when they are designed with separated cycle lanes; on-road bicycle lanes reduce injury rates and collision frequency, the impact of off-road bicycle paths is not clear; and riding on sidewalks increases crash and injury risk (Daniels, Brijs, Nuyts, & Wets, 2009b; Reynolds et al., 2009).

Overall, in the United States the bicycle crash and injury literature contains many gaps. Some areas of bicycle research have mixed findings, so conclusions cannot be definitively made, including the impact of socioeconomic status and how much rider error, motorist error, and environmental aspects individually contribute to crash risk (M. J. Thompson & Rivara, 2001). Understudied or missing knowledge also includes: study of shared lane arrows and bicycle-specific signage, low density population areas,

examination of the influence of risk factors across multiple levels (e.g., person, crash, environment, etc.), identification of risk factors as they relate to crash occurrence as opposed to injury severity, and a picture of the national burden from bicycle crashes.

Current Project

The long-term goal of this research is to reduce the number of fatalities and injuries associated with bicycle crashes and encourage more bicycling by finding ways to create safer environments for riders. To work toward this goal, we conducted two analytic studies of existing datasets and one case site-control site study using crash-sites as the cases and non-crash sites as the controls. These studies were designed to provide insight into the sources of this public health problem and provide an evidence base to guide prevention of crashes, including which groups to target educational campaigns to and which elements city planners and traffic engineers should consider in the design of roadways to accommodate bicyclists.

Additionally, the current body of work addresses many of the existing gaps in the literature. We started at the macro-level, by estimating the burden of injury and examining the outcomes of motor vehicle crashes (MVCs) and non-MVC bicycle crashes in the United States for all ages. We then narrowed our focus to the statewide-level and BMV crashes in the sparsely populated state of Iowa by intersection and non-intersection, again including all ages. Finally, we evaluated the safety impact of on-road bicycle facilities (bicycle lanes, shared lane arrows, and signage) on BMV crashes at intersections in four counties in Iowa.

Specifically, we had three aims:

Specific Aim 1: Estimate the burden of bicycle crashes on length of stay, total hospital charges, and non-routine discharge in the United States for years 2002 through 2009 stratified by motor vehicle involvement.

Specific Aim 2: Describe the characteristics and calculate the rates per capita of bicycle crashes in Iowa from 2001 to 2010, stratified by location (intersection/non-intersection).

Specific Aim 3: Identify the safety impact of on-road bicycle facilities on bicycle crashes in Iowa by comparing bicycle crash sites (case sites) with those of control sites from 2007 to 2010, with comparisons at both the overall facility-level vs. no facility-level and of differences between facility types.

CHAPTER 2

MOTOR VEHICLE INVOLVEMENT AND HOSPITALIZATIONS FOR BICYCLING INJURIES: UNITED STATES, ALL AGES, 2002-2009

Abstract

Background/Purpose: Bicycling and bicycling injuries have increased over the past decade in the US, but research on current risk factors and outcomes has lagged behind. This study aims to fill these gaps by examining outcomes and the burden of injuries resulting in hospitalizations for bicycle crashes with and without motor vehicle crashes (MVCs).

Methods: We included patients with primary or secondary diagnosis E-codes corresponding to MVC or non-MVC bicycle injury, drawn from the U.S. Nationwide Inpatient Sample (2002-2009). Descriptive statistics, linear regression, and logistic regression were used to examine patient and hospital characteristics (length of stay, total charges, non-routine discharges, and demographics) associated with hospitalizations for bicycling injuries by motor vehicle involvement.

Results: On average, from 2002 to 2009, there were an annually estimated 6877 MVC and 18 457 non-MVC bicycle injury hospitalizations nationwide. This translates to over $1 billion dollars of hospital charges overall, $425 million for MVC and $588 million for non-MVC per year. After controlling for covariates, MVC bicycling injury hospitalizations had an average length of stay that was two days longer (95% CI: 1.8-2.3) and an average hospitalization charge of $23 424 more (95% CI: $21 360-$25 538) than non-MVC. Those with MVC bicycling injuries were over two times as likely to have a non-routine hospital discharge than non-MVC (OR 2.22, 95% CI: 2.06-2.39).

Conclusions: MVC bicycling injuries result in longer hospital stays, higher costs, and result in more non-routine discharge than non-MVC, despite the fact that non-MVC hospitalizations are more frequent and result in overall higher total charges. Interventions are needed to focus on reducing the burden of MVC bicycle crashes and resulting injuries on society in the form of economics, productivity, and quality of life.

Introduction

Bicycling in United States has increased over the past two decades for both recreational and transportation purposes (Bureau of Transportation Statistics, 2002; League of American Bicyclists, 2009; Pucher & Dijkstra, 2000). The proportion of people who bike to work increased by 64% from 1990 to 2009 and the number of bicycle facilities (such as bicycle lanes) per square mile increased 29% in the two years from 2010 to 2012 (Alliance for Biking & Walking, 2012). These changes can be attributed to increasing individual and community priorities of physical fitness and environmentally-conscious transportation (Alliance for Biking & Walking, 2012).

Bicycle crashes and injuries are a public health priority because they are preventable, there are a large number of injuries and fatalities each year, and the number of vulnerable road users is increasing because bicycling is increasing. Bicyclists are identified as vulnerable road users due to lack of protection within a vehicle and differences in mass and speed compared to motor vehicles (Beck et al., 2007; Elvik et al., 2009), which leads to fatality and injury rates that are higher than passenger car occupants (Beck et al., 2007; Pucher & Dijkstra, 2000). For example, one nationally representative study found that bicyclists had 2.3 times as many fatalities and 1.8 times as many non-fatal injuries as the motor vehicle occupants, per 100 million person-trips s

(Beck et al., 2007), while others have reported bicyclists have up to 11 times the number of fatalities per billion kilometers traveled than passenger vehicle occupants (Pucher & Dijkstra, 2000).

The existing evidence regarding bicycle-related injuries has many shortcomings when attempting to estimate the current national burden. Much of the a priori research has focused on children, helmet use, limited geographic regions, and areas outside the United States, or was conducted over a decade ago (Mehan, Gardner, Smith, & McKenzie, 2009; Powell & Tanz, 2000; Puranik et al., 1999; Rivara et al., 1997; Shah, Sinclair, Smith, & Xiang, 2007; Siman-Tov et al., 2012). Previous studies showed that children and males were at the highest risk for injury and death from bicycle crashes (Rivara et al., 1997; Shah et al., 2007). However, the bicyclist fatality rates have changed considerably since 1975, when 67% of deaths were those age 16 or less. In 2000 this age group represented 28% of deaths and in 2010 represented only 11% (Insurance Institute for Highway Safety, 2012). Past research findings may not be generalizable to current bicycling populations and with bicycle-specific roadway infrastructure changes implemented in the United States throughout the past decade. Current research is needed to identify the incidence, burden, and characteristics of modern bicycling-related injuries.

One of the most important factors shown to be associated with bicycle crash severity is whether or not the bicyclist collides with a motor vehicle (MVC) or not (non-MVC). U.S. studies have shown that bicycle-MVCs are more severe and result in more deaths than non-MVCs (HCUP, 2012; Powell & Tanz, 2000; Rivara et al., 1997), although these findings are either limited in scope, dated, or strictly descriptive. For example, Rivara et al. (1997) found increased risk of fatalities and severe injuries when

bicycle crashes involved motor vehicles, but this study was restricted to the city of Seattle, Washington, and was conducted 15 years ago. A recent report examined bicycle-related hospitalizations and also found worse outcomes for MVCs, but they only looked at one year of data (2009) and did not adjust for potential confounding variables (HCUP, 2012).

With increases in bicycling miles traveled and changes in the bicycle roadway infrastructure, it is important to understand the overall burden and outcomes from bicycling injuries. The aims of the current study are to: 1) estimate the recent national burden of injury of bicycle crashes resulting in hospitalizations among all ages and crash types (MVC and non-MVC) and 2) examine the difference in outcomes and across risk factors when motor vehicles are involved.

Methods

Study design and setting, data source

The data source for this retrospective study was the Nationwide Inpatient Sample (NIS), years 2002 through 2009. The NIS is a nationally representative database of all-payer inpatient care in the United States and is part of the Healthcare Cost and Utilization Project (HCUP), maintained by the Agency for Healthcare Research and Quality (Agency for Healthcare Research and Quality, 2010). The NIS uses an algorithm that takes into consideration five different hospital characteristics (ownership/control, bed size, teaching status, urban/rural location, and region) to create a weight variable, available in the dataset, that can be used to estimate the total number of hospitalizations nationally.

Top procedures and diagnoses were aggregated by using Clinical Classifications Software (CCS) which takes the thousands of diagnosis and procedure codes from ICD-9-CM and collapses them into more meaningful and useful categories for describing the data (Healthcare Cost and Utilization Project, 2012). Hospitalizations with primary or secondary external cause of injury CCS e-codes 2607 and 2608 associated with pedal cyclist injuries were used to identify the study sample. The CCS e-code 2607 relates to crashes involving motor vehicles and the following ICD-9-CM e-codes within 2607 that include bicyclists are: E810.6, E811.6, E812.6, E813.6, E814.6, E815.6, E816.6, E817.6, and E818.6. CCS e-code 2608 relates to bicyclist crashes that do not involve motor vehicles and includes the following ICD-9-CM codes: E800.3, E801.3, E802.3, E803.3, E804.3, E805.3, E806.3, E807.3, E820.6, E821.6, E822.6, E823.6, E824.6, E825.6, E826.1, and E826.9.

Main outcome measures

The main outcomes of interest were length of stay (days), total hospital charges ($US dollars), and non-routine discharge. Hospital charges were adjusted for inflation to the year 2009 inflation rates for in-hospital care (Bureau of Labor Statistics, 2012). Non-routine discharge included: death and transfer to nursing facility, short-term hospital, or home health care.

Patient and hospital characteristics

Patient characteristics included age, race, sex, insurance type, and injury severity score (ISS). ISS ranges from 0 (least severe) to 75 (most severe) and is based on a scoring system that takes into account multiple injuries to a patient, divides them among six body regions, and then creates a total score based on the three most severely injured

regions (Baker, Oneill, Haddon, & Long, 1974). ISS for this study was obtained using a software program called ICDMAP-90 (Center for Injury Research and Policy of the Johns Hopkins University School of Public Health, 1997) which derived ISS from the primary and secondary ICD-9-CM diagnoses.

Due to missing values on race/ethnicity, 22% of cases were coded as unknown and retained for that variable, to avoid dropping them from the regression models. Missing values for all other variables were left out of analyses, with little impact because all had two percent or less missing.

Hospital characteristics serving as covariates included bed size, region, and hospital location (urban/rural). Prior to 2004, all metropolitan statistical areas (MSA) were categorized as urban, while all non-MSAs were rural (Healthcare Cost and Utilization Project, 2008). From 2004 to present, classifications were categorized by core-based statistical areas (CBSA), where metropolitan was considered urban, and micropolitan (population= 10 000 to 50 000)or non-core was rural, which resulted in slightly fewer rural designations for hospitals (Healthcare Cost and Utilization Project, 2008).

Analysis

Actual counts and national estimates of frequencies and percentages were tabulated for patient and hospital characteristics. National estimates were calculated using discharge-level weights that are provided by the Healthcare Cost and Utilization Project (HCUP) and available in the NIS dataset (Agency for Healthcare Research and Quality, 2010). A Rao-Scott chi-square test, which is a version of the Pearson chi-square test that

corrects for the clustered sample design, was conducted to test for an association between MVC and year (Rao & Scott, 1987).

Unadjusted logistic and linear regression models were used to evaluate the effect of motor vehicle involvement and potential confounders (sex, age, race/ethnicity, source of payment, hospital location, hospital bed size, and hospital region) on outcomes (LOS, total charges and non-routine discharge). ISS was not included as a covariate in any of the models because it is considered an intermediate in the causal pathway between the exposure (MVC/non-MVC) and the outcomes, and therefore inclusion would prevent the detection of the relationship between exposures and outcomes.

Multiple linear regression was used to examine motor vehicle involvement as a predictor of length of stay and total hospital charges. These adjusted models estimated how much longer lengths of stay (days) and how much more in hospital charges ($USD) MVC-related injury hospitalizations had in comparison to non-MVC. The total hospital charges model included LOS as a covariate in order to examine the difference in total charges between MVC and non-MVC that were not a result of the length of stay itself. Multivariable logistic regression was used to examine the impact of MVC-involvement on risk of non-routine hospital discharge.

Log transformations were performed on hospital charges and LOS to address the skewness of the data and to stabilize the variability of residuals in the models. Cook's D statistics were used to identify influential observations in model diagnostics. A cutoff of $D_i > 4/n$ (n=sample size) was used to remove observations that did not fit with the regression models. The LOS and hospital charges linear regression models were based on reduced samples, with 5.17% and 5.88% of influential observations removed, based on

model diagnostics. SAS Survey Procedures (e.g., PROC SURVEYLOGISTIC) in Version 9.2 were used to account for the complex study design by taking into account clustering variables and sample weights (SAS Institute Inc., 2002-2008).

Results

Hospitalization characteristics by MVC-Involvement (Table 2.1)

For 2002 through 2009, the NIS captured 11 260 MVC and 30 209 non-MVC-bicycling injury hospitalizations. This translates to a nationwide estimate of 6877 MVC-related and 18 457 non-MVC bicycle injury hospitalizations annually. The highest number of MVC-related hospitalizations occurred in 2003 (National estimate=7831), while the most non-MVC hospitalizations were in 2009 (National estimate=20 572). There was not a significant difference in frequency between years (Rao-Scott χ^2 p=0.24).

Males made up a majority of the hospitalizations overall (78.0%) and had more MVC-related (84.1%) than non-MVC (75.7%). A majority of hospitalizations, overall, were adults (18 or older; 66.5%) and non-MVC (72.8%). The youngest (0-10) and oldest (51-70 & 71+) age groups made up larger proportions of non-MVC than MVC (43.1% vs. 32%), while the older children (11-17) and middle age groups (18-30 & 31-50) were opposite, with larger proportions of MVC than non-MVC (67.7% vs. 56.2%).

For all races, a majority of hospitalizations were due to non-MVC crashes, with Whites making up the largest proportions across both categories. Blacks and 'Other' (includes Hispanic, Asian, & Pacific Islanders) made up 13.0% and 22.4% of MVC but only 6.3% and 13.3% of non-MVC bicycling hospitalizations. Conversely, Whites accounted for a greater proportion of MVC than non-MVC (56.3% vs. 46.6%).

A majority of both MVC (76.4%) and non-MVC (83.7%) hospitalizations were routine discharge or discharge alive, but more MVC were dead at discharge than non-MVC (3.0% vs. 0.5%). Over half of the hospitalizations were paid via private insurance for both MVC (51.0%) and non-MVC (53.2%). A larger proportion of MVC hospitalizations were self-pay or no charge (18.4%) compared to non-MVC (13.1%). Conversely, Medicare/Medicaid as payers made up a smaller proportion of MVC than non-MVC (22.8% vs. 27.8%).

In terms of hospital characteristics, most of the bicycle-related injuries were seen at large urban hospitals. MVC-related hospitalizations were 72.1% urban and 73.7% had a large number of beds, compared to 57.3% and 66.8% for non-MVC, respectively. The South and West regions of the United States had the largest proportions of crashes overall (29.9% and 31.9%). The South accounted for a larger proportion of MVC (32.2%) than non-MVC (29.1%), while the West had the reverse, with 29.0% MVC and 32.9% non-MVC.

Injury Characteristics: Injury Severity, Procedures, Diagnoses (Table 2.2)

MVC-related hospitalizations were more severe than non-MVC, with average injury severity scores of 10.41 (95% CI: 10.10-10.72) versus 7.80 (95% CI: 7.66-7.97). Among the diagnoses and procedures there were indications of increased severity for MVC hospitalizations. For example, 43% of diagnoses of MVC-related hospitalizations involved injuries to the head and face, compared to 32% among non-MVC. MVC-related hospitalizations had larger proportions of CT scans (6.29% MVC vs. 2.87% non-MVC) and continuous mechanical ventilation less than 96 hours (4.28% MVC vs. 1.88% non-MVC).

Total Hospital Charges, Length of Stay, and Non-routine Discharge (Table 2.3)

Annually, there are an estimated $1 billion dollars (95% CI 0.9-1.1) of total hospital charges, 102 965 days of stay (95% CI: 91 764-114 167) and 34 727 non-routine hospital discharges (95% CI: 31 500-37 954) resulting from bicycling injury hospitalizations. During the eight-year study period, 27% of the hospitalizations were MVC-related, but they made up 42% of the total annual hospital charges at a national estimate of $3.4 billion (95% CI: 2.8-3.9).

The average total hospital charges per visit were $62 214 (median $32 015) for MVC-related and $32 884 (median $20 577) for non-MVC. After adjusting for covariates including LOS, which is one of the main drivers of total charges, the average hospital charges were 38% more for MVC compared to non-MVC. The average LOS for MVCs was also longer than that for non-MVC at 5.88 days (median=2.44) versus 3.39 days (median=1.73). Adjusted LOS for MVC-related hospitalizations were on average 2.02 days (95% CI: 1.76-2.29) longer than non-MVC. Twenty-two percent of MVC-related hospitalizations resulted in non-routine discharge versus 15% of non-MVC. Adjusted odds of non-routine discharge for MVC-related injuries were 2.22 (95% CI: 2.06-2.39) times higher than non-MVC.

Discussion

During the eight-year study period, 2002-2009, more than 25 000 bicycling-related hospitalizations occurred annually. These hospitalizations accounted for a national estimate of $1 billion total hospital charges per year. Although not all bicycle crashes result in hospitalization, those that do carry a large financial burden on the healthcare system and the individuals involved.

Bicycle crashes that involved motor vehicles resulted in higher injury severity and increased risk of non-routine discharge (including death) than those that did not, but were less frequent than non-MVC hospitalizations. Average hospital charges per hospitalization and average LOS was longer for MVC vs. non-MVC hospitalizations. These results are consistent with previous studies. For example, one prospective cohort study reported 36% of admitted and 12.8% of not admitted injured bicyclists were involved in crashes with motor vehicles (Rivara et al., 1997). They also found that bicycle crashes that involved motor vehicles were 4.6 times (95% CI: 3.3-6.3) more likely to result in severe injury and 14.1 (95% CI: 4.1-53.5) times more likely to result in death (Rivara et al., 1997). However, that study was published over 15 years ago and showed a different distribution in age of hospitalized rider: they found 60% were aged 19 and under, while we found that 33% were 17 or under. Additionally, our study is nationally representative, while Rivara et al. (1997) focused on the city of Seattle, Washington.

A more recent study of trauma hospitalizations in Israel was also consistent with our results of poorer outcomes of bicycle crashes involving MVCs (Siman-Tov et al., 2012). They found crashes that involved motor vehicles had 10 times higher risk of death in hospital for adults (95% CI: 1.8-34.3) and 8 times for children ages 1 to 17 (95%CI: 1.2-85.3). They also found that MVC-related crashes had higher odds of LOS of seven or more days ($OR_{Children}$=1.3, 95% CI: 1.0-1.7; OR_{Adults}=1.6, 95% CI: 1.3-2.1), which is consistent with our results (Siman-Tov et al., 2012). However, demographically, our results differed somewhat from Siman-Tov et al. (2012) in terms of gender and age as our study had fewer males (78% vs. 87%) and fewer adults (28% vs. 37%) involved in MVC-

related bicycle crashes than the Israel study. This highlights the importance of proceeding with caution when generalizing results across borders.

Findings from this study can help to inform the development and evaluation of prevention approaches to reduce BMV crashes. Existing injury prevention approaches include helmet policies and promotion programs and the growing implementation of bicycle-specific infrastructure as part of the built environment, such as the installation of bicycle lanes and paths that has been rapidly growing in the United States in the past decade (Alliance for Biking & Walking, 2012; Pucher, Buehler, & Seinen, 2011). Use of information from this study, such as the impact of age, gender, and motor vehicle involvement on outcomes, can help to target and strengthen the impact of prevention efforts to reduce serious injuries and fatalities resulting from BMV crashes. Our results can also be used to explain the extent of the burden resulting from bicycle crashes, which can help bring this issue to the forefront and drive policy change. This is especially true given the existing knowledge that bicycling has been increasing in the United States and continues to grow, leading to increased exposure and potential risk of crashes and injuries (Alliance for Biking & Walking, 2012).

Limitations

This study used hospital charges to estimate financial burden, but the use of hospital charges does not capture the full cost to an individual and society in terms of long-term impacts. Additionally, the NIS provides weights which allows for calculation of national estimates, however these weights are based on a sample of hospitals nationwide, so we cannot be certain that the national estimates are a reflection of true numbers.

The use of e-codes to identify bicycle-related hospitalizations likely underestimates the actual number of cases. One study of the completeness of e-codes in the NIS database reported that 14% of injury cases were missing e-codes (Coben, Steiner, Barrett, Merrill, & Adamson, 2006), so we cannot be certain that our results speak to all bicycling crashes resulting in hospitalizations. We also cannot generalize our results beyond bicycle crashes resulting in hospitalizations. Our results are best generalized to like injuries, which do not include the least severe or most severe because crashes resulting in deaths prior to hospitalization, emergency department visits, and ones which did not require advanced medical care were not included in this study.

Conclusions

The NIS provides important and useful data. Our findings show that factors leading to hospitalization from a bicycle crash vary by motor vehicle involvement, resulting in longer stays, more charges, and poorer outcomes for motor vehicle-related crashes. This is especially important because the increases in bicycling increase exposure between bicycles and motor vehicles. Education, policy, and environmental changes are needed, with an emphasis on reducing collisions between bicycles and motor vehicles. The design for these changes needs to consider all ages.

Table 2.1
Characteristics of bicycling injury hospitalizations by motor vehicle traffic involvement, Nationwide Inpatient Sample, 2002-2009, United States (N=41 469)

	NIS Sample			National estimate				
	Total (N=41 469)	MVC (N=11 260)	Non-MVC (N=30 209)	Total (N=202 674)	MVC (N=55 018), n[a]	%	Non-MVC (N=147 656), n[a]	%
Year								
2002	4918	1345	3573	23 724	6560	11.9	17 164	11.6
2003	5370	1615	3755	26 133	7831	14.2	18 301	12.4
2004	5430	1484	3946	26 102	7091	12.9	19 011	12.9
2005	4936	1249	3687	24 014	6041	11.0	17 973	12.2
2006	4913	1381	3532	24 124	6743	12.3	17 381	11.8
2007	4944	1328	3616	24 191	6581	12.0	17 610	11.9
2008	5445	1430	4015	26 576	6933	12.6	19 644	13.3
2009	5513	1428	4085	27 810	7238	13.2	20 572	13.9
Sex[b]								
Male	32332	9466	22 866	157 994	46 247	84.1	111 746	75.7
Female	8347	1678	6669	40 759	8204	14.9	32 555	22.0
Age[b]								
0-10	5620	1204	4416	27 393	5851	10.6	21 542	14.6
11-17	8024	2358	5666	39 243	11 529	21.0	27 714	18.8
18-30	5260	1849	3411	25 845	9105	16.5	16 740	11.3
31-50	11 292	3400	7892	55 087	16 589	30.2	38 498	26.1
51-70	8754	1995	6759	42 843	9757	17.7	33 086	22.4
71+	2269	427	1842	11 012	2054	3.7	8958	6.1
Race/Ethnicity								
White	22 299	5249	17 050	108 814	25 617	46.6	83 198	56.3
Black	3383	1475	1908	16 414	7132	13.0	9282	6.3
Other	6531	2519	4012	31 923	12 335	22.4	19 589	13.3
Unknown	9256	2017	7239	45523	9935	18.1	35 588	24.1

Table 2.1 (continued)

Discharge disposition								
Routine or discharge alive	33 883	8598	25 285	165 636	42 040	76.4	123 596	83.7
Skilled nursing facility/ home health care/other facility	5913	1960	3953	28 879	9579	17.4	19 299	13.1
Short-term hospital	692	226	466	3395	1100	2.0	2294	1.6
Died	508	347	161	2454	1675	3.0	778	0.5
Against Medical Advice/Unknown	473	129	344	2312	623	1.1	1689	1.1
Payer Information[b]								
Medicare & Medicaid	10 970	2576	8394	53 660	12 569	22.8	41 091	27.8
Private, including HMO	21 771	5720	16 051	106 660	28 073	51.0	78 587	53.2
Self-pay/no charge	6063	2080	3983	29 498	10 113	18.4	19385	13.1
Other	2545	836	1709	12 270	4027	7.3	8242	5.6
Hospital location[b]								
Rural	16 139	3178	12 961	77 940	15 213	27.7	62 727	42.5
Urban	25 244	8057	17 187	124 329	39 688	72.1	84 642	57.3
Hospital bed size[b]								
Small	4071	839	3232	19 107	3851	7.0	15 255	10.3
Medium	9044	2155	6889	44 032	10 512	19.1	33 520	22.7
Large	28 268	8241	20 027	139 130	40 538	73.7	98 592	66.8
Hospital region								
Northeast	8457	2640	5817	43 589	13 692	24.9	29 897	20.2
Midwest	6754	1535	5219	33 871	7691	14.0	26 180	17.7
South	12 903	3797	9106	60 651	17 693	32.2	42 958	29.1
West	13 355	3288	10 067	64 564	15 942	29.0	48 622	32.9

MVC=motor vehicle crashes, HMO=health maintenance organization

[a] Weighted to discharges from all US community non-rehabilitation hospitals

[b] Sums < 41 469 are due to missing data.

Table 2.2
Injury characteristics for bicycle-related injury hospitalizations by motor vehicle collision involvement, Nationwide Inpatient Sample, 2002-2009.

MVC (N=55 018)[a]			Non-MVC (N=147 656)[a]		
	National Estimate[a]			National Estimate[a]	
	N	**95% CI**		**N**	**95% CI**
Average injury severity score	10.41	10.10-10.72	**Average injury severity score**	7.8	7.66-7.97
Top 10 Principal Diagnoses	**N**	**%**	**Top 10 Principal Diagnoses**	**N**	**%**
Fracture of lower limb	12982	28.36	Fracture of upper limb	26236	21.94
Other intracranial injury	10169	22.22	Fracture of lower limb	20533	17.17
Other fractures	5270	11.51	Other intracranial injury	17498	14.63
Concussion	4598	10.05	Fracture of neck of femur	11923	9.97
Fracture of upper limb	3705	8.10	Other fractures	10490	8.77
Skull and face fractures	3123	6.82	Skull and face fractures	8906	7.45
Open wounds of head, neck, and trunk	1635	3.57	Concussion	8661	7.24
Fracture of neck of femur	1450	3.17	Open wounds of head, neck, & trunk	3185	2.66
Open wounds of extremities	1100	2.40	Cellulitis and abscess	2484	2.08
Rehabilitation care, fitting of prostheses, or adjustment of devices	338	0.74	Open wounds of extremities	2140	1.79
Top 10 Principal Procedures			**Top 10 Principal Procedures**		
Treatment of fracture or dislocation of lower extremity (other than hip or femur)	8223	29.46	Treatment of fracture or dislocation of lower extremity (other than hip or femur)	14335	17.6
Treatment of fracture or dislocation of hip or femur	4049	14.51	Treatment of fracture or dislocation of hip or femur	12958	15.91
Other fracture and dislocation procedure	1934	6.93	Treatment of fracture or dislocation of radius or ulna	12602	15.47
CT scan	1755	6.29	Other fracture or dislocation procedure	11210	13.76
Continuous mechanical ventilation less than 96 hours	1194	4.28	Closed chest drainage	3093	3.80
Treatment of fracture or dislocation of radius or ulna	1138	4.08	Treatment of facial fracture or dislocation	3022	3.71
Traction, splints, or other wound care	1112	3.98	Hip replacement, total or partial	2285	2.8
Treatment of facial fracture or dislocation	949	3.40	CT scan	2342	2.87
Closed chest drainage	915	3.28	Traction, splints, or other wound care	1965	2.41
Endotracheal intubation	657	2.35	Continuous mechanical ventilation less than 96 hours	1532	1.88

MVC=Motor vehicle crashes, CI= Confidence interval

[a]Weighted to discharges from al US community, non-rehabilitation hospitals.

Table 2.3
Regression models predicting hospital length of stay, hospital charges, and non-routine discharge for bicyclists involved in motor vehicle traffic and non-motor vehicle traffic crashes, Nationwide Inpatient Sample, 2002-2009.

	Total	MVC[d] (N=55 018)	Non-MVC[d] (N=147 656)
Hospital charges, $USD[a,d]			
Total charges, $ billion (95% CI)[e]	8.1	3.4 (2.8-3.9)	4.7 (4.3-5.2)
Mean, per visit	40 903	62 214	32 884
Median, per visit	23 032	32 015	20 577
Predicted difference in average charges (95% CI)		23 424 (21 360-25 538)*	Ref
Length of stay, days[b,d]			
Mean, per visit	4.06	5.88	3.39
Median, per visit	1.86	2.44	1.73
Predicted difference in average LOS (95% CI)		2.02 (1.76-2.29)*	Ref
Non-routine discharge[c,d,e]			
Total N[f]	34 727	12 355 (22.4%)	22 372 (15.2%)
OR (95% CI)		2.22 (2.06-2.39)*	Ref

MVC=motor vehicle crashes, CI=confidence interval, Ref=reference, OR=odds ratio

[a]The model for hospital charges was based on 39 030 observations after 2439 potentially influential observations were removed. Total charges were adjusted for inflation to the year 2009 inflation rates for in-hospital care. This model was adjusted for race, sex, year, age, hospital bedsize, hospital location, payer, and length of stay.

[b] The model for LOS was based on 39 326 observations after 2143 potentially influential observations were removed. This model was adjusted for race, sex, year, age, hospital bedsize, hospital location, and payer.

[c] The model for non-routine discharge was based on 40 007 observations due to 1462 cases with missing values. This model was adjusted for race, sex, year, age, hospital bedsize, hospital location, and payer.

[d]Weighted to discharges from al US community, non-rehabilitation hospitals.

[e]Non-routine discharge includes discharge to skilled nursing facility, short-term hospital, home health care, or other facility

[f]Totals are for the entire 8-year study period.

*p<0.01

CHAPTER 3

PERSON, CRASH, ENVIRONMENT, AND POPULATION CHARACTERISTICS OF BICYCLE-MOTOR VEHICLE CRASHES IN IOWA BY INTERSECTION AND NON-INTERSECTION, 2001-2010

Abstract

Background: Bicycling has increased in popularity in the United States in the past decade, but crashes and resulting risk of injuries and fatalities remain high. The purpose of this study was to identify how crash characteristics differed for bicycle crashes that occur at intersections and non-intersections.

Methods: The Iowa DOT crash database for the years 2001 through 2010 was used to identify bicycle-motor vehicle (BMV) crashes and associated person, crash, and environment characteristics. Population-level data were drawn from the 2010 U.S. Census and the 2010 American Community Survey. Descriptive statistics, GIS mapping, and multivariable logistic regression were used to examine factors associated crash risk and crash location.

Results: Compared to intersections, non-intersection BMV crashes had higher odds of involving young bicyclists (0-9 years; OR: 1.9, 95%CI: 1.2-2.8), location outside city limits (OR: 6.0, 95%CI: 4.0-9.0), with driver vision obscured (OR: 1.5, 95% CI: 1.2-1.9), reduced lighting on roadway (OR: 2.0, 95% CI: 1.6-2.7), and in areas with low population density (population 467-1013; OR: 2.0, 95%CI: 1.1-3.5) and lower odds when the bicyclist (OR: 0.4, 95% CI: 0.3-0.6) or motorist (OR: 0.6, 95% CI: 0.5-0.9) failed to yield right of way.

Conclusions: BMV crashes involve factors at multiple levels and many of these factors vary by location (intersection/non-intersection). Results from this study support the need to include all types of road users, both motorists and non-motorists, in consideration of the built environment and when developing prevention methods for making roadways safer.

Introduction

In the United States bicycling has become more popular in the past decade and continues to grow. More people have been riding bicycles for both transportation and recreation purposes and this can be attributed, in part, to health and environmental benefits, avoidance of traffic congestion, rising gas prices, and changes in infrastructure to better accommodate bicyclists (Alliance for Biking & Walking, 2012; Bureau of Transportation Statistics, 2002; Pucher, Buehler, Merom, & Bauman, 2011; Reynolds et al., 2009). However, the number of bicycle crashes remains high and the fatality rates per distance traveled and per person-trips are much higher for bicycles than motor vehicles (Beck et al., 2007; Pucher & Dijkstra, 2000).

Research examining causes of and prevention methods for bicycle crashes has lagged behind the growth in the use of bicycling in the United States. The current body of literature related to bicycling is increasing, but the focus is on large metropolitan areas and does not fully explore rural areas, small towns, and small metropolitan areas (Pucher, Buehler, & Seinen, 2011). These overlooked areas have not been immune to the surge in bicycling rates and positive changes in bicycling infrastructure (Pucher, Buehler, & Seinen, 2011; Rails-to-Trails Conservancy, 2012).

This study investigates the characteristics and factors associated with BMV crash occurrence and which factors are variably attributable to where crashes happen: intersections versus non-intersections. Existing evidence on BMV crashes has found that intersection crashes are more prevalent than non-intersection crashes, but non-intersection crashes result in more severe injuries and a higher risk for fatality (e.g.,D. N. Moore, W. H. t. Schneider, P. T. Savolainen, & M. Farzaneh, 2011b; National Highway Traffic Safety Administration, 2011). However, the characteristics that account for these differences between intersection and non-intersection crashes have not been fully evaluated, which is especially true for sparsely populated areas, like the mostly rural state of Iowa.

The objective of this study is to examine characteristics of bicycle crashes, overall, and to determine which factors increase the odds of a crash occurring at a non-intersection versus an intersection. We examined bicycle crashes in Iowa from 2001 to 2010 across four categories of factors related to those crashes: person, crash, environment, and population.

Methods

Design and Data

This cross-sectional retrospective study includes person, crash, and environment data from the State of Iowa Department of Transportation (DOT) crash database for years 2001 to 2010. The Iowa DOT crash database contains all motor vehicle crashes (MVCs) that were reported via a police report or driver's report. Bicycle crashes were identified from the dataset by selecting non-motorist or seating type as "pedalcyclist" or "pedalcyclist passenger". The crash database is organized hierarchically with multiple

subsets of data starting at the crash-level and ending at the person-level. These subsets were linked by crash key and person identifiers, resulting in a person-level dataset. Three percent (N=140) of the persons in this dataset were in crashes that involved more than one bicyclist.

Education and household income by census tract were obtained from the American Community Survey, 5-year estimates, 2010. Population density by zip code tabulation area (ZCTA) was obtained from the 2010 U.S. Census. All of these population-level data were obtained via the American Fact Finder web site (U.S. Census Bureau, 2012) .

For each crash, X and Y coordinates of the crash location were available in the DOT dataset. We used these variables to map the crash locations using ArcGIS software (ESRI, 2011). ArcGIS was also used to spatially identify the ZCTA and census tract of each crash. A ZCTA is a U.S. Census entity that approximates a zip code area. Census tracts are larger than ZCTAs. ZCTAs were used for population density in this study because they are the small enough to approximate variations in population density as one would travel through a town. Census tracts were used for education and household income because they were the smallest division available for which reliable data could be assigned (these estimates are not considered reliable when reduced down to smaller areas, like a ZCTA). Crash locations were linked to population density by ZCTA and education and income by census tract, and appended to the crash dataset to be included in analyses.

Intersection vs. Non-Intersection Crashes

The main outcome used for this analysis was whether the crash occurred in an intersection or a non-intersection location. This location was determined using the geo-

mapped crashes and the road type variable in the Iowa DOT dataset. For this study, we defined intersections as locations where two roadways meet. Specifically, intersections in the current study are those coded as one of the following: four-way, T, Y, five-leg or more, offset four-way, intersection with ramp, on-ramp merge area, off-ramp diverge area, on-ramp, off-ramp, with bike/pedestrian path, or other intersection. Non-intersections are those reported as one of the following: non-intersection no special feature, bridge/overpass/underpass, railroad crossing, business drive, farm/residential drive, alley intersection, crossover in median, or other non-intersection. These definitions of intersection and non-intersection are standard in traffic engineering.

Person, Crash, and Environmental Variables

We examined four categories of variables to determine their relationship with crash location (intersection/non-intersection): person, crash, environment, and population. Person variables included age and gender of bicyclist and motorist and safety devices of bicyclist (helmet, reflective clothing, lighting). Crash characteristics included motor vehicle type and action, day of week, time of day, season, location (urban/rural), motorist and bicyclist contributing circumstances (e.g. failure to yield right of way), and major cause (both motorist & bicyclist, motorist only, bicyclist only, neither). Environmental characteristics included posted speed limit, vision obscurement (yes/no), surface conditions (dry, wet, other), and reduced lighting (yes/no). Person, crash, and environmental characteristics were all obtained from the Iowa DOT crash database.

Population Variables

Population-level characteristics included population density by ZCTA, education by census tract (high school degree or higher, bachelor's degree or higher), and annual

household income by census tract. Population density was categorized into quartiles, based on Iowa's population distribution in the 2010 census and then each ZCTA was assigned to one of the resulting four categories. Education and annual household income were categorized into above or below state median for each census tract.

Analysis

Descriptive statistics including frequencies and proportions were examined. Pearson chi-square tests were performed to examine the relationship between exposure and outcome variables. Crash rates per capita were calculated and mapped using ArcGIS. The GIS mapping was then used to obtain a visual representation of crash patterns and calculate crash rates per capita within ZCTAs. Distributions of crashes by intersection or non-intersection within selected counties were mapped.

Five sequential multivariable logistic regression models were used to identify the characteristics which were most strongly associated with non-intersection crashes, as compared to intersection crashes. These five regression models were built in succession and incorporated, in a cumulative sequence, four categories of variables (person, crash, environment, population). The first model examined person-level variables, and successive models added new variable categories while retaining only those that were significant from the previous model. Significance to remain in successive models was assigned at the $p=0.05$ level. Thus, the first model included person-level variables and those that were significant were retained in model two while adding crash variables. Variables significant in model two were retained in model three (person, crash, environment), and this continued through model five. Model five, the final model, contained all of the person, crash, environmental, and population variables that were

significant. Likelihood ratio tests were used to compare the nested models to each other and adjusted R^2 values were examined to determine how much variance was accounted for by each model.

Results

Bicycle Crashes in Iowa

From 2001 to 2010 there were 4136 bicyclist crashes in the Iowa DOT database, 72 of which were excluded due to missing data. The resulting 4064 crashes were included in this analysis. There was an increased number of crashes in 2004 and again from 2006-2008 when the number of crashes exceeded over 400 each year (χ^2 $p < 0.01$). Overall, the average number of police-reported crashes during the study period was 406 per year. Although intersection crashes were more frequent, there was not a significant difference in the proportion of crashes occurring at intersections versus non-intersections by year ($p=0.60$).

The driver of the motor vehicle was charged in 19.2% of crashes (N=782), although 31.1% were unknown. Whether or not the bicyclist was charged was not available in our dataset. Therefore, instead, we looked at contributing circumstances of both bicyclists and motorists.

Figure 3.1 shows annual average crash rates per 10 000 population by ZCTA, which were 2.7 overall and ranged from 0.0 to 28.4 across Iowa's ZCTAs. Additionally, there was a high correlation between high population density and number of crashes ($r=0.72$, $p<0.001$), which can be seen in Figure 3.1, but the figure also shows there were some places with high crash rates that do not have dense populations.

Population-level crash characteristics (Table 3.1)

Over 90% of all the BMV crashes occurred in the top 25% of the most densely populated parts of Iowa. In contrast, 75% of the zip code areas in Iowa have populations of 2456 or less, but only 9.5% of the crashes occurred in those areas.

More bicycle crashes happened in socioeconomically disadvantaged areas. Nearly three-quarters (74%) of crashes occurred in census tracts that were below the state median annual household income (state median=$48,872). Two-thirds (66%) of crashes occurred in census tracts that had below state median proportions of persons with bachelor's degrees or higher (state median=24.5%). Additionally, over half (57%) occurred in census tracts with below state median proportions of persons with high school degrees or higher (state median=89.9%).

Distribution of Crashes by Intersection/Non-Intersection

A majority of the BMV crashes in our dataset occurred at an intersection (N=2324, 57%). More non-intersection than intersection crashes occurred outside of incorporated city limits. Figure 3.2 highlights the distribution of intersection and non-intersection crashes in three counties to clearly illustrate this pattern. The three counties displayed were chosen because they were among the most densely populated counties in the state. However, the pattern shown is similar throughout the state.

Day of week, time of day, season, surface conditions, and age of motorist were not found to vary by location (intersection/non-intersection), therefore they were not considered in the regression analyses (see Tables 3.2 & 3.3). Bicyclist gender was included in Model 1, despite lack of significance at the p=0.05 level, due to the evidence

in the existing literature showing that gender is a strong predictor of crash risk (M. J. Thompson & Rivara, 2001). Bicyclist devices varied by intersection, with more safety devices (e.g., helmets) used in non-intersection crashes, but 16.6% of cases were other/unknown/not-reported, so we cannot draw any conclusions and did not include that variable in our regression model.

Risk factors for intersection and non-intersection crashes

Table 3.4 shows the results of the five sequential models that differentiate intersection and non-intersection crashes, with the goal of examining how different variables contribute, not strictly to find out how much variance is explained. The first model of person-level characteristics contains bicyclist age and gender and motorist gender. All three of these variables were significant ($p<0.05$) in this adjusted model, specifically with male (bicyclists and motorists) and the 0-9 age group having higher odds of non-intersection crashes.

All of the person variables from model 1 were included in model 2 and crash characteristics were added: location (rural or urban), bicyclist and motorist contributing circumstances, major cause (bicyclist, motorist, both, neither), and motor vehicle action (straight, turning, other). Most of the new crash characteristics were significant, as well as bicyclist age. Gender, bicyclist darting, and motorist swerving/evasive action were not significant in this model. Rural crashes had especially high odds of occurring at non-intersections (OR 6.2, 95% CI 4.2-9.2). Both bicyclist and motorist contributing circumstances (improper crossing, failure to yield right of way, etc.) were more likely to be reported at intersections.

For Model 3, gender and swerving/evasive action were removed and environmental characteristics (posted speed limit, vision obscurement, and reduced lighting) were added. Speed limit was not significant, but all other variables were. Vision obscurement and reduced lighting both showed increased odds of crash location being at a non-intersection.

In Model 4, population-level characteristics of population density, median household income, and education were added to the significant variables from Model 3. Population density was the only one of these new variables that showed a significant contribution to crash location; with non-intersection crashes more likely in the second-lowest quartile of density (467 to 1013 persons per zip code). All the included person, crash, and environment variables remained significant in this model.

Model 5, the final model, contained the significant variables from Model 4. This final model shows that variables from all four levels (person, crash, environment, and population) were independently significant in predicting the odds of non-intersection crashes compared to intersection crashes. Young children (0-9 years old) were nearly two times as likely to be involved in non-intersection crashes compared to older age groups (OR 1.9, 95% CI: 1.2-2.8).

Rural crashes, bicyclist and motorist contributing circumstances, major cause, and motor vehicle action were crash characteristics that influenced crash location (non-intersection vs. intersection). Crashes that happened outside city limits (rural) were six times more likely to happen at a non-intersection than an intersection (OR 6.0, 95% CI: 4.0-9.0). Crashes with a bicyclist who failed to yield right of way to a car (OR 0.4, 95%CI: 0.3-0.6) or failed to obey traffic signs/signals/officers (OR 0.1, 95%CI: 0.1-0.2)

were much less likely to occur at a non-intersection than intersection compared to those without those contributing circumstances. Crashes where the motorist failed to yield right of way were 40% less likely to be at non-intersections than those without this circumstance (OR 0.6, 95% CI: 0.5-0.9). Compared to crashes where neither the motorist or bicyclist were listed as responsible, crashes in which only the bicyclist was responsible were more likely to be at non-intersections (OR 1.6, 95% CI: 1.2-2.1). Crashes in which the motor vehicle was turning (left, right, U-turn) were 60% less likely to have been non-intersection crashes (OR 0.4, 95% CI: 0.3-0.4).

Non-intersection crashes were more likely to have vision obscurement (OR 1.5, 95% CI: 1.2-1.9) and reduced lighting (OR 2.0, 95% CI: 1.6-2.7).

Population characteristics did not play a large role in location (intersection/non-intersection) of bicycle crashes, with the exception of population density. ZCTAs that had populations between 467 and 1013, likely to be close to small towns, had two times the odds of the crash happening at a non-intersection (95%CI: 1.1-3.5), compared to the most densely populated ZCTAs (populations of 2457 or more).

A Hosmer-Lemeshow goodness-of-fit test indicated no evidence of poor fit ($\chi 2=13.52$, $p=0.10$) for the final model (Model 5). We also conducted likelihood ratio tests to compare Model 4 to Model 5, which showed significant contribution of the additional variables in Model 4 ($\chi 2=30.14$, $df=3$, $p<0.001$). However, Model 4 showed lack of fit according to Hosmer-Lemeshow goodness-of-fit test ($\chi 2=15.95$, $p=0.04$) and did not account for any more variance than Model 5 (adjusted R^2 for Model 4 and Model 5 = 0.22). Thus, Model 5 provided the best profile of predictive characteristics.

Discussion

Our results show that person, crash, environment, and population characteristics were all independent predictors of whether a crash occurred at an intersection or non-intersection. Compared to intersections, when a BMV crash occurs at a non-intersection it is more likely have the following characteristics: young bicyclist (0-9), location outside city limits (rural), driver vision obscured, reduced lighting on roadway, and in areas with low population density. Conversely, intersection crashes were more likely to involve bicyclists aged 10 and older, be cited for either bicyclist or motorist failing to yield right of way, and when the motor vehicle was turning.

A majority of crashes occurred in the most densely populated parts of the state and more so in lower income and lower education areas, but this did not vary by intersection/non-intersection. Reasons for this may be attributed to more traffic and/or poorer maintenance of roadways that pass through areas with those characteristics (Evans & Kantrowitz, 2002).

To our knowledge, our study is the first to examine the influence of factors at all four levels (person, crash, environment, and population) on crash location (intersection versus non-intersection). The risk factors we identified are consistent with the existing bicycle crash literature that has recognized differences in outcomes (e.g. fatalities or injury severity), between intersection and non-intersection crashes, but has not previously examined risk of crash. For example, our findings that crash characteristics vary by intersection or non-intersection are consistent with results of a study in Ohio that found factors were different for intersection and non-intersection BMV crashes, (e.g., crash geometry, vehicle type, bicyclist safety devices, and driver insurance status), but their study outcome was injury severity (Moore et al., 2011b).

Our findings were mostly consistent with a spatial study of pedestrians and bicyclists that examined similar person (age) and population characteristics (population density, education, income) by census tracts in Buffalo, New York (Delmelle, Thill, & Ha, 2012). In agreement with our findings, population density was identified as an important risk factor and income was not. They also found that education (no high school degree) was an important risk factor for bicyclists, while we did not. However, their aim was to identify variations in risk factors between pedestrian and bicycle crashes, therefore their outcome was relative risk of bicycle versus pedestrian crashes and they did not distinguish between intersection and non-intersection crashes. Our study also included crash characteristics that they did not examine, such as contributing circumstances, motor vehicle action, major cause, and intersection/non-intersection.

There is similar evidence to our BMV crash findings within the pedestrian-MVC literature as well. One study examined population-level and environmental characteristics as they related to pedestrian-MVC risk by location (intersection vs. mid-block) and age (adult vs. child) in census tracts of Buffalo, New York (Ha & Thill, 2011). Consistent with our bicycle findings, their results showed children pedestrians to have more mid-block crashes and adults to have more intersection crashes. Also consistent with our results, they found that age and location both varied by population and environmental characteristics, such as population density, poverty-level, roadway functional classifications, and traffic controls.

Our result showing young children had higher odds of non-intersection crashes was also similar to results from a child pedestrian-motor vehicle study in Long Beach, California, that compared midblock and intersection collisions (Lightstone, Dhillon,

Peek-Asa, & Kraus, 2001). They found that children under five years of age were most likely to be hit by a motor vehicle at midblock. They also found that both intersection and midblock crashes occurred more frequently in census tracts with the higher population densities, which is consistent with our finding that 90.5% of all the crashes included in our study occurred in the highest population density quartile (2457 people or more) census tract areas in Iowa.

Limitations

This study includes only BMV crashes that were recorded via a police crash report, which likely under-reports bicycle crashes. Thus, we cannot determine if our results would generalize to crashes that did not have police reports, which likely includes the least severe crashes or crashes that did not involve property damage.

The Iowa DOT dataset was also a limitation because it contains information on whether or not the motorist was charged, but not the bicyclist. Therefore, we had to rely on reports of bicyclist and motorist contributing circumstances to serve as a proxy for cause of the crash.

Conclusions

BMV crashes in Iowa are influenced by multiple factors and some of these factors vary by location (intersection or non-intersection), which is similar to findings within the bicycle and pedestrian-MVC literature. Results from this study demonstrate the complicated nature and attributing characteristics of BMV crashes where impacting factors are present at multiple levels, making possible multi-level avenues for prevention strategies. This study, combined with similar studies of bicycle and pedestrian collisions with motor vehicles, demonstrate the need to consider all types of road users, both

motorists and non-motorists, as well as the built environment, when developing prevention methods to make roadways safer.

Table 3.1
Population characteristics of bicycle-motor vehicle crashes based on 2010 census in Iowa, 2001-2010.

			Bicyclist Location				
	Total (N=4064)		Intersection (N=2324)		Non-intersection (N=1740)		
Variable	N	%	N	%	N	%	**p-value**
Population by zip code (state quartiles)[a]							<0.01
0-466	23	0.6	11	0.5	12	0.7	
467-1013	70	1.8	24	1.1	46	2.7	
1014-2456	284	7.1	160	7.0	124	7.4	
2457+	3601	90.5	2096	91.5	1505	89.2	
Median Household Income ($USD)[a]							0.06
Above state median	1046	26.4	576	25.3	470	27.9	
Below state median	2918	73.6	1705	74.7	1213	72.1	
% High School Degree or Higher[a]							0.04
Above state median	1710	43.1	1016	44.5	694	41.2	
Below state median	2254	56.9	1265	55.5	989	58.8	
% Bachelor's Degree or Higher[a]							<0.01
Above state median	1348	34.0	848	37.2	500	29.7	
Below state median	2616	66.0	1433	62.8	1183	70.3	

State median household income=$48872, State median high school degree=89.9%, State median bachelor's degree=24.5%

[a]Numbers do not sum to total because of missing data.

Table 3.2

Person characteristics of bicycle-motor vehicle crashes in Iowa, 2001-2010.

			Bicyclist Location				
	Total (N=4064)		Intersection (N=2324)		Non-intersection (N=1740)		
Age, bicyclist	N	%	N	%	N	%	**p-value**
0-9	636	15.7	280	12.1	356	20.5	<0.01
10-14	1020	25.1	586	25.2	434	24.9	
15-19	485	11.9	310	13.3	175	10.1	
20-29	578	14.2	349	15.0	229	13.2	
30-59	974	24.0	566	24.4	408	23.5	
60+	165	4.1	101	4.4	64	3.7	
Unknown	206	5.1	132	5.7	74	4.3	
Age, motorist							0.12
14-19	487	12.0	273	11.8	214	12.3	
20-29	759	18.7	457	19.7	302	17.4	
30-59	1785	43.9	1013	43.6	772	44.4	
60+	637	15.7	373	16.1	264	15.2	
Unknown	396	9.7	208	9.0	188	10.8	
Gender, bicyclist							0.21
Female	1004	24.7	598	25.7	406	23.3	
Male	3017	74.2	1702	73.2	1315	75.6	
Unknown/Not-reported	43	1.1	24	1.0	19	1.1	
Gender, motorist							<0.01
Female	1712	42.1	1025	44.1	687	39.5	
Male	1963	48.3	1093	47.0	870	50.0	
Unknown/Not-reported	389	9.6	206	8.9	183	10.5	
Safety Devices, bicyclist							0.03
Helmet	414	10.2	245	10.5	169	9.7	
Reflective clothing	15	0.4	5	0.2	10	0.6	
Lighting	28	0.7	12	0.5	16	0.9	
None	2933	72.2	1700	73.2	1233	70.9	
Other/Unknown/ Not-reported	674	16.6	362	15.6	312	17.9	

Table 3.3
Crash and environmental characteristics of bicycle-motor vehicle crashes in Iowa, 2001-2010.

			Bicyclist Location				
	Total (N=4064)		Intersection (N=2324)		Non-intersection (N=1740)		
Characteristic	N	%	N	%	N	%	p-value
Crash Characteristics							
Motor vehicle type							0.18
Passenger car	2425	59.7	1398	60.2	1027	59.0	
Pick-up truck	618	15.2	347	14.9	271	15.6	
Van or mini-van	372	9.2	211	9.1	161	9.3	
SUV	439	10.8	263	11.3	176	10.1	
Other/Unknown/Not reported	210	5.2	105	4.5	105	6.0	
Motor vehicle action							<0.01
Moving essentially straight	2374	58.4	1201	51.7	1173	67.4	
Turning (L, R, or U-turn)	1217	30.0	929	40.0	288	16.6	
Other/Unknown/Not reported	473	11.6	194	8.4	279	16.0	
Day							0.34
Weekend	824	20.3	1865	80.3	1375	79.0	
Weekday	3240	79.7	459	19.7	365	21.0	
Time of day[a]							0.38
10:00pm to 5:59 am	210	5.2	115	5.0	95	5.5	
6:00 am to 9:59 am	450	11.1	271	11.6	179	10.3	
10:00 am to 2:59 pm	986	24.3	574	24.7	412	23.8	
3:00 pm to 9:59 pm	2411	59.4	1362	58.7	1049	60.5	
Season							0.32
Winter (Dec-Feb)	199	4.9	118	5.1	81	4.7	
Spring (Mar-May)	952	23.4	546	23.5	406	23.3	
Summer (Jun-Aug)	1802	44.3	1004	43.2	798	45.9	
Fall (Sep-Nov)	1111	27.3	656	28.2	455	26.2	
Location							<0.01
Rural (outside city limits)	205	5.0	36	1.6	169	9.7	
Urban (within city limits)	3782	93.1	2259	97.2	1523	87.5	
Unknown/Not-reported	77	1.9	29	1.3	48	2.8	
Contributing circumstances, bicyclist							<0.01
Improper crossing	568	14.0	283	12.2	285	16.4	
Darting	254	6.3	101	4.4	153	8.8	
Failure to yield right of way	335	8.2	193	8.3	142	8.2	
Failure to obey traffic signs/signals/officer	401	9.9	335	14.4	66	3.8	
Wrong side of road	104	2.6	47	2.0	57	3.3	
None reported	393	9.7	232	10.0	161	9.3	
Other/Unknown	2009	49.4	1133	48.8	876	50.3	

Table 3.3 continued

Contributing circumstances, motorist							<0.01
FTYROW	950	23.4	653	28.1	297	17.1	
Swerving/evasive action	185	4.6	84	3.6	101	5.8	
Vision obstructed	131	3.2	51	2.2	80	4.6	
No improper action	1715	42.2	961	41.4	754	43.3	
Other/Unknown	1083	26.7	575	24.7	508	29.2	
Major cause							<0.01
Both Motor Vehicle and Bicycle	243	6.0	139	6.0	104	6.0	
Motor vehicle	1023	25.2	649	27.9	374	21.5	
Bicycle	1419	34.9	820	35.3	599	34.4	
Neither	1379	33.9	716	30.8	663	38.1	
Environmental Characteristics							
Posted Speed Limit							<0.01
25 & Under	2420	59.6	1410	60.7	1010	58.1	
30-35	1153	28.4	734	31.6	419	24.1	
40-50	124	3.1	65	2.8	59	3.4	
55+	367	9.0	115	5.0	252	14.5	
Vision obscurement							<0.01
No	2994	73.7	1780	76.6	1214	69.8	
Yes	474	11.7	218	9.4	256	14.7	
Unknown	596	14.7	326	14.0	270	15.5	
Surface conditions							0.71
Dry	3687	90.7	2113	90.9	1574	90.5	
Wet	243	6.0	139	6.0	104	6.0	
Other/Unknown/Not-reported	134	3.3	72	3.1	62	3.6	
Reduced Lighting							<0.01
No (daylight or lighted roadway)	3700	91.0	2174	93.5	1526	87.7	
Yes (dusk, dawn, unlighted roadway)	308	7.6	115	5.0	193	11.1	
Unknown/Not-reported	56	1.4	35	1.5	21	1.2	

[a]Numbers do not sum to total because of missing data.

Table 3.4
Predictors of bicycle-motor vehicle crashes occurring at non-intersections compared to intersections, Iowa, 2001-2010.

	Multivariable Logistic Regression									
	Model 1- Person N=4064		Model 2-Person & Crash N=4064		Model 3-Person, Crash, & Environment N=4064		Model 4-Person, Crash, Environment, & Population N=3955		Model 5- Final Model N=3978	
Variable	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**	**OR**	**95% CI**
Person Characteristics										
Age, bicyclist										
0-9	2.0	1.4-2.9	2.0	1.3-2.9	1.8	1.2-2.7	1.8	1.2-2.1	1.9	1.2-2.8
10-14	1.2	0.8-1.6	1.2	0.8-1.8	1.2	0.8-1.7	1.2	0.8-1.8	1.2	0.8-1.8
15-19	0.9	0.6-1.2	1.0	0.7-1.6	1.0	0.7-1.5	1.0	0.7-1.6	1.0	0.7-1.6
20-29	1.0	0.7-1.5	1.3	0.9-1.9	1.2	0.8-1.8	1.3	0.9-2.0	1.3	0.9-2.0
30-59	1.1	0.8-1.5	1.1	0.8-1.7	1.1	0.7-1.6	1.1	0.8-1.7	1.1	0.8-1.7
60+	1.0	ref	1.0	ref	1.0	ref	1.0	ref	1.0	ref
Unknown	0.8	0.6-1.3	0.9	0.5-1.4	0.9	0.5-1.4	0.8	0.5-1.4	0.9	0.5-1.4
Gender, bicyclist										
Female	1.0	ref	1.0	ref						
Male	1.2	1.0-1.4	1.1	1.0-1.3						
Unknown/Not-reported	1.4	0.7-2.6	1.1	0.7-2.7						
Gender, motorist										
Female	1.0	ref	1.0	Ref						
Male	1.2	1.0-1.4	1.1	1.0-1.3						
Unknown/Not-reported	1.4	1.1-1.8	1.1	0.8-1.4						
Crash Characteristics										
Location										
Rural (outside city limits)			6.2	4.2-9.2	4.9	3.2-7.6	6.1	4.0-9.3	6.0	4.0-9.0
Urban (within city limits)			1.0	ref	1.0	ref	1.0	ref	1.0	ref
Unknown/Not-reported			2.0	1.2-3.2	1.9	1.1-3.1	n/a		n/a	
Contributing circumstances, bicyclist										
Improper crossing (ref=no)			0.6	0.3-0.9	0.7	0.6-1.0	0.7	0.6-1.0	0.7	0.6-1.0
Darting (ref=no)			0.7	0.4-1.1						
Failure to yield right of way (ref=no)			0.3	0.2-0.5	0.4	0.3-0.6	0.4	0.3-0.6	0.4	0.3-0.6
Failure to obey traffic signs/signals/officer (ref=no)			0.1	0.1-0.2	0.1	0.1-0.2	0.1	0.1-0.2	0.1	0.1-0.2
Contributing circumstances, motorist										
Failure to yield right of way (ref=no)			0.4	0.3-0.6	0.6	0.4-0.8	0.6	0.5-0.9	0.6	0.5-0.9
Swerving/evasive action (ref=no)			0.6	0.4-1.1						
Major Cause (listed in police report)										
Both bicyclist and motorist			3.0	1.6-5.6	1.5	1.1-2.3	1.6	1.1-2.3	1.6	1.1-2.3
Motor vehicle only			1.8	1.2-2.6	1.2	0.9-1.7	1.1	0.8-1.6	1.2	0.8-1.6
Bicyclist only			2.1	1.3-3.2	1.6	1.2-2.1	1.6	1.2-2.1	1.6	1.2-2.1
Neither			1.0	ref	1.0	ref	1.0	ref	1.0	ref

Motor vehicle action								
Moving essentially straight		1.0	ref	1.0	ref	1.0	ref	1.0	ref
Turning (L, R, or U-turn)		0.3	0.3-0.4	0.4	0.3-0.4	0.4	0.3-0.4	0.4	0.3-0.4
Other/Unknown/Not reported		1.4	1.1-1.7	1.4	1.1-1.7	1.5	1.2-1.8	1.5	1.2-1.8
Environmental Characteristics									
Posted Speed Limit									
25 & Under				1.0	ref				
30-35				0.9	0.8-1.1				
40-50				1.1	0.7-1.7				
55+				1.3	0.9-1.7				
Vision obscurement									
No				1.0	ref	1.0	ref	1.0	ref
Yes				1.5	1.2-1.8	1.5	1.2-1.9	1.5	1.2-1.9
Unknown				1.1	0.9-1.4	1.2	0.9-1.4	1.2	1.0-1.4
Reduced Lighting									
No (daylight or lighted roadway)				1.0	ref	1.0	ref	1.0	ref
Yes (dusk, dawn, unlighted roadway				2.0	1.5-2.6	2.0	1.5-2.6	2.0	1.6-2.7
Unknown/Not-reported				0.7	0.4-1.3	0.7	0.4-1.4	0.8	0.4-1.4
Population Characteristics (based on 2010 census)									
Population by zip code (state quartiles)									
0-466						0.8	0.3-2.0	0.8	0.3-2.1
467-1013						1.9	1.1-3.4	2.0	1.1-3.5
1014-2456						0.8	0.6-1.1	0.9	0.7-1.2
2457+						1.0	ref	1.0	ref
Median Household Income ($USD)									
Above state median						1.0	0.8-1.2		
Below state median						1.0	Ref		
% High School Degree or Higher									
Above state median						0.9	0.8-1.1		
Below state median						1.0	ref		
% Bachelor's Degree or Higher									
Above state median						0.9	0.8-1.1		
Below state median						1.0	ref		

Notes: All models are adjusted, with all variables in the column included.

The sample size, N, decreases in Models 4 and 5 due to missing values.

Adjusted R^2: Model 1 (0.03), Model 2 (0.21), Model 3 (0.22), Model 4 (0.22), Model 5 (0.22).

Likelihood ratio tests: Model 2 vs. Model 1 ($\chi 2$=613.70, df=13, p<0.001), Model 3 vs. Model 2 ($\chi 2$=35.15, df=1, p<0.001), Model 4 vs. Model 3 ($\chi 2$=134.84, df=2, p<0.001), Model 4 vs. Model 5 ($\chi 2$=30.14, df=3, p<0.001).

Variables included in successive models (2-5) had to meet criteria of p<0.05

Figure 3.1 Annual average crash rate by zip code tabulation area, per 10,000 population, Iowa, 2001-2010

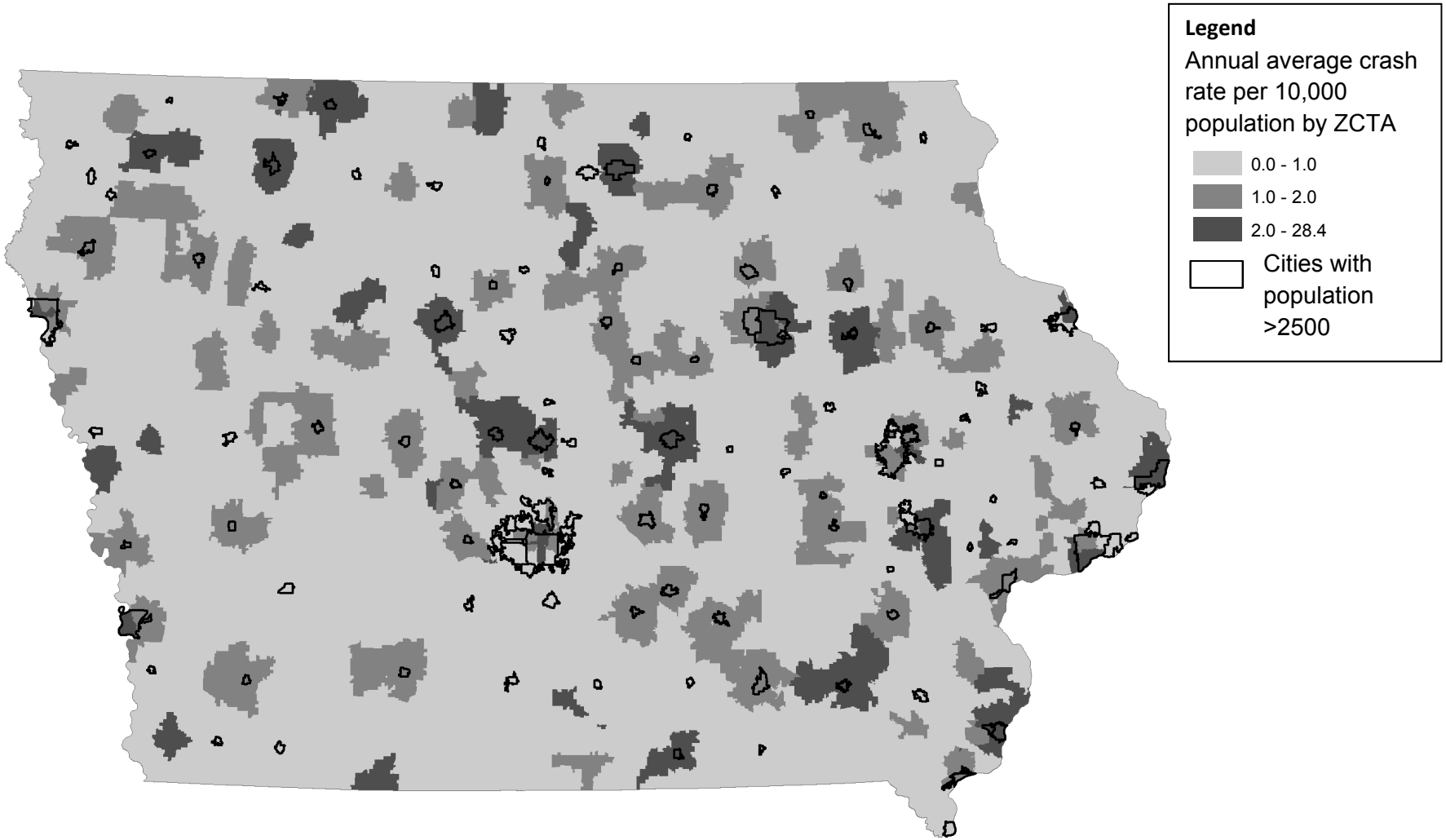
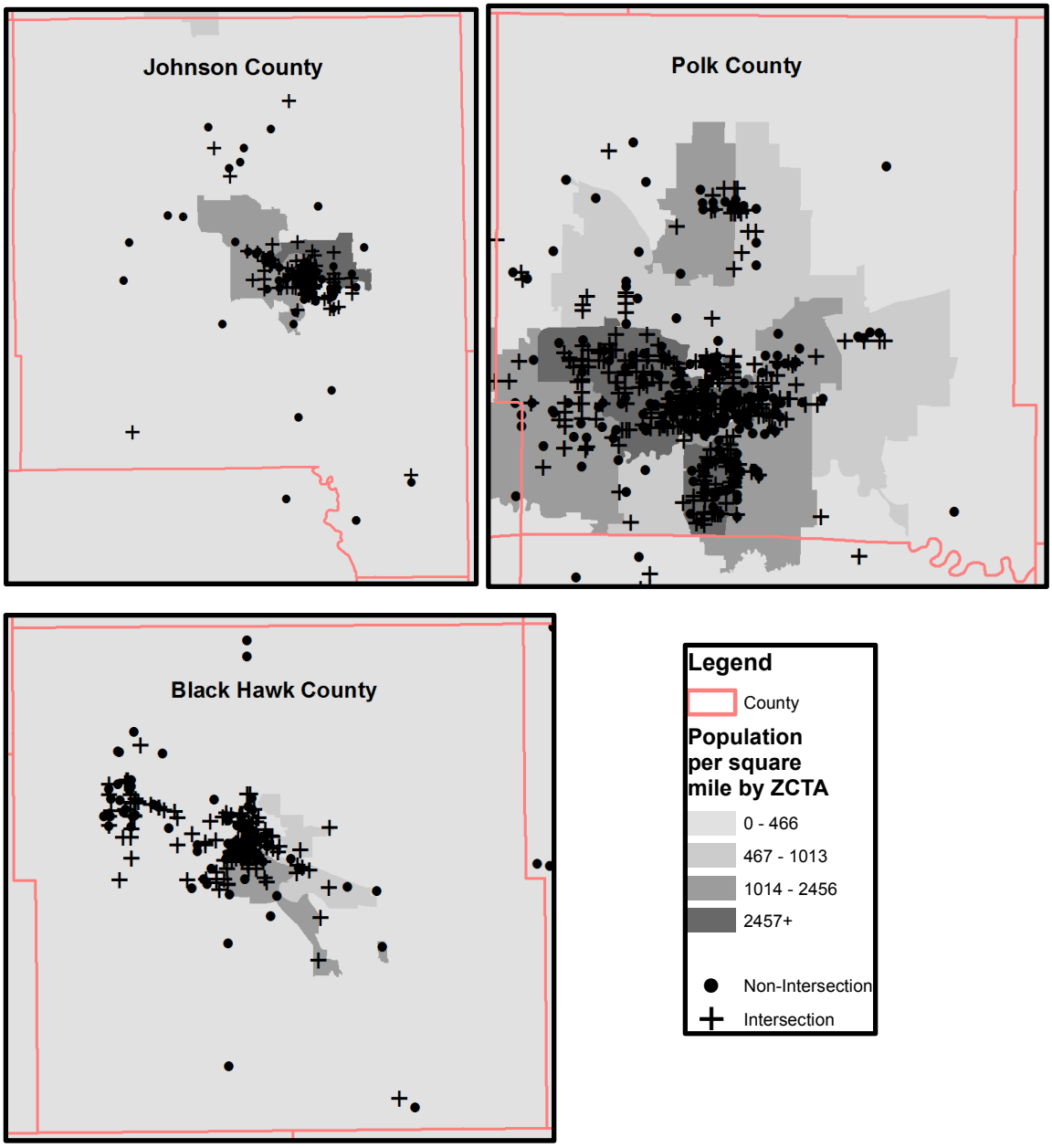


Figure 3.2 Bicycle-motor vehicle crash distribution at intersections and non-intersections, selected counties, Iowa, 2001-2010



CHAPTER 4

ON-ROAD BICYCLE FACILITIES AND BICYCLE CRASHES IN IOWA, 2007-2010

Abstract

Background: An average of 611 deaths and over 47,000 bicyclists are injured in traffic-related crashes in the United States each year. Efforts to increase bicycle safety are needed to reduce and prevent injuries and fatalities, especially as trends indicate that ridership is increasing rapidly. The objective of this study was to evaluate the effect of bicycle-specific roadway facilities (e.g., signage and bicycle lanes) in reducing bicycle crashes.

Methods: We conducted a case site-control site study of 147 bicycle crash-sites identified from the Iowa Department of Transportation crash database from 2007-2010 and 147 matched non-crash sites. Control sites were randomly selected from intersections matched to case sites on neighborhood (census block group) and road classification (arterial, feeder, collector, etc.). We examined crash risk by any on-road bicycle facility present and by facility type (pavement markings--bicycle lanes and shared lane arrows, bicycle-specific signage, and the combination of markings and signage), controlling for bicycle volume, motor vehicle volume, street width, sidewalks, and traffic controls.

Results: A total of 11.6% of case sites and 15.0% of controls had an on-road bicycle facility. Case intersections had higher bicycle volume (3.52 vs. 3.34 per 30min) and motor vehicle volume (248.77 vs. 205.76 per 30min) than controls. Our results are suggestive that the presence of an on-road bicycle facility decreases crash risk by as much as 60% with a bicycle lane or shared lane arrow (OR 0.40, 95% CI 0.09-1.82) and 38% with bicycle-specific signage (OR 0.62, 95% CI 0.15-2.58).

Conclusions: Investments in bicycle-specific pavement markings and signage have been shown to be beneficial to traffic flow, and our results suggest that they may also reduce the number of bicycle-motor vehicle crashes and subsequent injuries and fatalities. As a relatively low-cost traffic feature, communities should consider further implementation of these facilities in traffic planning.

Introduction

In the past two decades bicycle ridership has increased in the United States, while the number of crashes each year has remained fairly steady. However, with 51,000 traffic-related bicycling injuries and 630 deaths in the United States in 2009, prevention strategies are needed (Insurance Institute for Highway Safety, 2012; National Highway Traffic Safety Administration, 2009). The current body of literature indicates that in comparison to European countries, the United States has deficiencies in the physical traffic environment to accommodate bicyclists (Pucher & Dijkstra, 2000). Non-motorized transportation has been neglected in terms of planning, zoning, and land use in the United States (Pucher & Dijkstra, 2000).

One reason for this lack of infrastructure could be the inadequate evidence to support different approaches to reducing bicycle crashes. Existing data do not provide adequate evidence on the actual causes and contributing factors leading to these crashes and resulting injuries, challenging those interested in designing and optimally implementing prevention strategies. Transportation and urban planners face a critical gap in knowledge about which approaches work best to reduce crashes between cars and bicycles.

With the increases in ridership, many cities are adopting the 'complete streets' design concept, which accommodates all types of transportation modes, including bicycle facilities (National Complete Streets Coalition, 2010). Bicycle facilities can include bicycle lanes, shared lane arrows, and 'Share the Road' signage, as well as combinations of these strategies. These new facilities introduce changes in traffic flow for both motorists and bicyclists. Some research has been conducted regarding these approaches, but more is needed to fully understand the complexity of roadways and the risk factors that lead to crashes. For example, some roadway facilities (Pucher & Dijkstra, 2000; Walker, 2007) have been studied separately, but very few studies have looked at more than one facility or controlled for confounding factors to allow for comparisons of the impact on crash risk.

Existing literature has generally associated bicycle facilities with increased ridership and reduced crash occurrence (e.g., Alta Planning, 2004; Federal Highway Administration, 2006; Moritz, 1997; Parker, Gustat, & Rice, 2011; Reynolds et al., 2009). Yet, overall, little is known about the comparative effectiveness of bicycle-specific facilities on crashes. This knowledge deficit is especially large in rural areas in the United States, as the limited existing literature has focused on densely populated urban areas and has often lacked adjustment for bicycle and/or motor vehicle volume, which are different in rural and urban settings. Large urban areas in the United States are set up for better connectivity for implementation of bicycle-specific infrastructure than rural areas because of the density of both population and roadways, and many are taking advantage of this by integrating such infrastructure. Bicycle planning has also historically focused on design from an urban perspective, rather than incorporating larger regional areas that

would include surrounding rural communities (Aytur, Satinsky, Evenson, & Rodriguez, 2011; Evenson, Aytur, Satinsky, Kerr, & Rodriguez, 2011). Rural areas are not as easily adapted as urban, but should not be neglected.

The purpose of this study was to expand beyond findings from studies in large urban areas, which may not be generalizable to conditions in small towns and small urban areas. We also studied locations with multiple bicycle facilities and comparisons of individual types of facilities-- evidence needed to help planners choose which facility approach to use. We hypothesized that on-road bicycle facilities reduce crash risk and that this protective effect would vary by facility type.

Methods

We conducted a matched case site-control site study of intersections to investigate the impact of on-road bicycle facilities on bicycle-motor vehicle (BMV) crashes in the mostly rural state of Iowa. This design was based on a pedestrian-motor vehicle crash risk study in California and Washington (Koepsell et al., 2002) and was selected to optimize feasibility and efficiency in studying relatively rare outcomes compared to other study designs (e.g., cohort study), ability to integrate traffic volumes to control for confounding, and the ability to focus on environmental variables. The objective of this study was to determine the impact of different types of bicycle facilities on BMV crash risk.

Setting

Data collection was conducted from July to October of 2012 in the four counties in eastern Iowa with the highest number of BMV crashes (Black Hawk, Johnson, Linn, and Scott). We made the assumption that high frequencies of crashes could serve as a

proxy for places with the largest number of bicyclists. We used frequencies rather than rates because we did not have an adequate denominator, due to lack of readily available bicycle volume data. We selected four counties to optimize the sample size with available study resources. The months of June through October were chosen because they have the highest frequency of bicycle crashes.

Selection of cases and controls

Case sites were intersections where BMV crashes occurred, drawn from the Iowa Department of Transportation (DOT) crash database, June to October of 2007 to 2010 in Black Hawk (N=76, 25.9%), Johnson (N=64, 21.8%), Linn (N=78, 26.5%), and Scott (N=76, 25.9%) counties. This database includes crashes recorded by police or driver report, which includes all crashes resulting in death, personal injury, or property damage of $1500 or more (Iowa Department of Transportation, 2012). Intersection crashes were the focus of this study because they occur more frequently and have inherently different traffic flow and environmental characteristics than non-intersection crashes, which would require separate protocols for selecting controls and collecting data.

Control sites were intersections matched to case sites by neighborhood (census block group) and roadway classification. A list of eligible control sites was generated for each case site. To do this, we mapped all of the crashes in ArcGIS (ESRI, 2011) using X and Y coordinates available from the Iowa DOT database. We then labeled the roadway classifications within the road network and marked boundaries of block groups. From this map, we identified eligible controls for each case site with the same block group and combination of roadway classifications of the radiating streets as the case sites. One control site was matched to each case site by randomly choosing from the eligible pool

using a random number generator. If a block group had fewer than two eligible control sites we identified more controls within the surrounding block groups, working in concentric rings until two controls were identified. The distribution of roadway classifications among the cases and controls were as follows: Index street- 11% non-interstate principal arterial, 24% minor arterial, 20% major collector, and 44% local; Non-index street- 17% non-interstate principal arterial, 31% minor arterial, 14% major collector, and 37% local.

Intersections were excluded if they had changed significantly between the time the crash occurred and the time the data were collected, for both case and control sites (e.g., lane added, major construction, etc.). We determined these significant changes through consultation with city traffic engineers. Sites where changes occurred were excluded based on the presumption that the bicycle and motor vehicle volumes would have changed in the time between the index crash and the on-site data collection and that current volume data would not serve as a good proxy for volume at the time of the crash for those sites.

Sampling

Based on a sample size calculation using Cochrane-Mantel-Haenszel as the test statistic and pilot data from Johnson County crash data from 2008, we needed a sample of 294 intersections (147 cases and 147 controls) to ensure 80% power to detect an odds ratio of 0.5. Based on these sample size calculations, 147 case sites were randomly selected from 217 eligible intersections.

Since intersections can change in terms of environmental conditions and traffic volumes with time of day, day of week, and time of year, intersections qualified to be

included in the study more than once if they were at different dates and times and they were also retained in the eligible pool of controls. For example, two crashes that occurred at the same intersection during the study period were both included because environmental factors (e.g., traffic flow) were studied separately to correspond with the unique characteristics of each crash. The unit of analysis is crash site, which encompasses the intersection where a crash occurred and its corresponding characteristics at that time (e.g., time of day, day of week, season, etc.).

Data collection

Environmental variables (traffic volume, traffic controls, number of lanes, presence of sidewalks, and presence of bicycle facilities) were collected on-site. Data collection was conducted simultaneously, with two trained observers, one at the case site and one at the control site.

Traffic volume was collected during a 30-minute time interval that was 15 minutes before and 15 minutes after the time the index crash occurred, on the same day of the week, and as close to the original crash date as feasible (typically within two weeks). This was done to best approximate volume, light conditions, and traffic control timings at the time of the index crashes. All data were recorded manually and the 30-minute traffic counts were video recorded. Ten percent of the videos were reviewed for count accuracy which revealed a 0% error rate for bicycle counts and 3% error for motor vehicles. Still photographs of views from each intersection leg and of any bicycle facilities were taken.

Index street width was measured using ArcGIS (ESRI, 2011). Index street was defined as the street the motor vehicle was traveling on when the crash occurred and was identified from the existing DOT dataset.

Main exposures: Bicycle facility presence & bicycle facility type

Bicycle facilities included in this study were bicycle-specific signage, bicycle lanes, and shared lane arrows (Figure 1). Intersections without any of these features were classified as "none" for this variable. Bicycle lanes and shared lane arrows were combined into a category called pavement markings due to sample size restrictions within the shared lane arrows category.

Covariates

Speed limit, curb-to-curb width, traffic controls, bicycle volume & motor vehicle volume, and presence of sidewalks were examined in unadjusted analyses. All of these variables were included in multivariable analyses, except speed limit, which was not significant.

Sidewalk presence was categorized as full, partial, or none in acknowledgement of the impact these different conditions can have on bicyclist behavior. For example, a bicyclist might move from riding on the road to riding on the sidewalk when the road in question has a sidewalk on one side of the intersection and not the other. This change in bicyclist behavior can have an impact on exposure of the bicycle to motor vehicles and on motorist awareness of the bicyclist's presence.

Additionally, matching accounted for confounding by neighborhood and road type, both of which are associated with the presence of bicycle facilities and the risk of crash occurrence. We could not assume that these variables accounted for variance in

bicycle or motor vehicle volume, and thus we collected bicycle volume manually. Bicycle volume is specific to each site, while block group and road classification encompass a site and immediately surrounding areas. Roadways were classified into seven categories: 1) Interstate, 2) Other principal arterial, 3) Minor arterial, 4) Major collector, 6) Minor collector- rural only, and 7) Local. These are standard classifications used by the DOT and are based on capacity, traffic volume, and speed limit.

Data Analysis

Descriptive statistics, unadjusted, and multivariable conditional regression models for examining bike facility presence (yes/no) and bike facility type (pavement marking, signage, combination of both) as predictors of crash sites were used. Covariates included in multivariable analyses were chosen based on a combination of evidence from existing literature and significant variables ($p < 0.05$) in unadjusted analyses. Conditional multivariable logistic regression models were used because they were appropriate for matched data and the dichotomous outcome of case site versus control site. We examined separate independent variables: bicycle facility present and bicycle facility type. The main exposure in the first model was any type of bicycle facility present versus no bicycle facility (reference group). In the second model, the facility type categories included pavement markings (bicycle lanes and shared lane arrows), bicycle-specific signage, a combination of those two, and no facility (reference group). All analyses were performed using SAS 9.2 software (SAS Institute Inc., 2002-2008).

Results

Distribution of characteristics by case and control status (Table 4.1)

Bicycle lanes were the most common facility (6%), followed by bicycle-specific signage (4%), multiple facilities (2%), and then shared lane arrows (1%). Control sites had more on-road facilities (N=22, 15%), overall, than cases (N=17, 12%). Control sites had more bicycle lanes (7%) and more multiple facilities (pavement markings and signage; 3%) compared to case sites (5% and 1%, respectively). Three of 17 total intersections with bike lanes had both bike lanes and bicycle-specific signage (e.g., Share the Road sign). Case intersections had higher motor vehicle volume (248.77 vs. 205.76 per 30min) than controls.

Unadjusted predictors of crash sites (Table 4.2)

Intersections with a bicycle facility present were 42% less likely to be a crash site than a control site (95% CI =0.23-1.48). Compared to no bicycle facility, pavement markings were 58% less likely (95% CI = 0.10-1.80) and the combination of pavement markings and signage were 80% less likely (95% CI = 0.02-1.93) to be a crash site. However, these results were not statistically significant.

Sidewalks present on both sides of the index street significantly increased crash risk 2.53 times (95% CI 1.01-6.35) compared to streets with no sidewalks. Streets with partial sidewalks also suggested increased risk compared to no sidewalks, but this was not statistically significant (OR 1.78, 95% CI=0.71-4.44). These effects were in the same direction for non-index street sidewalks, but not significant. There were not significant trends for index and non-index sidewalks (Cochrane-Armitage trend tests, p=0.13 and p=0.48, respectively). Presence of traffic controls on the non-index street increased odds

of being a crash site 2.75 times (95%CI=1.22-6.18) compared to uncontrolled streets. Speed limit, traffic controls on the index street, and bicycle volume were not significant in unadjusted analyses.

Higher motor vehicle volumes and curb-to-curb width of the index street were associated with higher crash risk. For each 10 feet increase in curb-to-curb width, the odds of being a crash site increased 1.48 times (95% CI = 1.15-1.91). For every five motor vehicles during a 30-minute period, the odds of being a crash site increased 1.04 times (95% CI=1.01-1.07).

Multivariable predictors of crash-sites (Table 4.3)

We built two multivariable models: Model 1 predicted the impact of any type of on-road bicycle facility on crash risk. Model 2 predicted the impact of the different types of on-road bicycle facilities (pavement markings, signage, or a combination of both) on crash risk.

Model 1 suggested the presence of any type of on-road bicycle facility can decrease odds of a crash by as much as 52% (95% CI=0.18-1.36). Curb-to-curb width was the only covariate that remained significant, showing a 38% increased risk (95%CI=1.06-1.79) of a crash with every 10 feet increase in width.

Model 2 suggested all three categories of bicycle facilities were protective, including bicycle-specific signage, which was not significant in unadjusted analyses. The combination of pavement markings and signage was the most protective (OR=0.36, 95%CI=0.03-4.32), followed by pavement markings (OR=0.40, 95% CI=0.09-1.82), and then bicycle-signage (OR=0.62, 95% CI=0.15-2.58). As in Model 1, the only covariate that remained significant in this model was curb-to-curb width, which showed a 37%

increased risk (95% CI: 1.05-1.79) of a crash with every 10 feet increase in index street width.

Discussion

We used a novel study method, incorporating retrospective crash data with current traffic counts, to examine the impact of on-road bicycle facilities in Iowa. Our findings suggest that bicycle facilities are protective against crashes, especially pavement markings (bicycle lanes or shared lane arrows). Although our main findings were not statistically significant, all effects were in our hypothesized direction.

Our findings are also consistent with much of the bicycle safety literature, which has shown protective effects of bicycle lanes, although many of the studies have relied on self-reported survey data. For example, a survey of 2,978 cyclists found that the odds of a crash decreased by 40% if riding in a bike path or lane compared to a regular roadway (Rodgers, 1997). Another study in Davis, California found that bike lanes can reduce crashes by 53%, although this study was conducted over 35 years ago (Lott & Lott, 1976). Our study results provide updated evidence regarding bicycle lanes and allowed for comparison between pavement markings, signage, and combinations of those, which was lacking in the literature.

Studies on shared lane arrows are very recent because this intervention was not recommended in the Manual on Uniform Traffic Control Devices (MUTCD) until 2009, prior to which they were considered experimental and very rare; they have been increasingly incorporated since 2009 (Federal Highway Administration, 2009) . A report from the Federal Highway Administration investigated the impact of shared lane arrows in Massachusetts, North Carolina, and Washington and found that the presence of shared

lane arrows increased the amount of space motorists gave to the bicyclist, helped to position the bicyclists in the safest part of the road, and reduced sidewalk riding (Hunter, Thomas, Srinivasan, & Martell, 2010). Similar results regarding shared lane arrows were found in Austin, Texas (Brady, Loskorn, Mills, Duthie, & Machemehl, 2011) and San Francisco, California (Alta Planning, 2004). All of these factors are likely to contribute to reduced crashes, but to the best of our knowledge this was the first study to examine effects on crash risk.

Another recent study evaluated a three-foot passing law in Baltimore, Maryland, and found that cars did not violate the three-foot zone when the bicyclist was riding in a bicycle lane, but violations occurred in 17% of the observations with standard lanes and 23% with shared lane arrows (Love et al., 2012). We were not able to separately evaluate bicycle lanes and shared lane arrows due to very small numbers of shared lane arrows in our sample, so we cannot address further their shared lane arrow finding. However, the consistency between the findings on bicycle lanes and pavement markings suggests that bicycle lanes have protective properties in reducing collisions between motor vehicles and bicyclists (Love et al., 2012).

Beyond bicycle-specific facilities, we also found that the greater the curb-to curb-width of the index street (roadway motor vehicle was traveling on) the greater the crash risk. We believe this could be explained by circumstances where a bicycle and motor vehicle collided as the bicycle was crossing the index street. The wider the road, in that circumstance, the longer the bicyclist would have been exposed to opposing cars.

Our study design was based on a pedestrian-motor vehicle crash study by Koepsell et al. (2002) in Washington and California. One of the main strengths of this design is the

combination of existing crash data with current traffic counts to examine crash risk. Bicycle research is difficult to conduct because traffic volume counts are generally not readily available and, historically, many bicycle studies have failed to control for volume. Additionally, the case site-control site design is useful for studying bicycle crashes because these crashes are rare relative to the number of motor vehicle crashes. This design also has major cost and time savings compared to other approaches, such as prospective cohort studies.

Schepers et al. (2011) used a similar study design in the Netherlands to study BMV crashes at unsignalized intersections, by using existing police crash reports combined with current traffic volume counts. However, their traffic counts were based on 20-minute counts, off-peak hours and non-school vacation periods, which were then extrapolated to make estimates of counts. Both our study and Koepsell et al. (2002) used 30-minute observation periods for traffic counts, which corresponded to the same day of week and time of day as the index crash. Our study also differs significantly from the Schepers et al. (2011) for several reasons: their setting was European (the Netherlands) where there are different facility types (e.g., raised cycle tracks separated from the motorist road), they focused on specific features of the bicycle facilities (e.g., red color and visibility), and they stratified by two crash types (bicyclist right of way and motorist right of way). Their facility variables were too different to compare to our findings because they were either different facility types or they were examining specific features of facilities. We were able to compare traffic volumes and found our results were consistent with their findings of an increase in crash risk, for both crash types, as the number of both cyclists (OR range 1.6-1.8) and motorists (OR range 1.6-2.0) increased.

However, several studies in the literature have suggested a “safety in numbers” protective effect when a critical mass of bicycles is reached that is not found with motor vehicles (Elvik, 2009).

Our study had a limited sample size based on the small budget, and thus had limited power that resulted in wider confidence intervals. When the power was originally calculated, we anticipated a higher prevalence of bicycle facilities. We were also unable to compare bicycle lanes and shared lane arrows because of the low prevalence of shared lane arrows, in particular. Bicycle crashes were identified from police crash report data, which may underestimate the actual number of roadway BMV crashes because not all such crashes are reported. Crashes that led to injury or significant property damage are more likely to be reported, and thus these findings may generalize better to bicycle crashes that led to injury (61% of these crashes indicated an injury and 35% indicated possible injury). Finally, our traffic counts are proxies for the traffic volume at the time the index crash occurred. Although we collected these data on the same day of week and same time of day as the index crash, we cannot determine how accurate these are in comparison to the actual traffic volumes at times of crashes.

Conclusions

Our results suggest that on-road bicycle facilities, especially in the form of bicycle lanes and shared lane arrows, are protective against BMV crashes. More research is needed to further compare facility types, examine specific features of facility types, and determine which configurations work best in given areas (e.g., rural versus urban). Evidence from this study and the body of existing evidence indicate that bicycle facilities appear to reduce crash risk and no apparent harm is introduced, supporting that there may

be sufficient evidence to move forward in implementing these practices now, while continuing to work toward developing recommendations for optimal configuration and features of bicycle facilities.

Bicycle-specific signage | Bicycle lane | Shared lane arrow

Figure 4.1. On-road bicycle facilities photographed during study data collection, Iowa, June-October 2012.

Table 4.1
Characteristics of case and control intersections, Iowa, 2007-2010

			Intersection			
Variable	**Total (N=294)**		**Case (N=147)**		**Control (N=147)**	
On-road bike facilities present at intersection	N	%	N	%	N	%
None	255	86.7	130	88.4	125	85.0
At least one	39	13.3	17	11.6	22	15.0
Bicycle Lane	18	6.1	7	4.8	11	7.5
Bicycle-specific signage	11	3.7	6	4.1	5	3.4
Multiple Facilities (e.g., bike lane & signage)	7	2.4	2	1.4	5	3.4
Shared Lane Arrows	3	1.0	2	1.4	1	0.7
Sidewalks, index street[a]						
Full	206	70.1	108	73.5	98	66.7
No	47	16.0	19	12.9	28	19.1
Partial	41	14.0	20	13.6	21	14.3
Sidewalks, non-index street[b]						
Full	215	73.1	111	75.5	104	70.8
No	49	16.7	23	15.7	26	17.7
Partial	30	10.2	13	8.8	17	11.6
Traffic controls present, index street[a]						
Yes (light, stop sign, yield sign, or combination)	226	76.9	115	78.2	111	75.5
No	68	23.1	32	21.8	36	24.5
Traffic controls present, non-index street[b]						
Yes (light, stop sign, yield sign, or combination)	188	64.0	101	68.7	87	59.2
No	106	36.1	46	31.3	60	40.8
	N	**SD**	**N**	**SD**	**N**	**SD**
Bicycle volume (Avg # in 30 min obs period)	3.4	4.9	3.5	4.9	3.3	5.0
Motor vehicle volume (Avg # in 30 min obs period)	228	285	249	300	206	270
Curb to curb width, index street[a] **(Avg Feet)**	45.7	19.3	48.0	20.7	43.4	17.5
One lane width, index street[a] **(Avg Feet)**	14.7	4.4	14.8	4.9	14.5	3.9
Speed Limit, index street[a] **(Avg)**	28.0	5.3	28.0	5.0	28.1	5.5
Speed limit, non-index street[b] **(Avg)**	28.8	5.4	28.7	5.2	28.8	5.5
Number of lanes, index street[a] **(Avg)**	1.4	0.6	1.4	0.7	1.4	0.6
Number of lanes, non-index street[b] **(Avg)**	1.3	0.6	1.2	0.6	1.3	0.6

Avg=average; obs=observation

[a]Index street = street motor vehicle was traveling on when crash occurred

[b]Non-index street = street motor vehicle was not traveling on when crash occurred

Table 4.2
Unadjusted conditional logistic regression models predicting bicycle crashes at intersections, Iowa, 2007-2010, N=294.

Predictor of bicycle crash	Unadjusted OR	95% CI
On-road bicycle facility present (ref=none)	0.58	0.23-1.48
On-road bicycle facility type (ref=none)		
Pavement markings (bicycle lane or shared lane arrows)	0.42	0.10-1.80
Bicycle-specific signage	1.14	0.30-4.33
Pavement markings & signage	0.20	0.02-1.93
Sidewalks, index street[a,b] (ref=none)		
Full	2.53	1.01-6.35
Partial	1.78	0.71-4.44
Sidewalks, non-index street[c,d] (ref=none)		
Full	1.57	0.62-3.95
Partial	1.03	0.38-2.79
Traffic controls present, index street[a] (ref=no)	1.36	0.63-2.97
Traffic controls present, non-index street[b] (ref=no)	2.75	1.22-6.18
Bicycle volume (per 5)	1.09	0.76-1.56
Motor vehicle volume (per 5)	1.04	1.01-1.07
Curb to curb width (per 10ft)	1.48	1.15-1.91
Speed limit, index street[a] (per 5mph)	0.94	0.60-1.48
Speed limit, non-index street[b] (per 5mph)	0.89	0.49-1.63

Ref=reference

[a]Index street= street motor vehicle was traveling on when crash occurred

[b]Cochran-Armitage trend test p=0.13

[c]Non-index street = street motor vehicle was not traveling on when crash occurred

[d]Cochran-Armitage trend test p=0.48

Table 4.3
Predictors of bicycle crashes, multivariable conditional logistic regression, Iowa, 2007-2010, N=294.

	Model 1[a]		**Model 2**[b]	
	Any Facility		*Facility Type*	
Characteristic	Adjusted OR	95% CI	Adjusted OR	95% CI
On-road bicycle facility present (ref=none)	0.48	0.18-1.36		
On-road bicycle facility type (ref=none)				
Pavement markings (bicycle lane or shared lane arrows)			0.40	0.09-1.82
Bicycle-specific signage			0.62	0.15-2.58
Pavement markings & signage			0.36	0.03-4.32
Sidewalks, index street (ref=none)[c]				
Full	2.60	0.95-7.10	2.65	0.96-7.29
Partial	1.66	0.61-4.49	1.66	0.61-4.54
Traffic controls present, non-index street (ref=no)[d]	1.97	0.80-4.84	1.91	0.77-4.73
Bicycle volume (per 5 bicycles)	1.10	0.73-1.66	1.10	0.73-1.67
Motor vehicle volume (per 10 vehicles)	1.02	0.99-1.05	1.02	0.99-1.05
Curb-to-curb width, index street (per 10 feet)[c]	1.38	1.06-1.79	1.37	1.05-1.79

Ref=reference

[a] Model 1 includes: on-road bicycle facility present, sidewalks, traffic controls, bicycle volume, motor vehicle volume, and curb-to-curb width. Likelihood ratio test: Model 1 vs. Univariate model (χ^2=23.42, df=6, p<0.001)

[b] Model 2 includes: on-road bicycle facility type, sidewalks, traffic controls, bicycle volume, motor vehicle volume, and curb-to-curb width. Likelihood ratio test: Model 2 vs. Univariate model (χ^2=21.46, df=6, p=0.002)

[c] Index street = street motor vehicle was traveling on when crash occurred

[d] Non-index street = street motor vehicle was not traveling on when crash occurred

CHAPTER 5

CONCLUSIONS

Current Study

Exposure to crashes and injuries from bicycling has increased in the United States due to increased ridership. However, prevention of crashes is challenging because contributing factors are numerous and wide. The objectives of this project were to examine the outcomes and estimate the burden of bicycle crashes resulting in hospitalizations in the United States, examine the contribution of BMV crash risk factors at multiple levels (person, crash, environment, and population), and determine the variation in impact of different types of bicycle facilities on BMV crash risk.

Chapter II informs the literature by estimating the current burden of injury nationwide for all ages In Chapter II we found that bicycling crashes resulting in hospitalizations carry a large burden economically and in relation to poor outcomes. It is important to remember that this is a very conservative estimate of the true burden of bicycle crashes because it only includes the most severe injuries, with the exception of deaths that occurred prior to hospitalization. The burden of bicycle crashes that led to emergency department visits or did not require emergent care, but may have had other impacts (e.g., missed work days) were not examined but are likely high because the majority of bicycle crashes do not result in hospitalizations.

Chapter II also showed that bicycle crashes involving motor vehicles have longer lengths of stay, more hospital charges per visit, and poorer outcomes than non-motor vehicle involved crashes, which is consistent with previous research (HCUP, 2012; Siman-Tov et al., 2012; M. J. Thompson & Rivara, 2001). These results justify the need

to determine contributing factors of bicycle crashes involving motor vehicles, to gain the knowledge necessary for prevention.

As a result of this need, the aim of Chapter III was to identify the contribution of risk factors of BMV crashes and how factors vary by location: intersection and non-intersection. This filled several gaps in the literature: 1) the inclusion of adults, 2) the geographic location was Iowa, which has low density population unlike the urban locations of much of the past studies that have been conducted in the United States, and 3) we examined multiple levels of characteristics, to determine their contributions to crash location (intersection/non-intersection) when examined together.

We found that variables at all levels (person, crash, environment, and population) were contributed to where a crash occurred. Specifically, we found that BMV crashes involving young children (0-9 years old), rural areas, circumstances where the bicyclist and motorist were both listed as contributing to the cause, vision obscurement, and in areas with low population (467-1013 persons per zip code) were most likely to be at non-intersections. On the other hand, BMV crashes with failure to yield right of way by the bicyclist, swerving or evasive action by the motorist, and motor vehicle action of turning (L, R, or U-turn) were most likely to occur at intersections. We also found the contributions to crash location by gender, darting by bicyclist, swerving by motorist, and posted speed limit were explained away once other factors at the crash-, environment-, and population-levels were taken into account.

From Chapters II and III we know that BMV crashes have the worst outcomes, carry a large burden and are complex in nature, involving many factors. Chapter IV aimed to further examine BMV crashes in Iowa and evaluate the impact of one prevention

approach—infrastructure changes. Specifically, we examined and compared the impact of bicycle lanes, shared lane arrows, and bicycle-specific signage on BMV crash occurrence. This environmental study built upon the existing bicycle infrastructure literature by comparing the impact between the different facility types and examining intersections in small towns/cities and rural areas, as opposed to large urban areas.

Our results suggest that the combination of pavement markings (bicycle lanes and shared lane arrows) with bicycle-specific signage are the most protective against crashes, followed by pavement markings alone, and then bicycle signage. We also confirmed conclusions from previous research (Moritz, 1997; Reynolds et al., 2009; Rivara et al., 1997; Wachtel & Lewiston, 1994) that sidewalks and wider roadways increase crash risk.

Future directions

Overall, this research project informs and supports prevention methods at multiple levels (person, crash, and environment), across all age groups, with continued implementation of bicycle infrastructure. Still, the bicycle crash and injury evidence base remains incomplete. Future work is needed to address several areas:

Consideration of all ages

In the United States there has been a historical focus on preventing bicycle crashes and injuries among children. Results from this project combined with other recent studies indicate that injuries and fatalities from bicycle crashes remain a problem in children, but are a growing problem among adults (Frank, Frankel, Mullins, & Taylor, 1995; National Highway Traffic Safety Administration, 2011; Rosenkranz & Sheridan, 2003). The majority of injuries and fatalities are among adults, but prevention efforts and research is

needed for all ages, keeping in mind that the contributing factors to bicycle crashes vary between adults and children (Frank et al., 1995; Rosenkranz & Sheridan, 2003)

Beyond large urban areas

Although the current project explores the state of Iowa, a state with low density population with only two cities over 100,000 population (U.S. Census Bureau, 2010), this is just a start at investigation of lower population density areas, as much of the current body of literature conducted in the United States has focused on large urban areas. A recent study using 2009 National Household Travel Survey data shows the highest share of trips to bike to work was among small rural areas (1.61%), higher than urban centers (0.83%) and large rural areas (0.27%; Rails-to-Trails Conservancy, 2012). Small cities like Iowa City, Iowa, (population 67,830) which was included in this study, are found among the top fifteen metropolitan statistical areas for non-driving commuters with 2.2% of trips to works by bicycle (Rails-to-Trails Conservancy, 2012). It is important to continue to evaluate prevention approaches in less populated areas, as they may have different impact and outcomes than in large urban areas due to different characteristics (Carter & Council, 2007; Rails-to-Trails Conservancy, 2012).

Evaluation of Infrastructure

As the number of bicycle-specific facilities grows in the United States, we need to not only examine them in different geographic areas, but we also need to evaluate specific features of the facilities and newly emerging types of facilities in the United States (e.g., shared lane arrows, bicycle boxes, roundabouts, etc.). The current literature is very sparse in scope and narrow geographically (e.g., Dill, Monsere, & McNeil, 2012). Bicycle infrastructure studies in European countries have evaluated a wider array of

facility types and specific features of infrastructure, such as color, width of cycle lanes, separation from traffic, and intersection geometry (Daniels, Brijs, Nuyts, & Wets, 2009a; Dondi, Simore, Lantieri, & Vignali, 2011; Pucher & Dijkstra, 2000; Rasanen & Summala, 2000; Schepers et al., 2011), but these types of studies are few and far between in the United States.

Robustness of data

Finally, a limitation of this body of work and an ongoing problem within the bicycle crash and injury literature is lack of a full picture, because there is no one data source that can accurately monitor all crash types. We separately examined hospitalization and police records, but lacked emergency department visits and crashes that did not have hospital or police records. Nationwide emergency department visit data are available and crashes that did not have hospital or police records have been examined via self-report surveys or direct observations in previous studies, but integration of multiple data sources are needed to gain a more comprehensive understanding of contributing causes and impact of prevention methods and to have a greater impact (Wegman, Zhang, & Dijkstra, 2012).

This research project has shown that bicycle safety in the United States is an important public health problem. In order to make bicycling safer we need a holistic approach that employs prevention methods and risk factors at multiple levels-- education, policy, research, and evaluation.

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