Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Urban Transportation Infrastructure and Cyclist and Pedestrian Safety

Project No. 20SAUTSA35

Lead University: University of Texas at San Antonio

Final Report

October 2021

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

Acknowledgments

This project was conducted in cooperation with the City of San Antonio Transportation and Capital Improvements (TCI) division. The authors would like to cordially thank the following TCI employees who provided guidance or assistance during the project, assisted with data collection, and offered helpful suggestions: Gregory Reininger, Bianca Thorpe, Marco Hinojosa, and Lauren Simcic.

TECHNICAL DOCUMENTATION PAGE

1. Project No.	2. Government Accession No.	3. Recipient's Catalog No.
20SAUTSA35		

4. Title and Subtitle	5. Report Date
Urban Transportation Infrastructure and Cyclist and Pedestrian Safety	October 2021
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
PI: Hatim Sharif https://orcid.org/0000-0001-9805-8080 Co-PI: Samer Dessouky https://orcid.org/0000-0002-6799-6805	
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Transportation Consortium of South-Central States (Tran-SET) University Transportation Center for Region 6 3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803	**11. Contract or Grant No.** 69A3551747106
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
United States of America Department of Transportation Research and Innovative Technology Administration	Final Research Report August 2020 – August 2021
	14. Sponsoring Agency Code

15. Supplementary Notes

Report uploaded and accessible at: http://transet.lsu.edu/

16. Abstract

The goal of this project was to perform a comprehensive evaluation of crash causes and risk factors to identify the root causes of crashes involving bicyclists and pedestrians in San Antonio, TX. The research included the development of a database of bicycle and pedestrian crash reports in the target area, calculation of crash counts and rates, identifying road segments and intersections with highly concentrated bicycle and pedestrian crashes, and the development of effective safety countermeasures. Several variables and factors were analyzed, including driver characteristics such as age and gender, road-related factors, and environmental factors such as weather conditions and time of the day. Bivariate analysis and logistic regression were used to identify the most significant predictors of severe pedestrian/bicyclist crashes. Geospatial analysis was used to investigate crash frequency and severity. High-risk locations were identified through heat maps and hotspot analysis. The downtown area had the highest crash density, but crash severity hotspots were identified outside of the downtown area. The strongest predictors of severe injury include lighting condition, road class, road speed limit, traffic control, collision type, and the age and gender of the pedestrian/bicyclist. Fatal and incapacitating injury risk increased substantially when the pedestrian/bicyclist was at fault. Resource allocation to high-risk locations, a reduction in the speed limit, an upgrade of the lighting facilities in high pedestrian activity areas, educational campaigns for targeted audiences, the implementation of more crosswalks, pedestrian refuge islands, and raised medians, and the use of leading pedestrian/bicyclist interval and hybrid beacons are recommended.

17. Key Words	18. Distribution Statement
Crashes, Pedestrians Safety, Bicyclist Safety	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	52	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway Transportation Officials
COSA	City of San Antonio
CRIS	Crash Record Information System
FHWA	Federal Highway Administration
GIS	Geographic information system
MEV	Million Entering Vehicles
NHTSA	National Highway Traffic Safety Administration
TCI	Transportation and Capital Improvement
TCDS	Traffic Count Database System
TxDOT	Texas Department of Transportation
USDOT	United States Department of Transportation

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) has designated eight cities in Region 6 as Bicycle and Pedestrian Safety Focus Cities to highlight the need for improved safety for the most vulnerable road users in these cities. Moreover, FHWA's Highway Safety Improvement Program (HSIP) safety performance measures call for state and regional targets to help minimize highway fatalities and injuries, including those involving pedestrian and cyclists. The Texas Department of Transportation (TxDOT) has taken several initiatives and implemented ideas to improve safety conditions to ultimately achieve Vision Zero. The SHSP consists of a total of seven emphasis areas (EAs): Distracted Driving, Impaired Driving, Intersection Safety, Older Road Users, Pedestrian Safety, Roadway and Lane Departures, and Speeding. Bicyclist crashes have also been increasing in San Antonio and all over Region 6.

The purpose of this study is to perform a comprehensive evaluation of pedestrian and bicyclist crashes, explore the relationship of pedestrian and bicyclist crashes with other factors, identify locations with highest crash concentrations, and recommend impenetrable countermeasures to ensure effective and efficient use of available resources. This study also explores how the pedestrian/bicyclist safety is related to other EAs.

San Antonio experienced a total of 248,410 crashes from 2013-2017. These crashes included 781 fatal crashes and 3,999 serious injury crashes. A total of 442,074 drivers, 1,575 bicyclists, and 4,470 pedestrians were associated with these crashes. Pedestrian crashes were responsible for 257 fatal crashes and 602 severe injury crashes whereas bicyclist crashes resulted in 27 fatal crashes and 117 severe injury crashes during the study period. The table below shows associated total crashes/drivers, fatal and serious injury crashes, and percentage of fatal and severe (K&A) crashes for pedestrian and bicyclist crashes. The results suggest that pedestrian crashes are more likely to result in fatal/severe injury crashes compared to bicyclist crashes. The proportion of pedestrian K&A crash in total K&A crash (18.0%) was substantially higher than the proportion of pedestrian crash in total crash (1.8%) in San Antonio during 2013-2017.

Table 1. Summary of pedestrian and bicyclist crashes•

Emphasis Area	Number of related crashes	% of total crashes	Number of related fatal crashes	Number of related severe injury crashes	% of K&A crash in total K&A crashes
Pedestrian safety	4,459	1.8	257	602	18.0
Bicyclist Safety	1,561	0.63	27	117	3.0

This study found time of day, day of week, lighting condition, age, gender, and weather condition to be important determinants of crash occurrence. Targeted safety campaigns, inclusion of public figures in campaigns, introduction of automated speed enforcement and variable speed limit system, encouraging ridesharing services and vehicles with advanced safety features, ensuring affordable and efficient public transport, and construction of pedestrian overcrossings at busy intersections might help reduce fatal and serious injury crashes in San Antonio. Further investigations and statistical analysis of pedestrian and bicyclist crashes might help to better understand the root causes and help in recommending more effective and specific countermeasures.

1. INTRODUCTION

First implemented in Sweden in 1997, Vision Zero strategy has since gained success all over the Europe. Roadway injuries and fatalities are often thought to be a necessary evil to ensure public mobility, but Vision Zero, as the name suggests, aims to achieve the safest possible roadway by reducing serious injury and fatality causing crashes to zero. This goal might seem to be unrealistic to achieve, but the important idea here is that no crash is unavoidable. This redefined view changes the way we think of road safety and instead of accusing only the road users, both road users and designers are held accused. Identification of contributing factors of fatal and serious injury crashes is necessary to plan effective strategies. The City of San Antonio led by the Transportation & Capital Improvements Department along with partner agencies decided to achieve Vision Zero which aims to eliminate all fatal crashes from roadways. The city of San Antonio's approach to Vision Zero was implemented through a combined approach of five key elements: Education, Encouragement, Engineering, Enforcement and Evaluation. Improving the existing conditions of crosswalks, walkways, and bikeways is essential for the city of San Antonio to enhance safety and accessibility of road users. Statewide data were analyzed within the categories of driver behaviors, system users, and crash types to select the Emphasis Areas (EAs). The following EAs were initially selected by the stakeholder group: pedestrian safety, older road users, impaired driving, intersection safety, roadway and lane departures, speeding, and distracted driving. Additionally, bicyclist safety was also considered for further exploration. Bicyclist crashes are comparatively less frequent to the seven major EAs but should not be overlooked if the Vision Zero goal is to be achieved. Governing factors for these crashes are similar to pedestrian crashes. The pedestrians and the bicyclists are more vulnerable road users compared to motor vehicle drivers and they are involved in substantially higher proportion of fatal and serious injury crashes. Detailed analysis of crashes involving pedestrians and bicyclists is expected to provide appropriate and effective countermeasures to reduce these crash incidents.

1.1. Economic Impact

Crashes on US roadways are responsible for an economic loss of billions of dollars each year (representing value of lifetime economic costs for fatalities, non-fatal injuries, and damaged vehicles) and pedestrian and bicyclist crashes are major contributors to this cost. The total cost of pedestrian and bicyclist injuries in 2000 was estimated to reach a total of $40.4 billion over the lifetimes of the injured while cost per person being comparatively higher for children aging 14 or less (*1*). However, there are many indirect costs that occur from pedestrian/bicyclist-motor vehicle collisions such as loss of bodily and mental functions, productivity, etc. For example, the lifetime economic costs for 41,821 fatalities, 5.3 million non-fatal injuries, and 28 million damaged vehicles which occurred in 2000 in terms of 2002 monetary value was determined to be $230.6 billion (*2*).

1.2. Study Area and Current Conditions

When overall crashes on roadways, pedestrian crashes, and bicycle crashes are considered, Texas is one of the states leading the chart. Starting from 2015, Bexar County has experienced more than 50000 crashes each year with an overall increasing trend. To reduce fatalities and injuries on Texas roadways, the Strategic Highway Safety Plan (SHSP) had been introduced in Texas in 2006.

Several initiatives have been taken by the Texas Department of Transportation (TxDOT) to enhance the safety condition since the development of SHSP. Located within the Bexar County, San Antonio (total area 1205.4 km^2) is one of the rapidly growing cities in the United States. San Antonio was the seventh most populous city of the United States in 2019 with an estimated population of 1.533 million (*3*). San Antonio experienced 15.5% growth in its population from 2010 to 2018 and currently the proportion of females (50.6%) is greater than males (*4*). From 2016 to 2017, the growth in population of San Antonio was the highest (24,408) in the United States (*5*). The proportion of pedestrians, bicyclists, and vehicles on the roads is expected to increase with the rapid growth of population and this might cause increased interaction among the road users. As a result of the increased interaction, the number of fatal and serious injury related pedestrian and bicycle crashes might also increase unless proper countermeasures are taken.

San Antonio was ranked 57th in the USA in terms of percentage of bicycle commuters in 2014 (only 0.3% of total population using bicycles as means of commuting). San Antonio experienced 110% growth of bicycle commuters from 2000 to 2014 (*6*) and expected an increase in bicycle commuters from 0.3% in 2014 to 1% by 2020 *(7*). San Antonio has a "Walk Score" of only 38 (out of 100) as reported in 2020 (*8*) and is ranked at 18th in the list of the most dangerous metro areas for pedestrians (*9*). This project analyses the characteristics of pedestrian and bicyclist crashes and how these crashes relate to other Emphasis Areas in addition to analyzing the spatial distribution of pedestrian and bicyclist crashes. Findings from this study will be helpful to the policymakers in taking informed decisions.

2. OBJECTIVE

The main objective of this study is to perform a comprehensive evaluation of pedestrian and bicyclist crash causes and risk factors, explore the relationship of pedestrian and bicyclist crashes with other factors, and identify the root causes of pedestrian and bicyclist crashes in the city of San Antonio, Texas. The research team developed a database of heat maps related to pedestrian and bicyclist crashes; calculated total, fatal, and serious injury crashes for categories; and identified the locations with highest crash concentrations. The evaluation also includes reporting of the behaviors of drivers, pedestrians, and cyclists. The evaluation helped the research team to determine ways to address safety issues at hotspot roadway sections and provide the safest possible solutions.

3. LITERATURE REVIEW

Pedestrian-motor vehicle crashes are a common global occurrence. Each year, millions of people get injured or killed from these crashes. Pedestrians are fragile and since they usually travel at a much slower speed compare to the motor vehicles, they are often at a disadvantage in crash cases compared to drivers or vehicle occupants. The safety situation of pedestrians in the United States is in much worse condition when compared to the European countries. In the United States, pedestrian fatality count per one hundred thousand people was 1.80 (*10*). On the other hand, some European countries such as Netherlands and Sweden had fatality rate of 0.70 and 0.84 per one hundred thousand people in 1999, which is substantially lower compared to the United States (*11*). Although the European countries have greater proportions of pedestrians in their population compared to the United States, their roads are significantly safer for pedestrians, indicating that the United States has substantial scope of improvement in ensuring safety to the vulnerable road users.

In recent years, bicycle ridership has gradually become one of the most common commuting systems for urban populace in the US, as it is economic, less energy-cost than automobiles, and has less impact on the environment. With the increase in automobile usage, vulnerable road users are expected to become more susceptible to traffic crashes, especially in places where traffic laws are poorly enforced (*12*). Each year, about half-million emergency department visits happen due to non-fatal bicycle injuries and the safety of bicyclists is a major concern for transportation policymakers (*13*, *14*). Bicycle crash frequency trend has become an interesting topic for researchers (*15, 16*). According to NHTSA, bicyclist proportion in total traffic fatalities gradually increased from 1.8% to 2.2% during 2004-2013 (*17*). However, mixed results have been observed in different studies about bicycle crash trends. One California study which considered all types of bicyclist injury during 2005-2012 observed a decreasing injury rate (*16*). Another study considered school-age bicyclists of 26 states of United States and found decreasing bicycle crash rate (*18*). However, contrast results have been also observed. An increasing trend of severe bicycle crashes from 1997-2013 has been observed using National Electronic Injury Surveillance System data which adjusted age and population size (*19*). Ensuring the safety of pedestrians and bicyclists has become a major concern for planners, engineers, and stakeholders because of the unprotected nature of individuals who use walking or cycling as their means of transportation as well as developing a safe, sustainable, and dynamic transportation systems with zero accidents.

The significant contribution of walking in reducing chronic disease rate and health care costs and improving public health has resulted in an increasing trend of walking practice (*20*). Pedestrian and bicyclist safety can be enhanced either through the reduction of collision risk or by reducing injury severity risk from a crash. Pedestrian-motor vehicle collisions are influenced by several governing factors, such as pedestrian age, driver age, location type, vehicle type, drug or alcohol impairment, lighting conditions, built environment characteristics, speeding, alcohol, lack of safety belt use, and other problematic driver behaviors (*21*). Male pedestrians are found to be more vulnerable to severe injuries and fatalities compared to their female counterparts (*22*, *23*). Although pedestrians of all ages are affected by collisions with motor vehicles, several epidemiological studies have indicated that the severe injury and mortality rate is substantially higher among seniors than any other age group (*24, 25*) Children and older pedestrians are more vulnerable to crashes as they require more time while crossing the roads. In 2015, 19% of all pedestrian deaths involved older pedestrians (>65 years) and 20% of children (<15 years) killed in traffic crashes were pedestrians (*26*). Alcohol influence of drivers and/or pedestrians increases the odds of pedestrian and bicyclist crashes. In 2016, alcohol involvement for the pedestrian and/or driver was reported in about 50% of all fatal pedestrian crashes. Almost one-third of all fatal pedestrian crashes involved pedestrians with a blood alcohol concentration of at least 0.08 g/dL (*26*). Using motor vehicle mortality data from 1980-2010, age–period–cohort analysis was conducted by a study which concluded that the age group 16-24 had the highest fatality risk due to alcohol involvement (*27*). Insufficient lighting facilities on roadways affects the vision of drivers, bicyclists, and pedestrians alike and often leads to more frequent crashes and severe injuries. Pedestrians are more susceptible to fatal crashes under dark lighting condition compared to other light conditions based on crash data analysis done from 1997 through 2006 in the United States (*28*). During low-light conditions, the rod photoreceptors of human eyes require more reaction time to process information, resulting in greater stopping distances for drivers (*29*). The party at fault in a crash can be an important determinant of crash severity and few studies explored how crash severity was influenced by the party at fault in a crash (*30-32*). The primary fault of pedestrians is the failure to provide the right of way to motor vehicles. The motor vehicle drivers have comparatively lesser reaction time when the pedestrians are at fault, and this increases the injury severity risk (31).

Several environmental factors influence crash frequency. The visibility of drivers can be affected by adverse weather conditions such as rain, snow/freezing precipitation, fog, hail, and other weather conditions which reduces visibility and can make the maneuvering task difficult. In addition to reduced visibility, rainy weather condition reduces the friction between tires and road surface, which might result in increased crash frequency. In the United States, about 12% of all crashes occur during rain (*33*). Visibility is reduced under foggy weather and maneuvering becomes difficult with snow on roadway, resulting in increased probability of crashes, injuries, and fatalities. Adverse weather is responsible for about 22% vehicle crashes, 16% fatal crashes, and 19% injuries resulting from crashes each year in the United States (*34*). Rain, sleet, snow, fog, ice, or some combination of these adverse weather condition were responsible for 991,000 crashes out of 6,181,000 crashes in 2004 in the United States (*35*).

Fatigue or distraction of primary persons (drivers, pedestrians, bicyclists) can occur from stress, lack of sleep, or sickness which might affect perception of drivers, bicyclists, and pedestrians. This distraction can increase the response time of primary persons as well as affect their judgement. One study concluded that the road users (drivers, pedestrians, bicyclists) might find it difficult to follow traffic rules when they are distracted or fatigued which could make them more likely to be involved in crashes (*36*). Pedestrian crashes are also affected by street patterns and loops and lollipops design patterns were found to be associated with greater pedestrian crash frequency compared to grid-iron or warped parallel patterns (*37*). However, the same study found that the grid-iron or warped parallel patterns are more likely to result in more severe pedestrian injuries and property-damage. Motor vehicle speed and pedestrian injury severity are considered to have positive correlation. One study used logistic regression on pedestrian crash data from 1994-1998 for the United States and standardized the associated risk to represent the average risk in years 2007–2009. The study concluded that the average risk to result in a severe injury or fatality reaches 10% at impact speed of 17.1 mph and 24.1 mph, 25% at 24.9 mph and 32.5 mph, 50% at 33.0 mph and 40.6 mph, 75% at 40.8 mph 48.0 mph, and 90% at 48.1 mph and 54.6 mph, respectively (*38*). Bicyclist injury severity is also correlated to mean travel speed. Analysis of bicycle crashes occurring at seventy-seven selected accident sites in Sweden for the years 2004-2008 found that the injury severity of bicyclists, the speed environment, and age of bicyclists have statistically significant correlation (*39*).

Although pedestrians, bicyclists, and vehicles share the roadways, the decision makers are often more concerned with the safety and movability of motor vehicles compared to pedestrians and bicyclists while designing the roads. This puts the pedestrians and bicyclists in difficult situations while sharing the roads with motor vehicles, ultimately leading to increased injury and fatality rate of pedestrians and bicyclists from collisions with motor vehicles. According to a report from World Health Organization (WHO) in 2018, more than 1.25 million lives are taken away per year from traffic crashes, making it one of the leading causes of death for people aging between 15-29 and a substantial portion of them are pedestrians and bicyclists (*40*). About 5,000 pedestrian fatalities and 70,000 critical injuries occur each year in the United States. Even though these numbers are staggering, they do not represent the actual numbers as crashes are often underreported, specially crashes with minor injuries (*41*). One study which compared police-, hospital-, and insurance reported injury data found that about 20 percent of crashes resulting in severe injuries, 50 percent of crashes resulting in minor injuries, and up to 60 percent of crashes with no known injuries were not reported (*42*). A substantial percentage of crash incidents occurring in non-roadway locations (i.e., parking lots, driveways, and sidewalks) remains unreported (*43*).

Bicycling has become one of the most common and popular means to commute by urban population in recent years in the United States for being economical, healthful, and environment-friendly. Many programs are being developed in cities across the world to promote bicycling as a more sustainable transportation alternative as it helps in minimizing road congestions and reduces air pollution (*44, 45*). The factors which might be attributed to the bicyclist injuries and fatalities could be broadly classified in the following categories: roadway related, person related, and environmental related factors. It is important to identify relevant factors responsible for bicyclist crashes while exploring bicyclist safety. Three categories of issues contribute to traffic crashes involving bicyclists: motorist behavior, non-motorist behavior, and infrastructure. Poor compliance with traffic laws and improper use of facilities, speeding, inadequate separation, crossing locations, inadequate conspicuity, and impairment and distraction are some of the major problems (*46*). Bicyclist ethnicity, bicyclist gender, bicyclist age, speed, alcohol influence, helmet use of bicyclist, lighting condition of road, day of the week, road class, and presence of intersection are some of the factors which significantly affect bicyclist injury severity (*47-50*).

To lessen automobile use and promote sustainable transportation system, several cities have adopted different programs to increase the use of bicycles (*51, 52*). Studies found that modification of existing bicycle infrastructure and an increase of bicycle lane mileage can improve the use of bicycle by the populace (*53, 54*). Addition of bicycle share programs and improvement of signage and street markings have also been found to increase bicycle use as observed from studies (*55, 56*). However, extensive integrated methods have been found to be one of the most effective means in increasing bicycle use (*51*). Different types of facilities could be provided for the bicyclists (such as on-street facility/shared-use path/curb lane) to improve their safety and mobility and studies have been conducted to evaluate their effectiveness and suitability (*57-59*). However, the results are often mixed and case-specific.

4. METHODOLOGY

4.1. Story of the Data

The crash data for the study period (2013-2017) was downloaded from the Crash Record Information System (CRIS) database (https://cris.dot.state.tx.us/) maintained by Texas Department of Transportation (TxDOT). The crash data are a collection of all crashes that occurred on roads throughout the State of Texas and reported by police officers. The database is updated around every two months. The intervals between collected datasets are not exactly two months in a year but the intervals are consistent with previous years. The crash data documentation is enforced by law, and the data are generally documented in the Texas Peace Officer's Crash Report (form CR-3). Crash data can be submitted to TxDOT using one of the approved formats:

i) C.R.A.S.H.: This is an internet-based application available to all Law Enforcement agencies.
ii) Submission Services: Developed for agencies with an existing internal application. It requires a web services client and is available to all Law Enforcement agencies.
iii) Paper forms: This method involves using the CR-3 form developed by TxDOT to submit crash data.

It is required by the law enforcement officer, investigating a motor vehicle crash, to forward a report on a crash which resulted in injury or death of any person, to TxDOT no later than the 10th day after the date of the crash by Texas Transportation Code Section 550.062. Additionally, any crash that results in property damage to any one person's property of $1,000 or more should be reported to TxDOT after investigation. TxDOT only accepts crashes involving at least one motor vehicle in transport as reportable traffic crashes. A non-reportable crash is not necessary to be forwarded to TxDOT even if police agency chooses to investigate further. All crash reports submitted to TxDOT that do not include at least one motor vehicle in transport will be returned to the reporting agency for retention at the local level only.

The CRIS data are in categorized form and data of each year are categorized in the following files: crash, charge, person, primary person, unit, damage, restriction, and endorsement category. For each category, the data for a whole year are divided in multiple files and needs to be merged to get data for a whole year. Crash files contain data about weather condition, road condition, lighting condition, coordinates, and time of crash; charge files contain data about crash associated charges; person and primary person files contain data about person age, sex, ethnicity, seat position, and injury details; unit files contain details about crash associated vehicle; damage files contain data of damaged property; restriction files contain driver license restriction ID; and endorsement files contain driver license endorsement ID. Primary person refers to driver, pedal cyclist, pedestrian, and driver of motorcycle type vehicle while person files contain information of passengers or occupants. The lookup file is helpful in interpreting data from several categories. Each crash record in the CRIS database has a unique crash identification number that can be used to merge different file categories.

4.2. Data Sorting

The downloaded data included all the crashes occurred within Texas. The City ID variable was used to subset the data for San Antonio only. The "unit" and "primary-person" files contain information about the unit type and person type involved in a crash, which were used to subset the data for pedestrians and bicyclists. The reported contributing factors of a crash were used to subset the data for distracted/impaired/speeding/lane departure crashes.

4.3. Variables Analyzed

The CRIS database contains over 170 variables. The following variables in Table 1 were analyzed in this study. The selection of the variables was based on past studies (*60-62*). Apart from very few variables (for example, "Age of Primary Person"), variables used in this study are mostly categorical.

Crash date and crash time are mandatory data fields in the report filed by the peace officer in duty. The actual time of a crash incident is reported by the officer in charge as best as it can best be established using the Military Time (24 HR) format (0000-2359). Midnight is considered the beginning of a new day and should be entered as 0000. Reporting of time in a range is unaccepted. When crash time cannot be determined exactly, the discovery time of the crash or injury should be reported. In this analysis, each hour is considered to start from the first minute of the hour (for example, 0001 is the start of "1 a.m." hour). The weekend period is considered to start from 0001 of Saturday. The weather condition variable represents the prevailing atmospheric conditions (clear, cloudy, rain, sleet, hail, fog, snow, crosswinds, blowing sand etc.) that existed at the time of the crash. The lighting condition variable expresses the type/level of light existing at the time of crash occurrence. The surface condition variable includes several values such as dry, wet, standing water, snow, ice, and muddy. The Road class variable indicates the type of road on which the crash occurred and could be any type from highways, farm to market roads, city roads, non-trafficways, county roads, and tollways.

Table 2. List of variables considered•

S/N	Variable Name
1	Day of Week
2	Age of Primary Person
3	Crash Time
4	Day of Week
5	Intersection Presence
6	Crash severity
7	Crash Month
8	Weather condition
9	Lighting condition
10	Surface Condition
11	Person Type
12	Road Class
13	Contributing factors
14	Gender of Primary Person
15	Ethnicity of Primary Person
16	Helmet Status
17	Latitude
18	Longitude
19	Vehicle Type
20	Crash Severity

4.4. Safety Analysis

This study used R and RStudio software in processing and analyzing the datasets (*63*). When statistical computation and graphical representation is considered, R and RStudio software have proven to be very effective and practical. R is a free software environment and a wide variety of platforms (UNIX platforms, MacOS, and Windows) can compile and run R. RStudio is an integrated development environment for R software which is also free and open source. RStudio enables the users to visualize the data tables, graphs, R code, and output at the same time and makes the work environment user friendly. RStudio has a rich library of readily available basic and advanced statistical analysis tools and graphic packages which makes the use of R more attractive over its competitors. This study also used ArcGIS Desktop (version 10.6) and ArcGIS pro (version 2.6) for spatial analysis and graphical representation (*61*). ArcGIS is a client/server software and provides online geographic information system services. ArcGIS enables the users to apply location-based analytics which can aid in gaining insights by using contextual tools which can help in visualizing and analyzing data. ArcGIS Pro is basically a modern version of ArcGIS Desktop which uses a 64-bit system and functionalities (ArcCatalog and ArcMap) are integrated in the same application in ArcGIS pro, a feature which is unavailable in the ArcGIS Desktop. ArcGIS Pro is more graphics intensive due to the upgraded visualization and supports streamlined workflows.

Each row in the "crash" file has a unique Crash ID, meaning that the total row numbers in the crash file for a year is essentially the total number of crashes for that year. However, "unit", "primary person" and other files can have more than one row for a single Crash ID. A crash often includes several units or primary persons involved, and figures were represented in this study based on either the total crash count or the total involved primary person count based on context.

The contributing factor variable is available in the "unit" file. Each crash could be associated with up to three contributing factors (primary contributing factor, secondary contributing factor, other contributing factor). Contributing factor has been defined as "Any circumstance contributing to a result without which the result could not have occurred; an element which is necessary to produce the result, but not by itself, sufficient." in the state of Texas instructions to police for reporting crashes handbook. In the form, contributing factor 1 must be populated before contributing factor 2 and contributing factor 2 must be populated before contributing factor 3. Contributing factor 1 is considered to be more relevant to the crash compared to contributing factor 2 and contributing factor 3. The selection of contributing factor is dependent on the opinion of the inspector. Distracted driving crashes were selected using crash contributing factors and any crash associated with distraction in vehicle, driver inattention, and cell/mobile phone use was considered as distracted driving associated crash. Lane departure crashes were identified when crash contributing factor was either failure to drive in single lane or failure to give half of roadway. Impaired driving crashes refer to crashes in which the involved primary person had been drinking, under influence of alcohol, or under influence of drug. Speeding crashes were selected when crash contributing factor was failure to control speed, unsafe speed, or speeding (over limit).

The selection of pedestrian-at-fault crashes were based on crash associated contributing factors. Any crash where at least one of the contributing factors for a pedestrian crash was the failure of a pedestrian to yield the right of way to vehicles is considered a Pedestrian-at-fault crash. Bicyclist-at-fault crashes were not analyzed in this study. However, the following contributing factors could be used while selecting bicycle-at-fault crashes: disregarded stop and go signal, changed lane when unsafe, inattention of bicyclist, disregarded stop sign or light, disregarded warning sign at construction, disregarded turn marks at intersection, faulty evasive action, fleeing or evading police, failure to control speed/speeding, bicyclist following too closely, had been drinking, turned improperly, under influence of alcohol/drug, overtook and passed with insufficient clearance, driving on wrong side/way, and using a cellphone.

The police officer on duty reports the severity of injury of the involved persons after assessing and determining the severity and the injury severities from the data have not been cross-checked with external sources (e.g., hospital data). The party at fault in a crash incident was determined from the contributing factors from the data which are reported by the officer and could be prone to judgement errors. Pedestrian/bicycle crashes that result in minor or no injuries are often under-reported, and this might result in a biased outcome. The spatial analysis could not include traffic volume data due to unavailability of city-wide detailed traffic volume data. This study considered the dataset to be static over the years which is a potential limitation of this study. Crash incidents which occurred on roadways not maintained by the City of San Antonio were excluded from this study. Crash locations were not available for all crash incidents. So, when mapping the crash locations, only crashes with available coordinates were used.

4.5. Heat Map Analysis

A heat map is essentially a technique of visualizing data and showing the magnitude in color in two dimensions. The color variation provides visual cues about how an incident is clustered or distributed over space. Heat maps can be fundamentally classified into categories: clustered heat map and spatial heat map. In case of cluster heat map, fixed cell size matrix is used while laying out the magnitude. In this type of heat map, the columns are considered as discrete phenomena and the sorting is intentional for rows and columns. The goal here is to suggest clusters using statistical analysis. The cell size should be large enough to make it clearly visible. On the other hand, in case of a spatial heatmap, the position of a magnitude is forced by its location within the space and the procedure is continuous and does not require cell size.

Heat maps were produced in this study to analyze the spatial distribution of pedestrian and bicyclist crashes (lower to higher density of crashes). During the calculation of the density, this study adopted the kernel density method as it is suitable in visualizing a continuous surface for the crash data. This method uses the total crash count at each location for density estimation. The maximum density value is provided at the center or location of crash and the density is considered to be gradually declining away from the center (*57*, *58*). The kernel density estimation tool uses the following quartic kernel function:

$$K_2(x) = \begin{cases} 3\pi^{-1}(1 - x^T x)^2 & if\ x^T x < 1 \\ 0 & otherwise \end{cases} \qquad [1]$$

where:

$K_2(x)$ = represents the kernel function for 2-dimensional x.

x = the variable represented by the data.

Generally, K represents a unimodal probability density function which is radially symmetric.

The following formula determines the predicted density at any (x, y) location:

$$Density = \frac{1}{(radius)^2} \sum_{i=1}^{n} \left[\frac{3}{\pi} \cdot pop_i \left(1 - \left(\frac{distance_i}{radius} \right)^2 \right)^2 \right] \quad For\ distance_i < radius \qquad [2]$$

where $i = 1, \dots, n$ are input points or point crashes,

pop_i represents the population field value of point i, and $distance_i$ represents the distance between point i and the (x, y) location.

5. ANALYSIS AND FINDINGS

Results obtained from analysis of data from 2013-2017 for pedestrian and bicyclist crashes are summarized below:

5.1. Pedestrian Safety

Although the roads are shared by both pedestrians and vehicles, often less consideration is given to pedestrians while designing the roads. Pedestrians are fragile, travel at a much slower speed than vehicles, and are more vulnerable to severe injuries and fatalities from pedestrian-motor vehicle collisions. The pedestrian safety analysis includes all the crashes involving at least one pedestrian and one motor vehicle.

Pedestrian crashes accounted for 4,459 crashes from 2013-2017, or 1.8% of total crashes in San Antonio. In Figure 1, primary and secondary Y-axis represents the annual pedestrian crashes and pedestrian crashes as a percentage of total annual crashes respectively. Pedestrian crashes increased in 2016 and 2017 but the percentage of pedestrian crashes in total crashes lowered from 2013 to 2014 and then remained somewhat constant for 2014-2017.

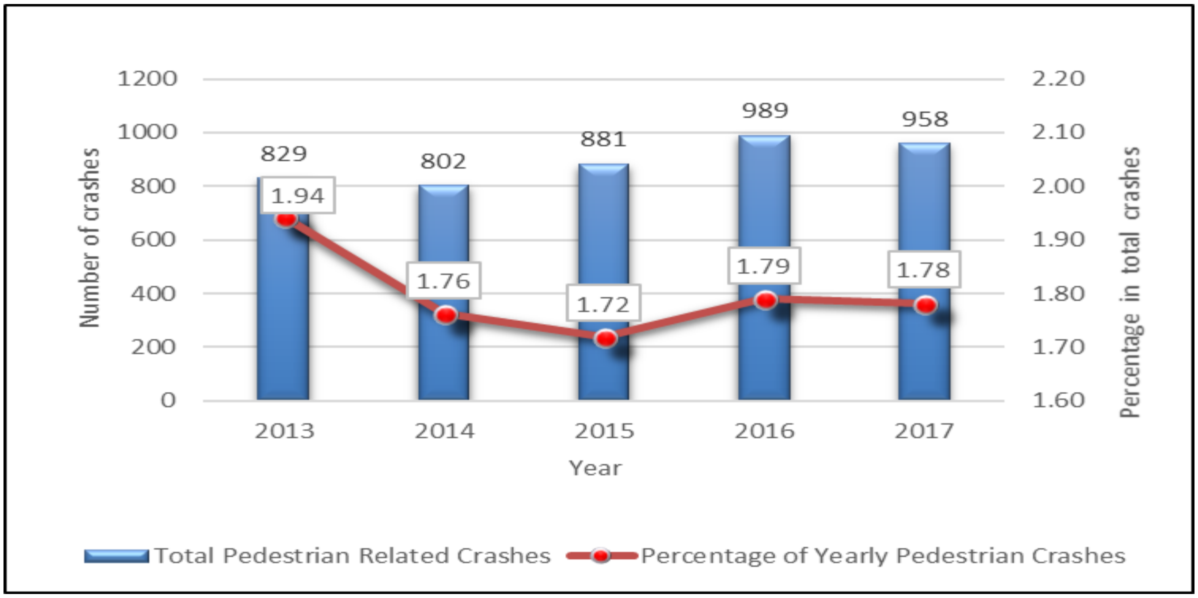

Figure 1. Annual variation of frequencies and percentages of pedestrian crashes

Pedestrian related crashes include 257 fatal crashes (32.9% of all fatal crashes) and 602 serious injury crashes (15.1% of serious injury crashes) from 2013–2017. 859 pedestrian crashes (19.3% of all pedestrian crashes) resulted in a fatal or serious injury. Fatal and serious injury crash counts by year are shown in Figure 2.

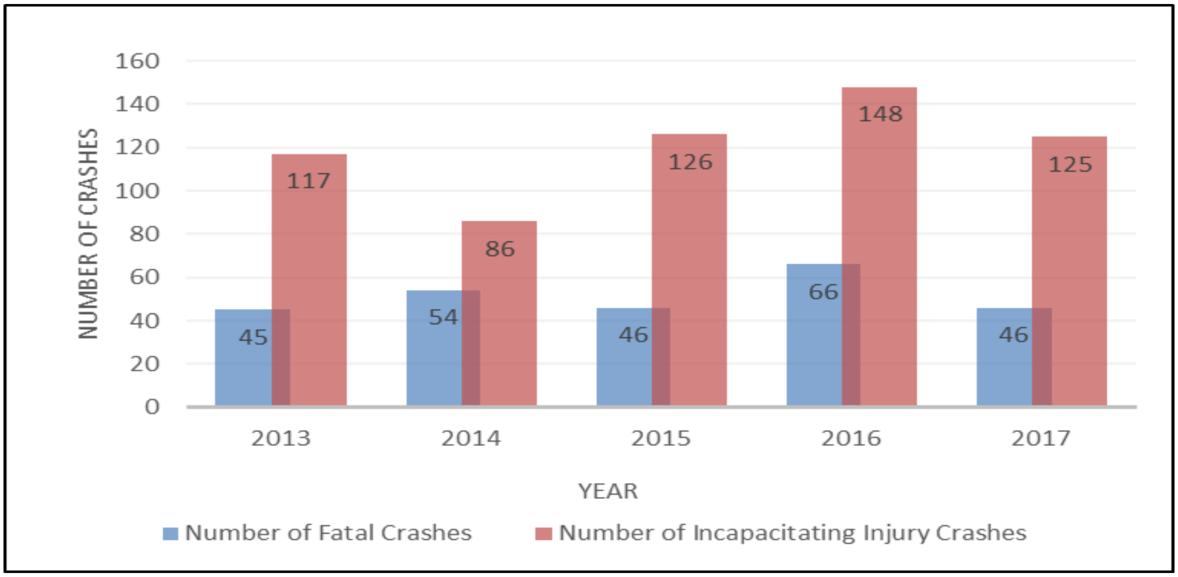

Figure 2. Fatal and serious injury pedestrian crashes

In Figure 3, fatal and serious injury pedestrian crashes are shown as a percentage of total pedestrian crashes along the secondary Y-axis. 2014 and 2017 had lowest percentages of fatal and serious injury crashes.

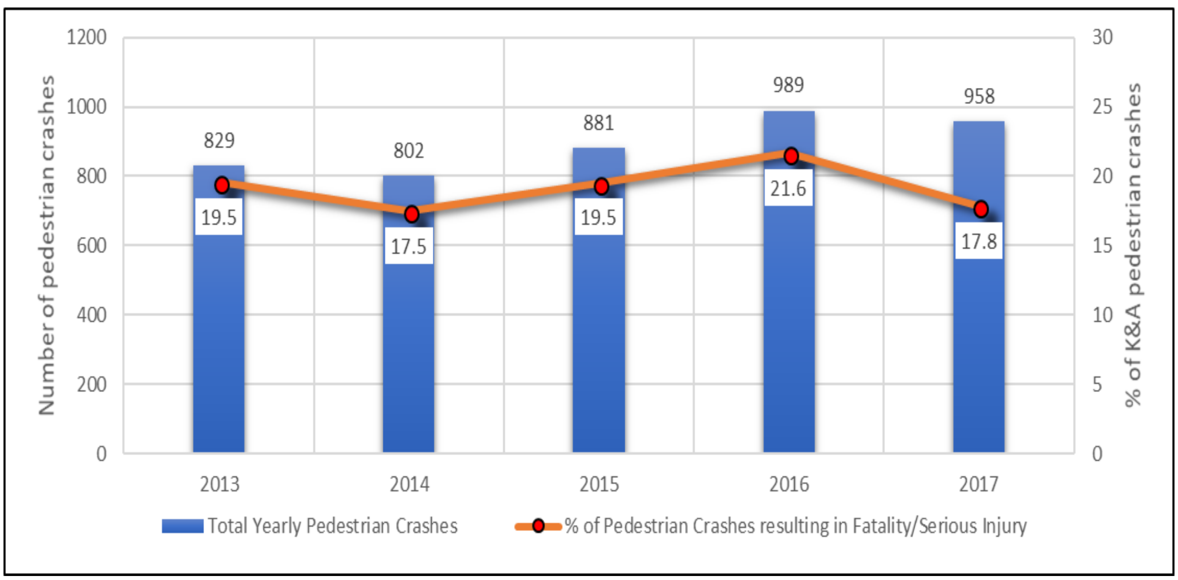

Figure 3. Annual variation of frequencies and percentages of fatal and serious injury pedestrian crashes

As shown in Figure 4, a total of 4,770 pedestrians (including 706 pedestrians under the age of 17, and 539 older pedestrians over the age of 64) were associated with 4,459 crashes. The ages of 112 pedestrians were unavailable. The ratio of female to male pedestrians was highest for older pedestrians and lowest for younger pedestrians.

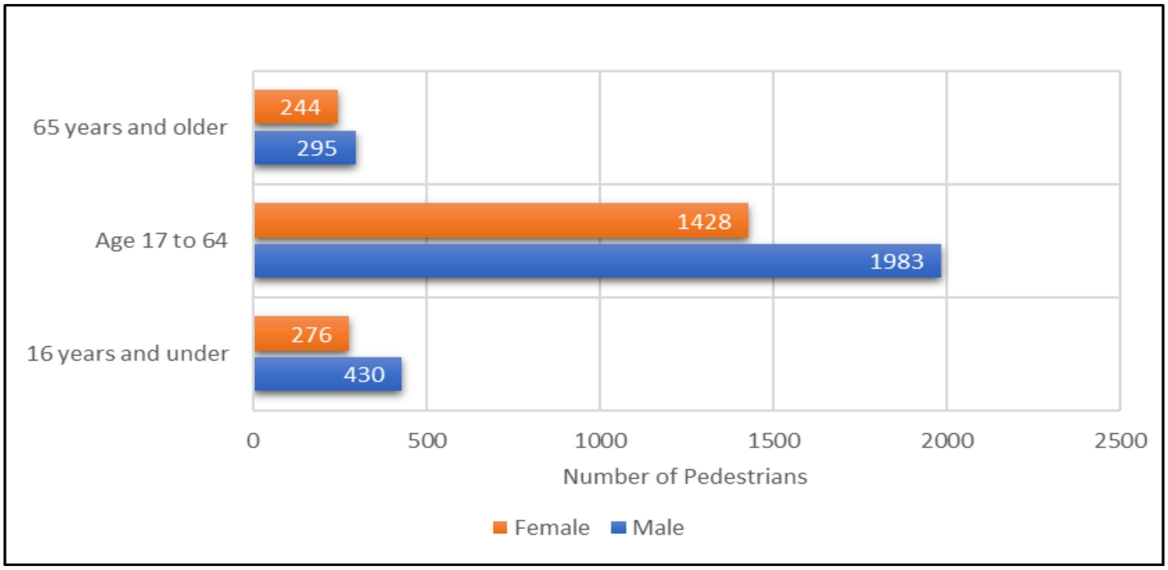

Figure 4. Age and gender distribution of pedestrians involved in crashes

In Figure 5**,** the variation of pedestrian crash frequency by day of the week is shown. Friday was associated with the highest pedestrian crash frequency. Weekend period, especially Sunday, had relatively low pedestrian crash frequency. However, detailed study found that the proportion of fatal and serious pedestrian injury crashes was substantially higher during the weekend period (*64*).

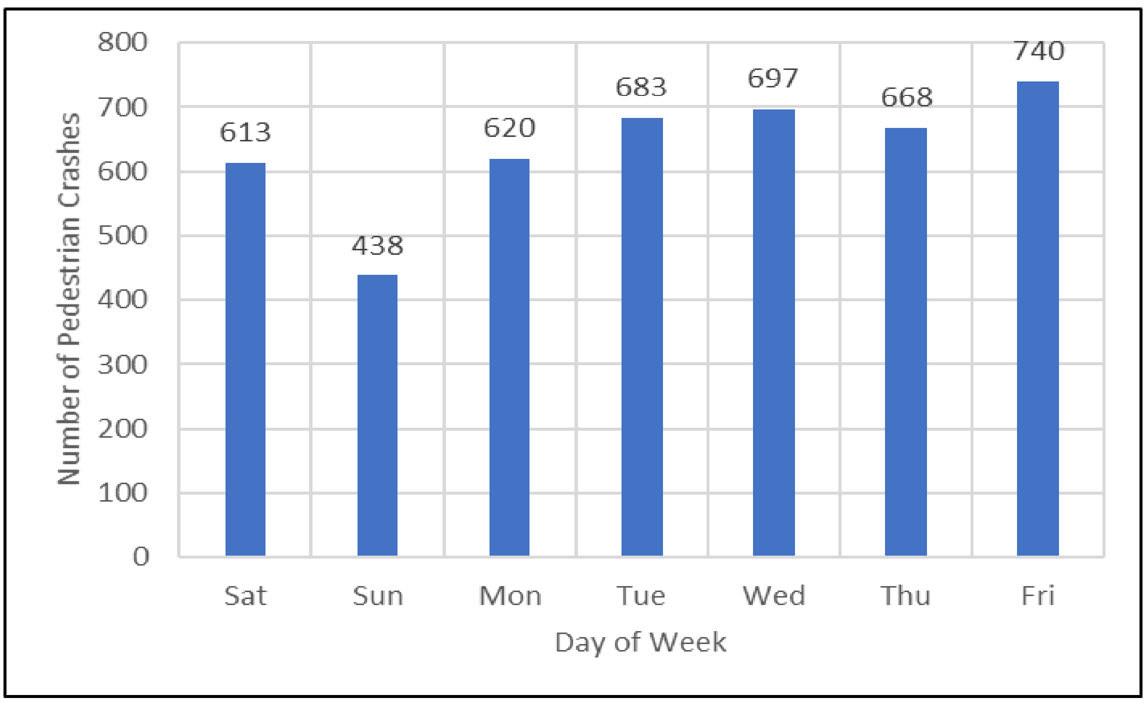

Figure 5. Pedestrian crash frequency by day of the week•

The variation of pedestrian crash frequency by time of the day is shown in Figure 6. Pedestrian crash frequency gradually increases from the morning throughout the day, experiences its peak during evening (7:00 p.m.), and starts to decrease gradually afterwards. However, there is an abnormal increase during the period 2:00 a.m.-3:00 a.m. which might be attributed to the closing hour of the bars.

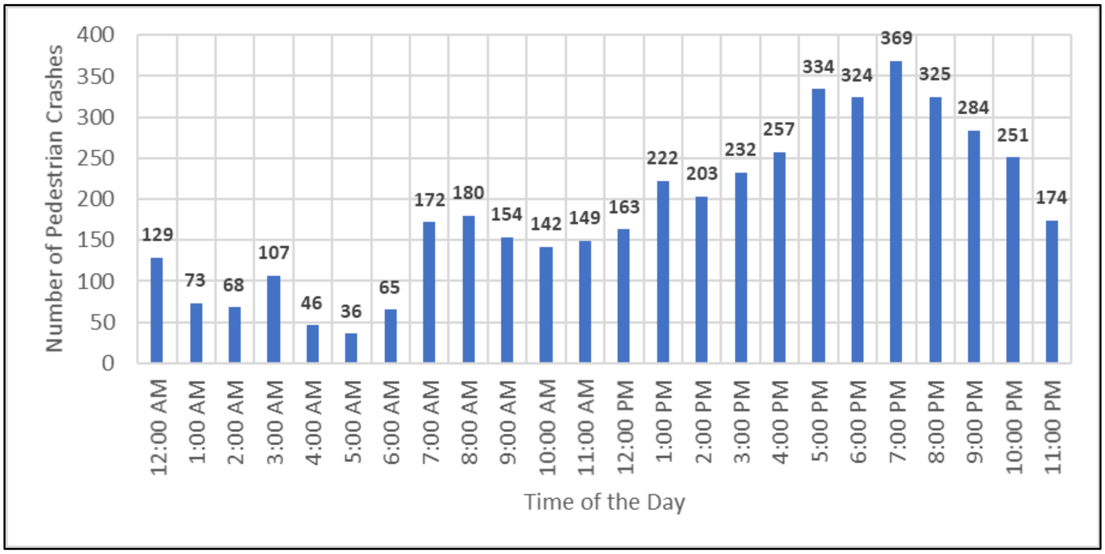

Figure 6. Pedestrian crash frequency by time of the day•

Pedestrian crash frequency by month of the year is shown in Figure 7. Summer months have relatively lower pedestrian crash frequency while winter months have the highest. This might be related to the difference in walking practice based on season. The number of pedestrians might be relatively lower during the summer months due to the hot weather, which eventually results in lower pedestrian crash frequency.

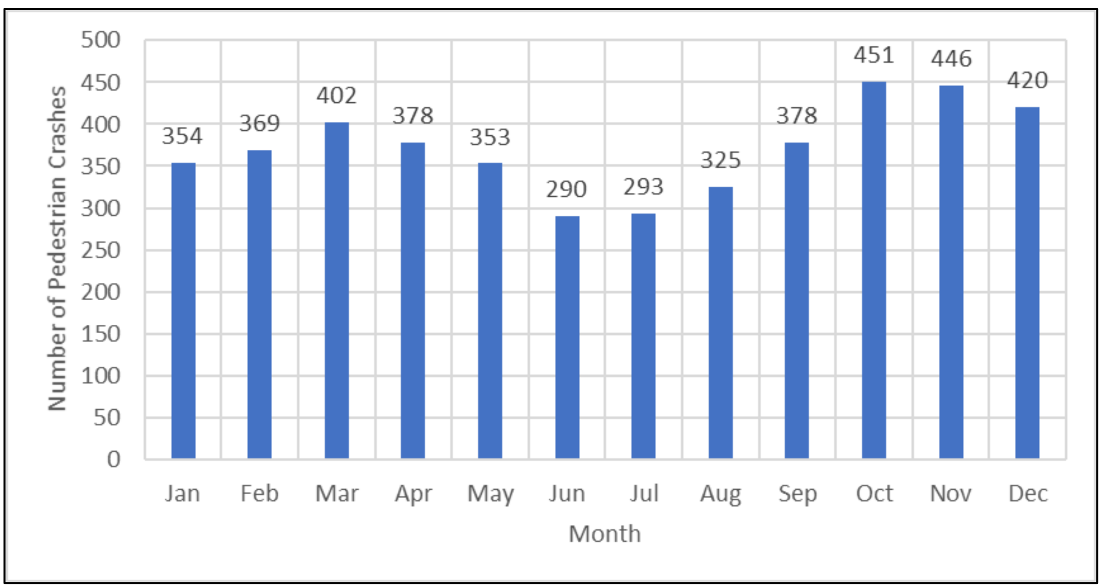

Figure 7. Pedestrian crash frequency by month of the year•

As shown in Figure 8, the majority proportion of pedestrian crashes occurred under clear weather condition, which is expected. About 6% of all pedestrian crashes occurred during rainy weather condition. Further analysis found that inclement weather condition had no significant effect on pedestrian crash severity (*65*).

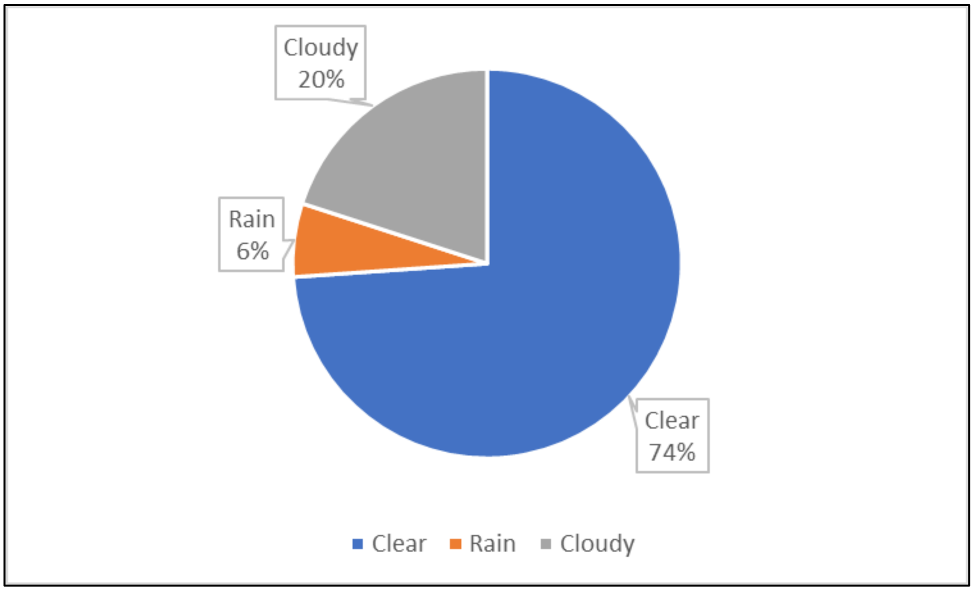

Figure 8. Proportion of pedestrian crash by weather condition•

Pedestrian fatal and incapacitating injury counts under different weather conditions are shown in Figure 9. The results suggest that if crashes which result in severe pedestrian injuries are considered, clear weather condition is more likely to result in an incapacitation injury whereas rainy weather condition is more likely to result in fatality.

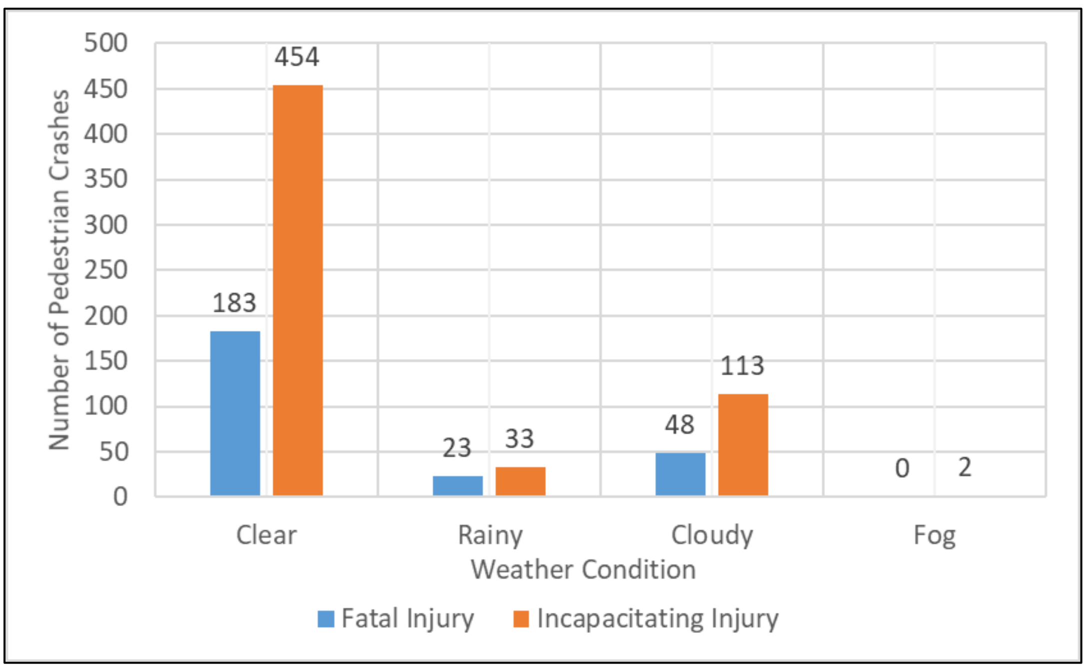

Figure 9. Fatal and incapacitating pedestrian crash frequency by weather condition•

As shown in Figure 10, about 59% of all pedestrian crashes occur in daylight lighting condition. Further studies show that pedestrian crashes occurring in dark lighting condition have high risk (statistically significant) of resulting in a severe pedestrian injury.

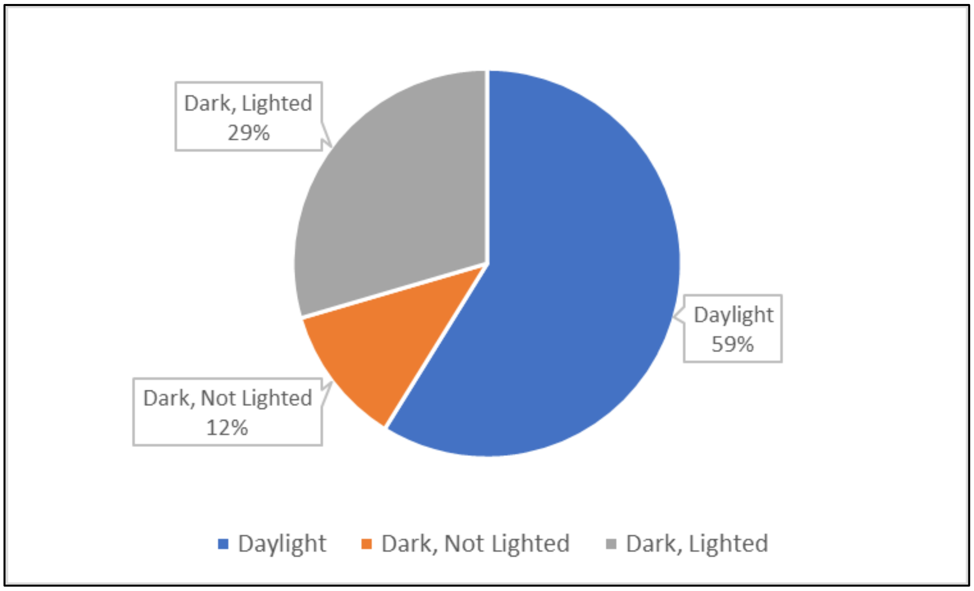

Figure 10. Proportion of pedestrian crashes by lighting condition•

Pedestrian fatal and incapacitating injury counts occurring in different lighting conditions are shown in Figure 11. Although dark lighting conditions (lighted and not lighted) consist of only 41% of all pedestrian crashes, they result in substantially greater proportion of severe pedestrian crashes compared to daylight lighting condition.

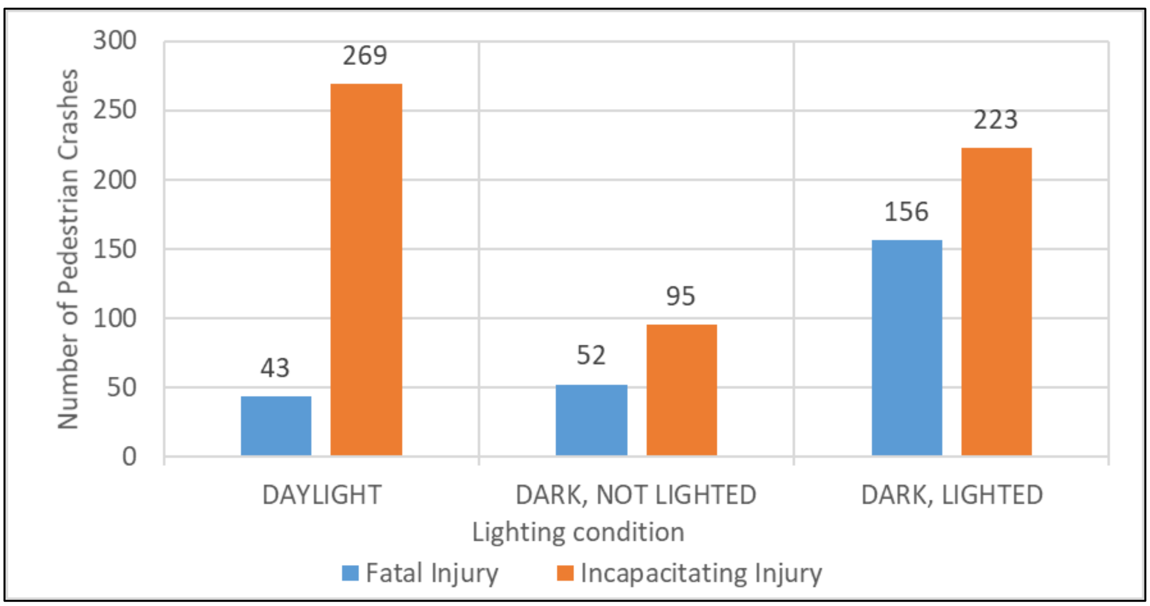

Figure 11. Fatal and incapacitating pedestrian crash frequency by lighting condition•

As expected, majority of pedestrian crashes occur on dry roads (Figure 12). Wet/Standing Water surface condition usually results from rain and only a small percentage of all pedestrian crashes occur during rainy weather.

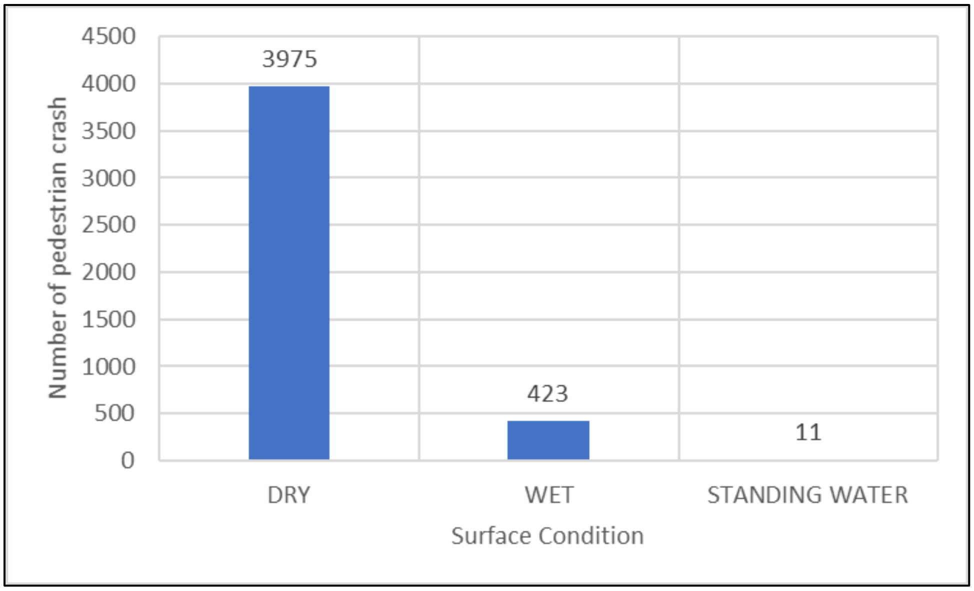

Figure 12. Pedestrian crash frequency by surface condition•

Fatal and incapacitating injury pedestrian crash counts for different types of road surface conditions are shown in Figure 13. The results suggest that a pedestrian crash on wet surface is more likely to result in a fatal pedestrian crash compared to pedestrian crashes on dry road surface.

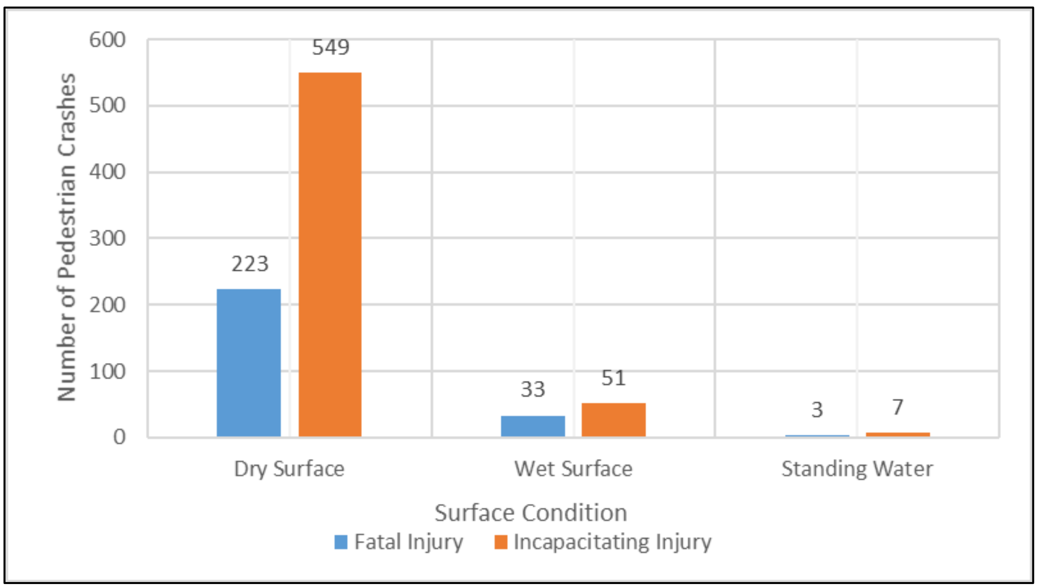

Figure 13. Fatal and incapacitating pedestrian crash frequency by surface condition•

As shown in Figure 14, about half of all pedestrian crashes occur on city streets and about one-fourth of all pedestrian crashes occur on non-trafficways. Although only 6% of all pedestrian crashes occur on interstate roads, higher speed limit of these roads suggests a severe pedestrian injury is almost inevitable for crashes occurring on these roads.

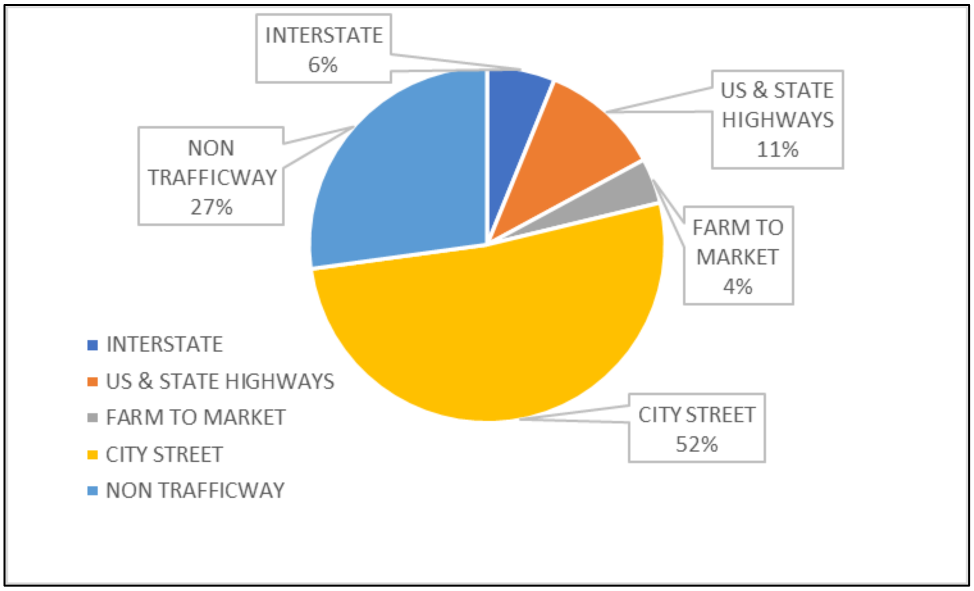

Figure 14. Proportion of pedestrian crashes by road class•

Fatal and incapacitating injury pedestrian crash counts on different road classes (Figure 15) indicate that non-traffic ways are the safest among all road classes. This is understandable as pedestrian injury severity is largely affected by vehicle speed. Interstate roads, on the other hand, have more fatal crashes than incapacitating injury crashes, which also should be attributed to the vehicle speed.

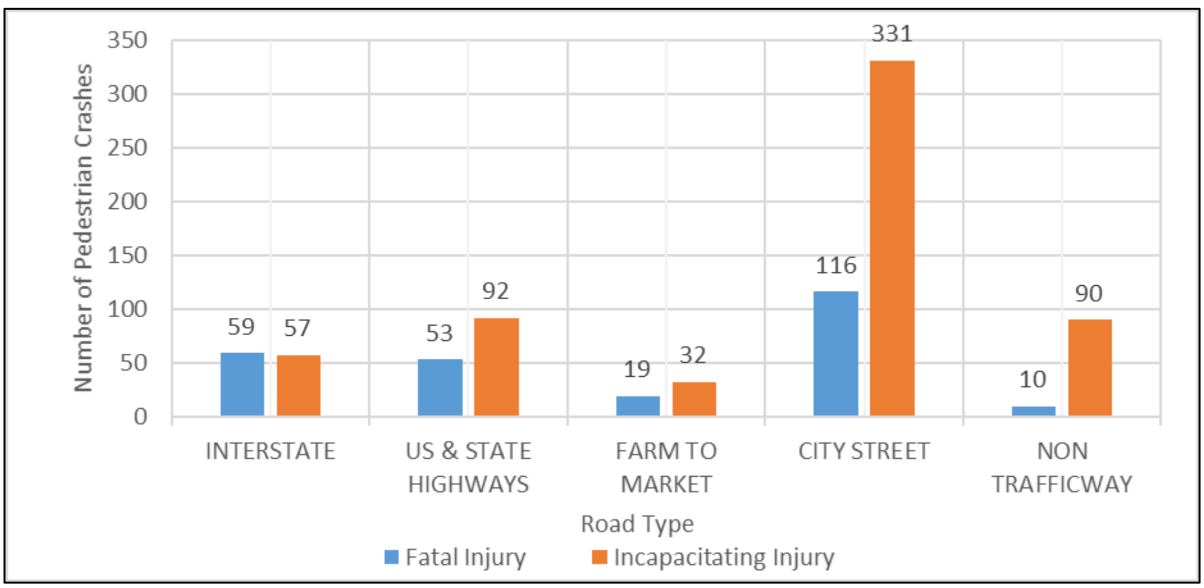

Figure 15. Fatal and incapacitating pedestrian crash frequency by road class•

Passenger cars, SUV, and Pickup trucks are primarily involved in pedestrian crashes (Figure 16). These vehicles are more prevalent on roadways and are expected to be involved in pedestrian crashes at higher proportions compared to other vehicles.

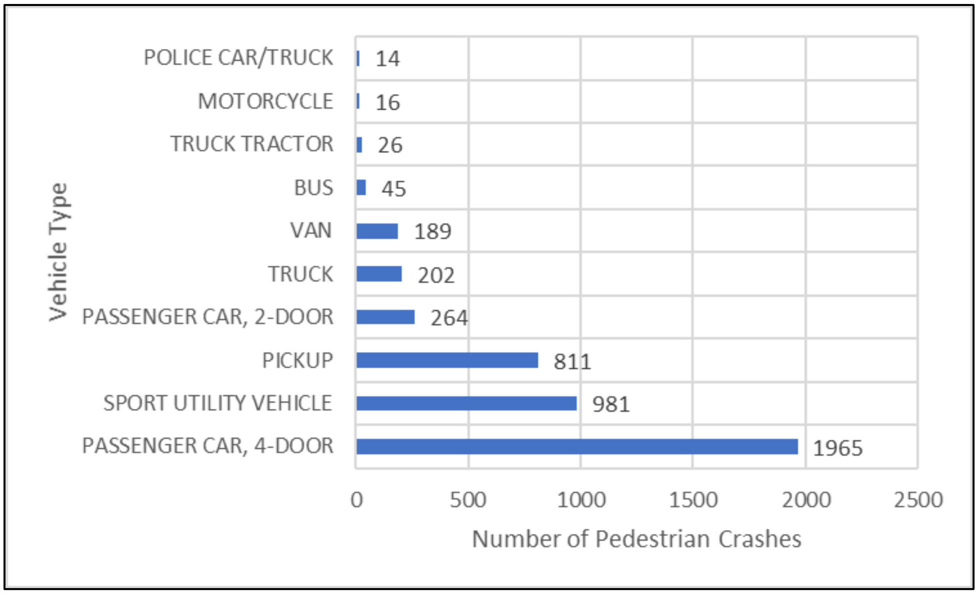

Figure 16. Pedestrian crash frequency by vehicle type•

Pedestrian fatal and incapacitating injury crash counts for different vehicle types are shown in Figure 17. Bus and police car/truck were associated with relatively high proportion of fatal crash incidents, possibly due to their higher speed/body structure.

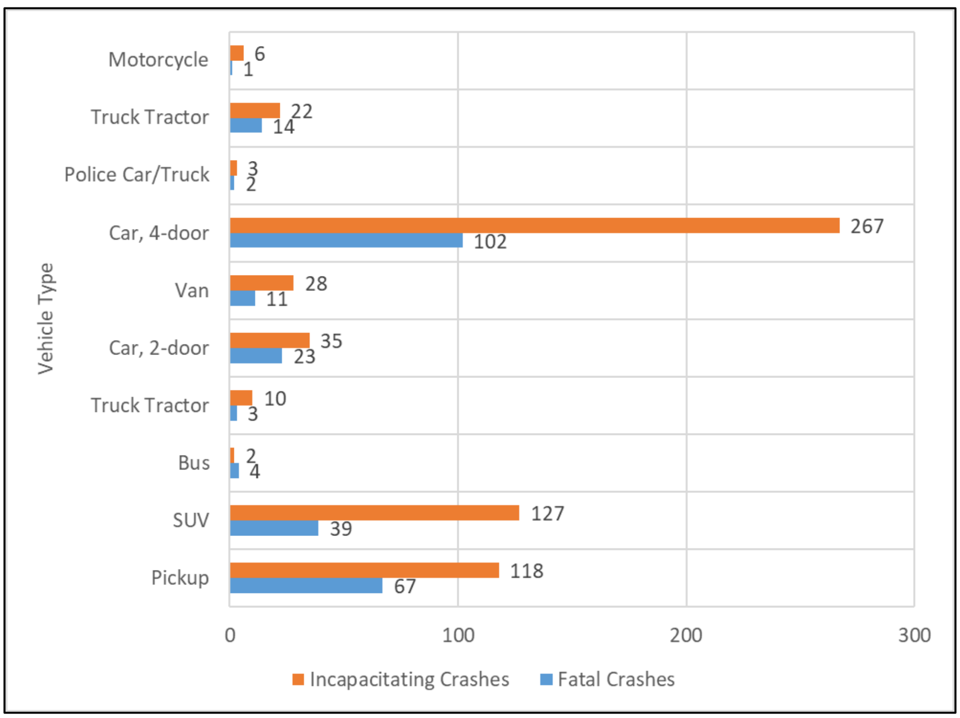

Figure 17. Fatal and incapacitating pedestrian crash frequency by vehicle type•

The spatial distribution of all pedestrian crashes during the study period is shown with a heat map in Figure 18. Pedestrian crashes were mostly concentrated in the downtown area and at the intersections just outside of the city center. Similar results were obtained in more detailed studies (*67-68*). Downtown area experienced the highest pedestrian crash density (especially at intersections) which is expected as pedestrians constitute an essential element of downtown traffic in San Antonio. The intersections on E Travis St, E Houston St, S Zarzamora St, E Commerce St, Fredericksburg Rd, E Market St, and Wurzbach Rd experienced frequent pedestrian crashes

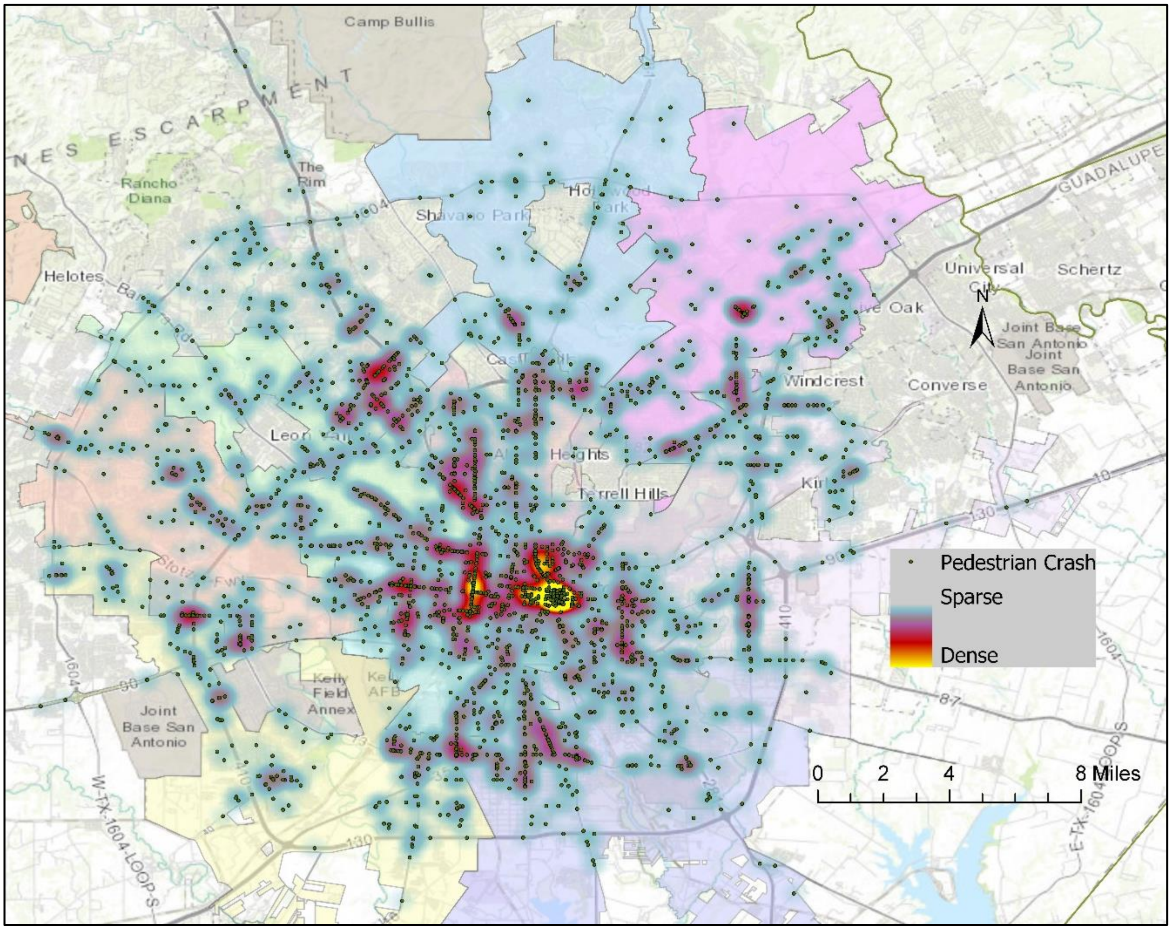

Figure 18. Heat map of pedestrian crashes•

5.1.1 Correlation of pedestrian crashes with other emphasis areas

Intersection crashes accounted for a total of 1,371 pedestrian crashes from 2013-2017, or 30.7% of the total pedestrian crashes in San Antonio as shown in Figure 19. These crashes were responsible for 34 fatal pedestrian crashes (13.2% of all fatal pedestrian crashes) and 165 incapacitating pedestrian crashes (27.4% of all incapacitating pedestrian crashes).

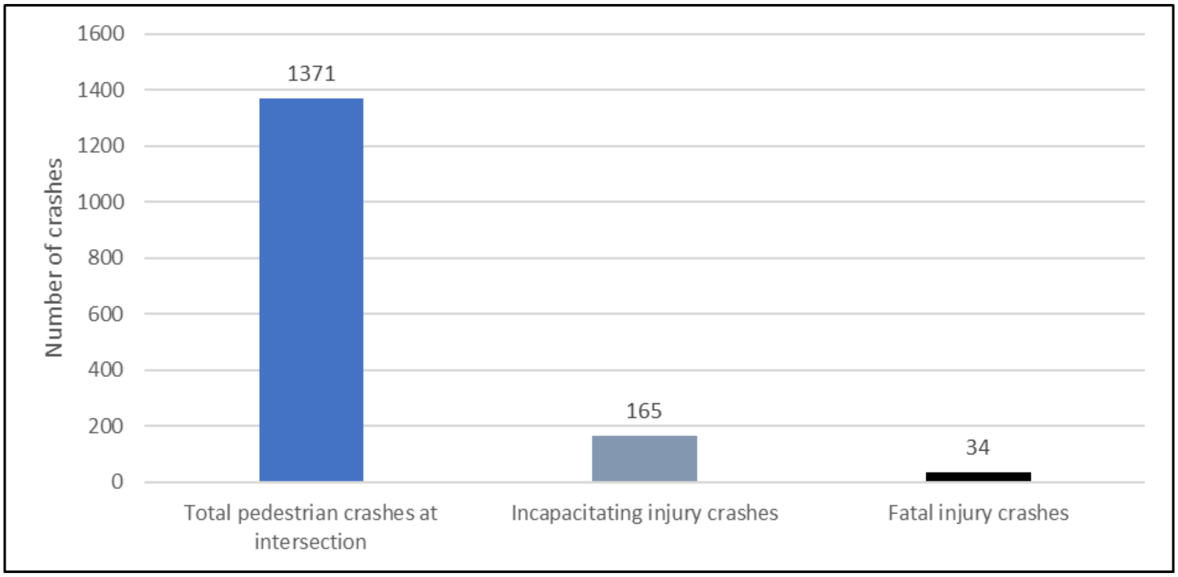

Figure 19. Pedestrian crashes at intersections•

Fatal and serious injury crash counts by year are shown in Figure 20. 2013 was associated with highest fatal pedestrian crashes and 2016 had highest fatal injury pedestrian crashes. Total K&A crashes exhibited a decreasing trend from 2013 to 2015 but the numbers increased in the next two years.

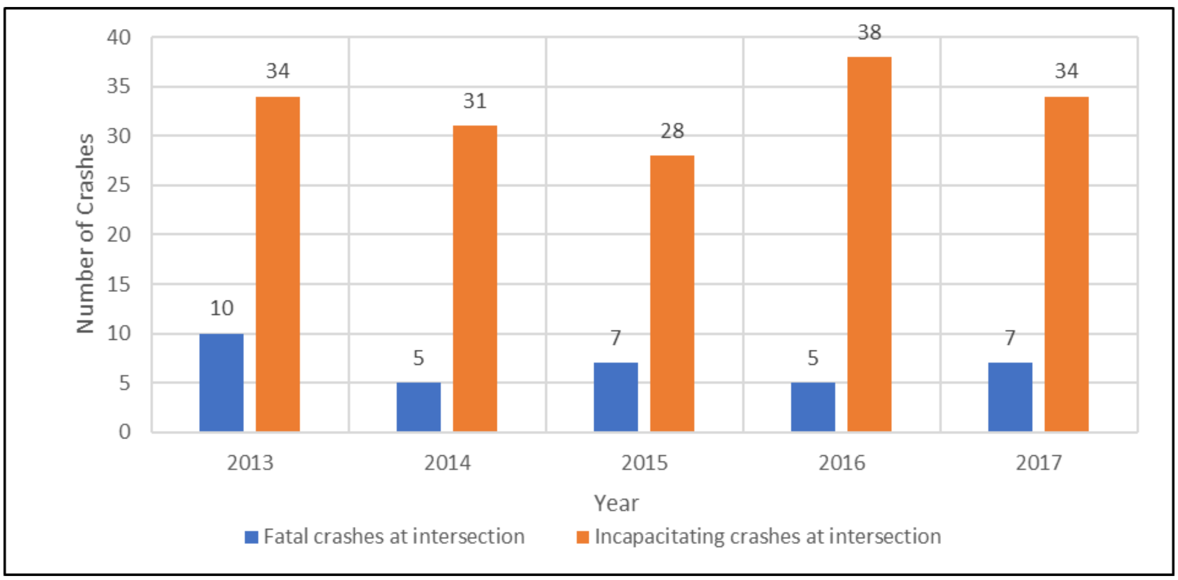

Figure 20. Variation of K&A pedestrian crashes at intersection•

In Figure 21, fatal and serious injury pedestrian crashes resulting from crashes at intersection are shown as a percentage of total intersection crashes along the secondary Y-axis. The percentage of fatal pedestrian crashes decreased steeply from 2013 to 2014, and then fluctuated moderately in subsequent years. The percentage of serious injury pedestrian crashes continued to decrease from 2013 to 2015 and then had a steep increase in the next year. The total number of pedestrian fatal and serious injury crashes each year showed an overall increasing trend.

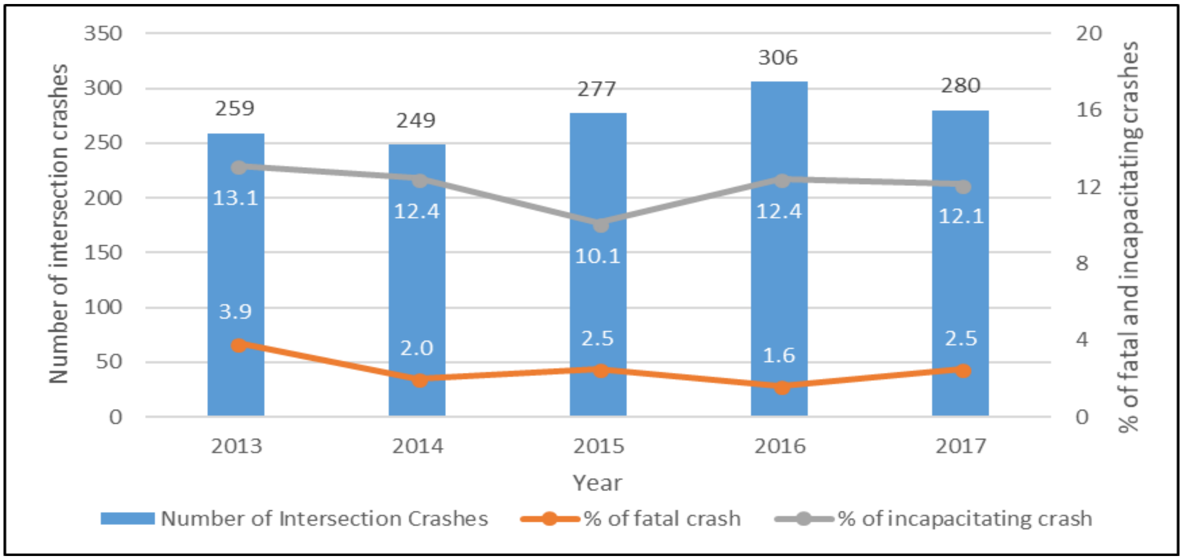

Figure 21. Annual variation of pedestrian crashes at intersections and percentage of fatal and serious injury crashes•

The frequency of weekend and weekday pedestrian crashes was affected by the lighting condition of the intersection. The ratio of weekend to weekday pedestrian crashes was higher for "DARK, LIGHTED" and "DARK, NOT LIGHTED" conditions than for the "DAYLIGHT" condition, as shown in Figure 22.

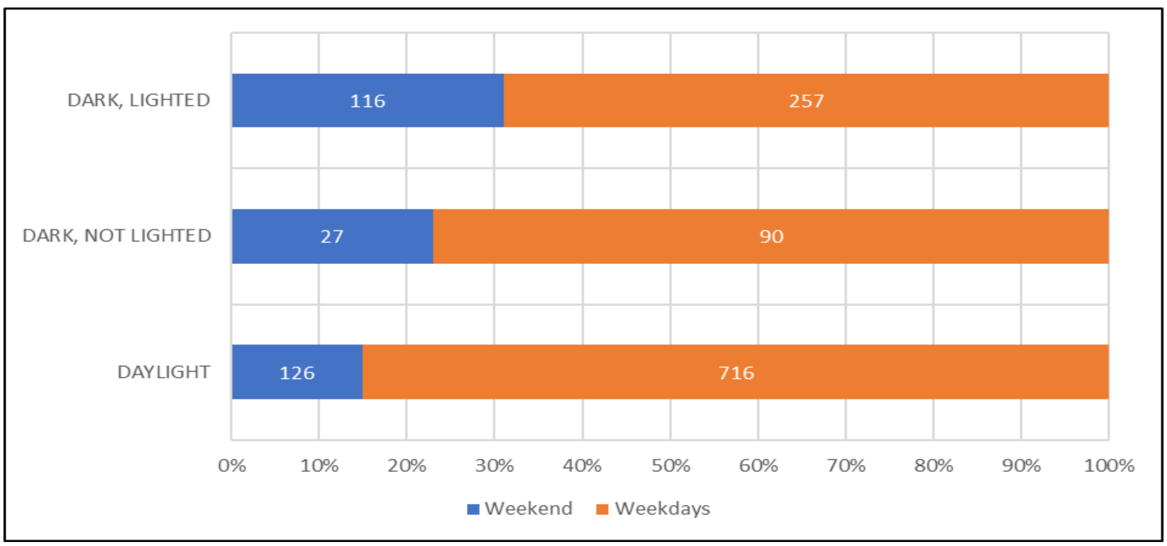

Figure 22. Proportion of pedestrian crashes at intersections by lighting condition and day of week•

The heat map of pedestrian crashes occurred at the intersections of San Antonio is shown in Figure 23. Pedestrian related intersection crashes were more concentrated in the downtown area and the area surrounding the city center. The intersections on E Travis St, E Commerce St, E Market St, and S Flores St in the city center experienced relatively more pedestrian crashes.

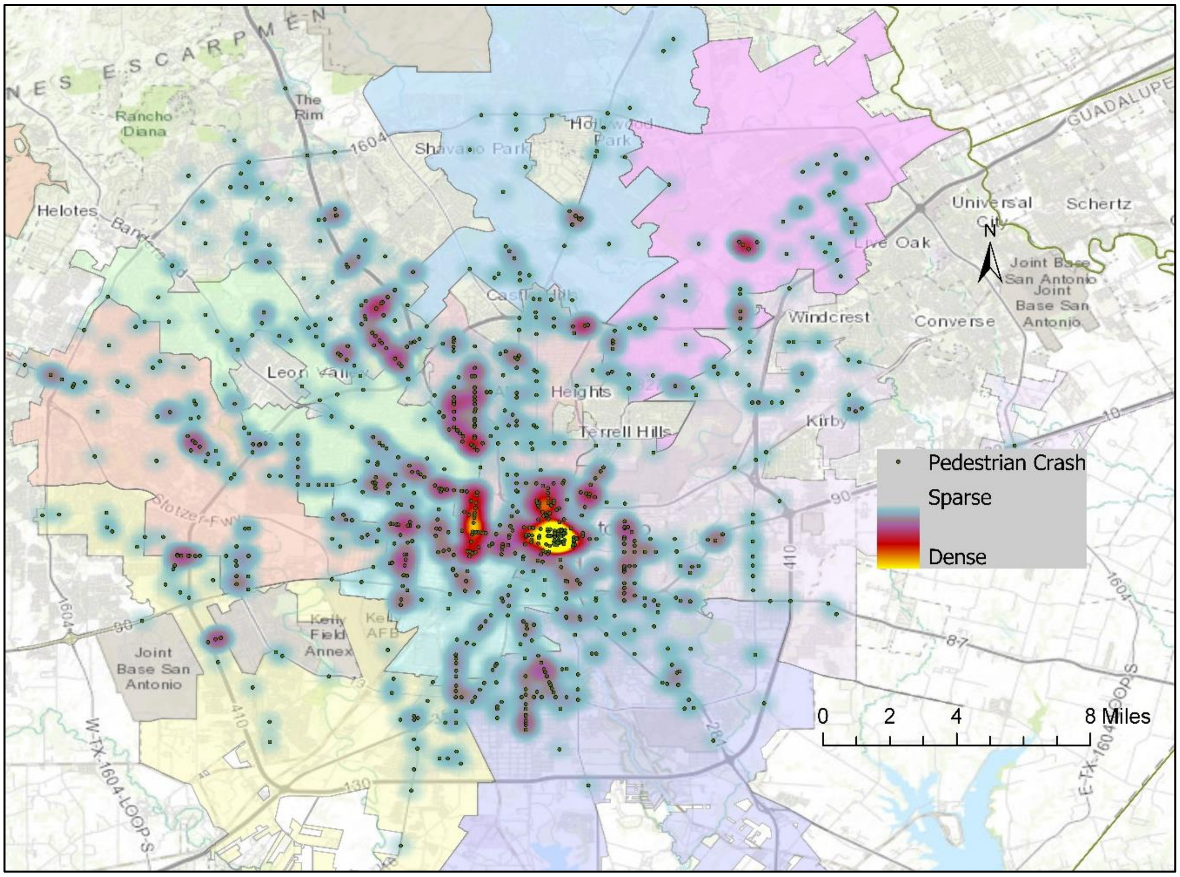

Figure 23. Heat map of pedestrian crashes at intersections•

A total of 1,808 pedestrian crashes due to distracted driving occurred in 2013-2017, or 40.5% of total pedestrian crashes in San Antonio. The number of annual distracted driving pedestrian crashes is shown along the primary Y-axis in Figure 24. The secondary Y-axis represents distracted driving pedestrian crashes as a percentage of total annual pedestrian crashes. The percentage of distracted driving crashes in total crashes declined from 2013-2016 but increased in 2017.

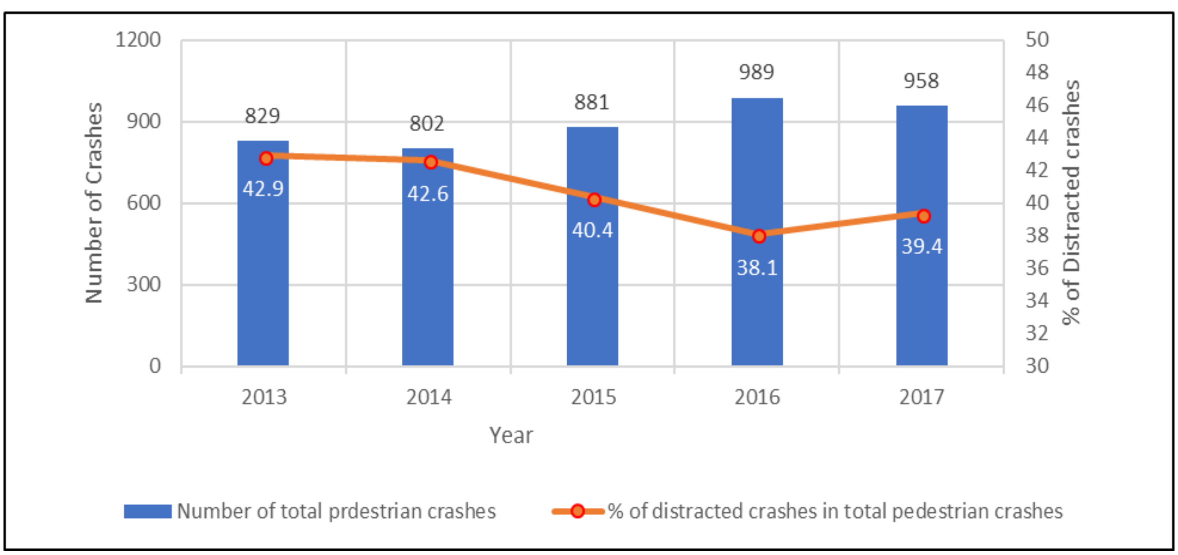

Figure 24. Yearly percentage of distracted driving pedestrian crashes to total pedestrian crashes•

Figure 25 expresses the hourly variation of distracted driving crashes for 2013-2017. The percentage of distracted driving was higher from 9 a.m. - 5 a.m., with the peak being at 1 p.m. The percentage was lower at the morning and after sunset. There was an unusual deviation in the trend at 3 a.m. which coincide with the closing time of bars.

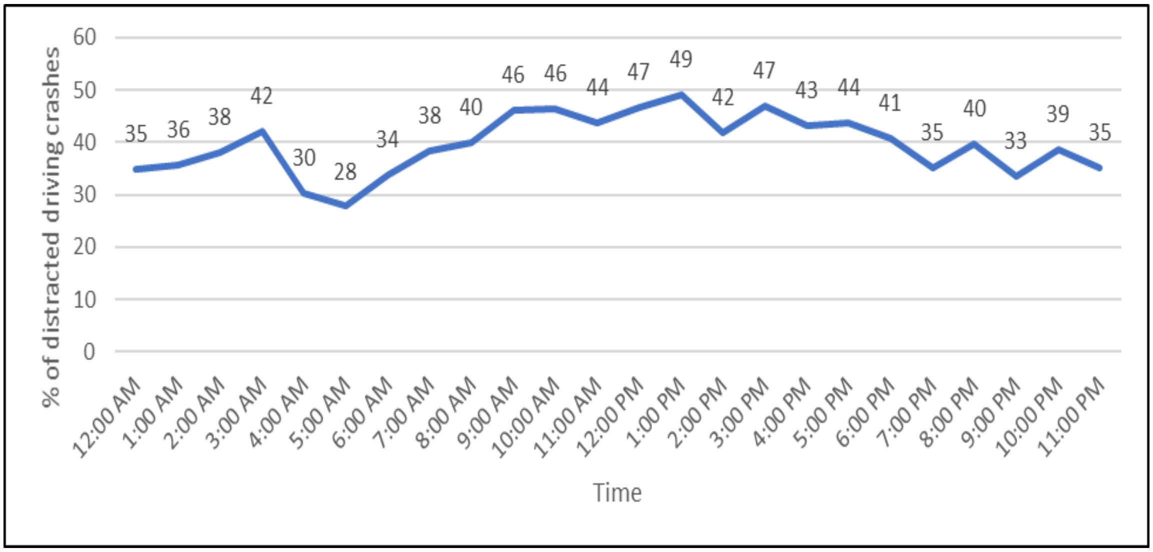

Figure 25. Percentage of distracted driving pedestrian crashes to total pedestrian crashes at each hour•

Distracted driving was responsible for 54 fatal crashes (26.6% of all fatal pedestrian crashes) and 203 serious injury crashes (42.7% of all serious injury pedestrian crashes) from 2013–2017. Fatal and serious injury crash counts by year due to distracted driving are shown in Figure 26.

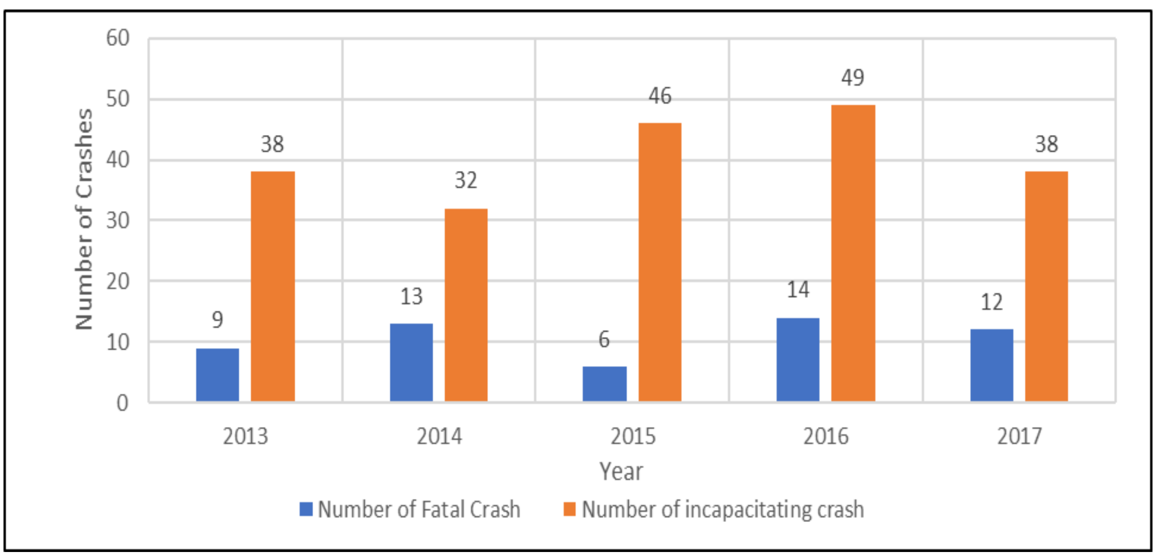

Figure 26. Yearly variation of K&A pedestrian crashes due to distracted driving•

The primary Y-axis in Figure 27 shows number of distracted driving pedestrian crashes. The secondary Y-axis shows the percentage of fatal and incapacitating pedestrian crashes for each year as a percentage of total pedestrian crashes for that year. Distracted driving crashes were more frequent in 2016 and 2017 and lowest in 2014. The percentage of fatal crashes was inconsistent over years. 2016 had highest percentage of incapacitating pedestrian crashes and second highest percentage of fatal pedestrian crashes due to distracted driving. Both percentages reduced in 2017 from 2016.

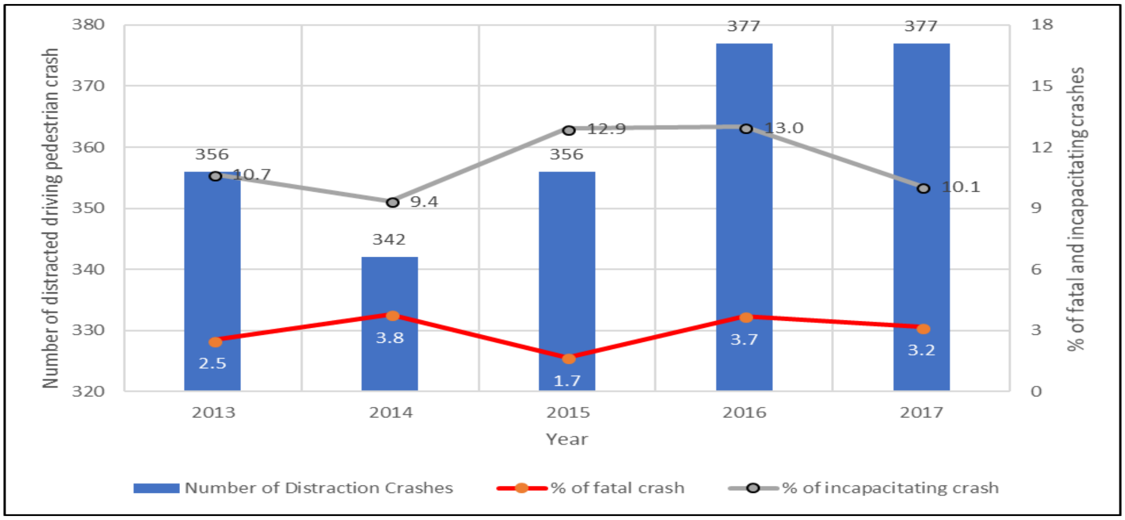

Figure 27. Variation of percentage of K&A pedestrian crashes due to distracted driving•

Apart from the city center, which is expected to have relatively high distraction crash concentration related to pedestrians due to more pedestrian activities, S Zarzamora St experienced relatively high concentration of distracted driving related pedestrian crashes (Figure 28).

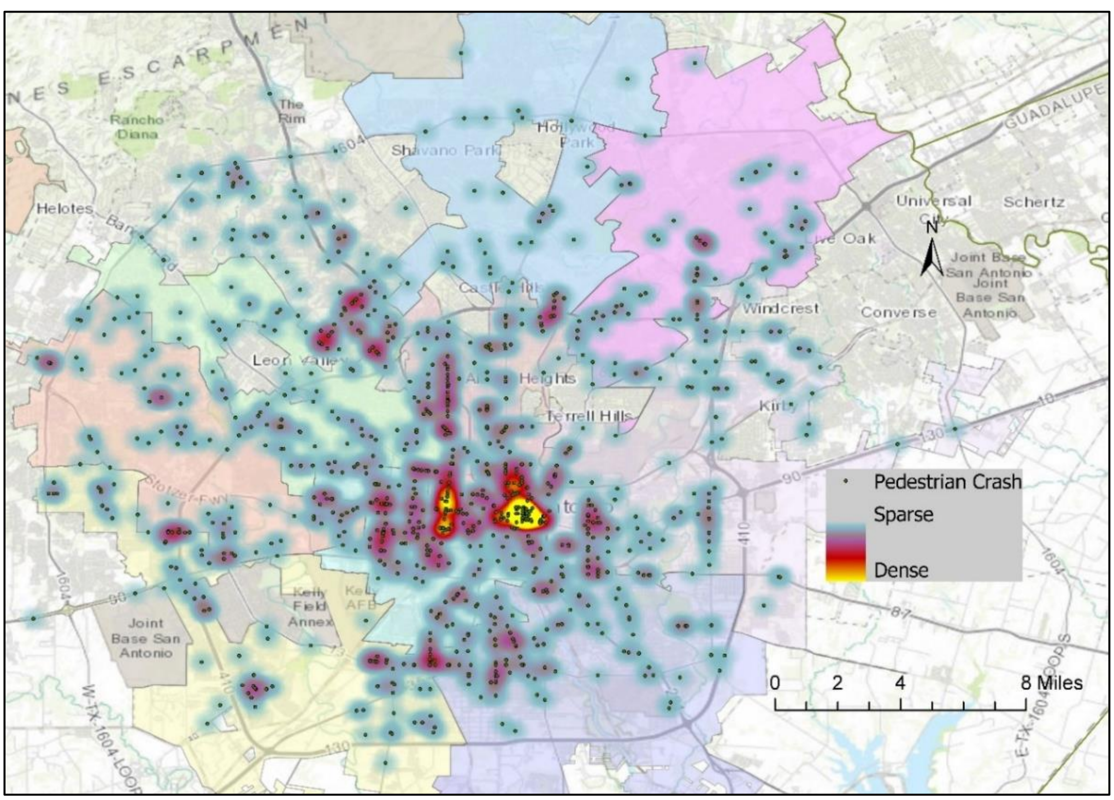

Figure 28. Heat map of pedestrian crashes due to distracted driving•

Impaired driving was the identified cause for 209 pedestrian crashes (231 associated pedestrians) from 2013-2017, or 4.7% of total pedestrian crashes in San Antonio as shown in Figure 29. In case of pedestrian crashes under impaired driving charge, the driver must be under alcohol or drug influence and the crash must involve a pedestrian. So, the percentage of pedestrians involved in impaired driving crashes should be smaller than the general impaired driving crash percentage. When all crashes in San Antonio are concerned, driving while intoxicated was the identified cause for 8,750 crashes from 2013-2017, or 3.5% of total crashes in San Antonio.

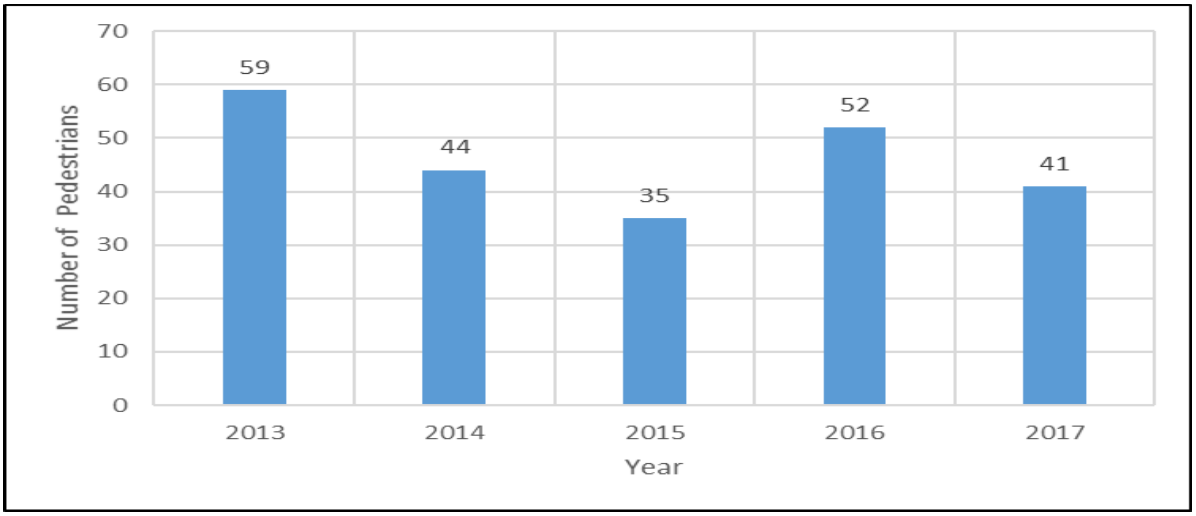

Figure 29. Yearly variation of pedestrians involved in impaired driving crashes•

Fatal and serious injury crashes were more frequent during the weekend than on weekdays, as shown in Figure 30. Sunday had considerably higher frequency of impaired driving crashes. Any crash that occurs after Saturday midnight are considered to happen on Sunday. In general, Saturday night experiences considerably higher volume of people going out to bars and parties. Consuming alcohol affects the perception of both pedestrians and drivers and might be the reason behind high volume of pedestrian crashes due to impaired driving on Sunday.

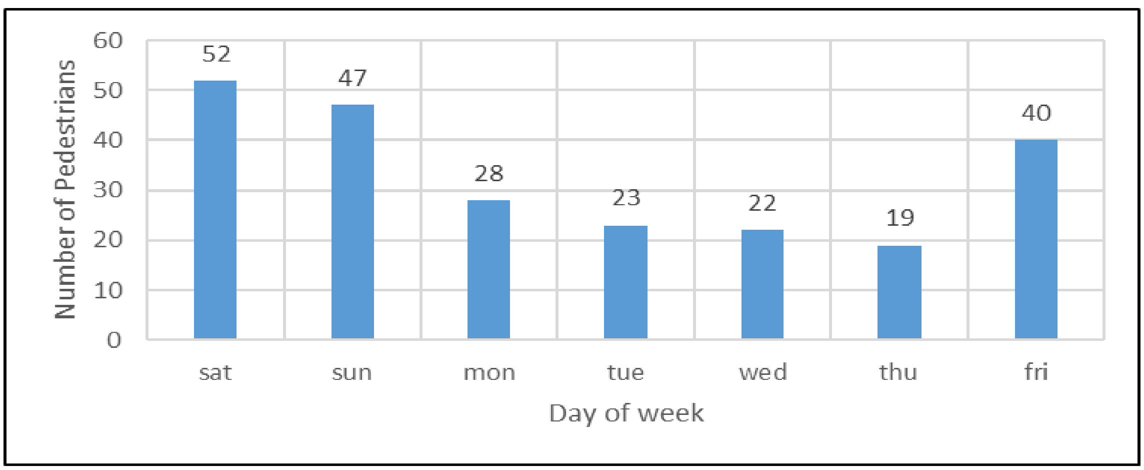

Figure 30. Daily variation of pedestrians involved in impaired driving crashes•

Figure 31 expresses the hourly variation of pedestrians involved in impaired driving crashes for 2013-2017. The number of driving under influence crash involving pedestrians was exceptionally higher at 3 a.m. This clearly coincides with the bars closing at 2 a.m. The frequency was lower during the day and started to increase from evening. Except for the 3 a.m. peak, 7:01-9 p.m. and 10:01-12 p.m. had higher number of pedestrian crashes. This can be due to more drunk drivers and pedestrians on road in the evening, or due to the scarcity of light, or a combination of both. More data and detailed analysis is required to see if there is an actual surge in number of impaired driving pedestrian crashes at that time.

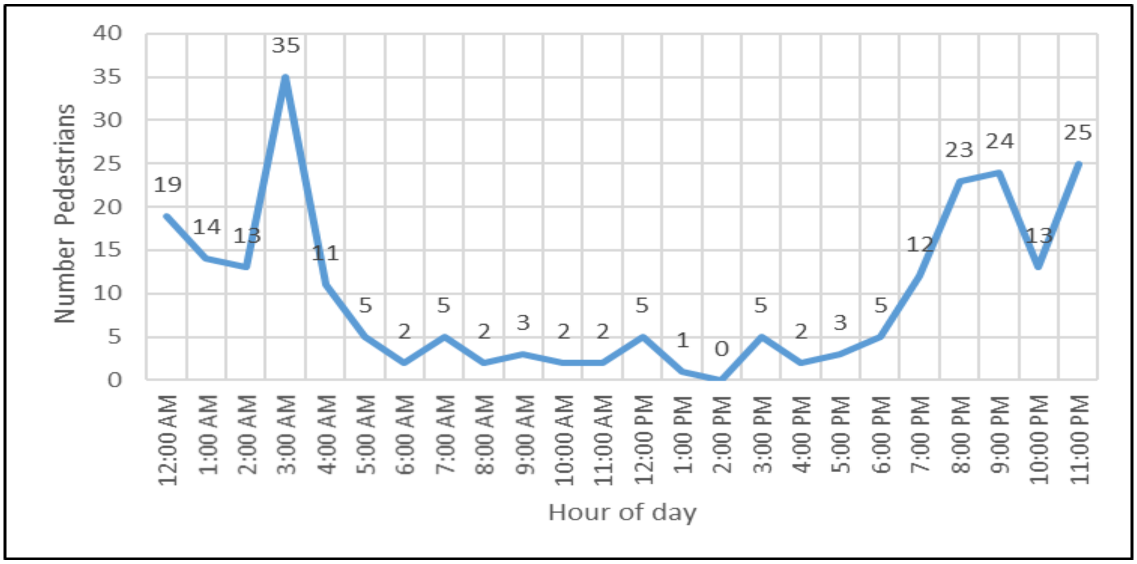

Figure 31. Hourly variation of pedestrians involved in impaired driving crashes•

Impaired driving was responsible for 29 pedestrian fatality and 58 serious pedestrian injuries from 2013–2017. Number of pedestrians involved in K&A crashes by year are shown in Figure 32. From 2016 to 2017, number of incapacitating injury crashes involving pedestrians decreased but number of fatal crashes involving pedestrians increased.

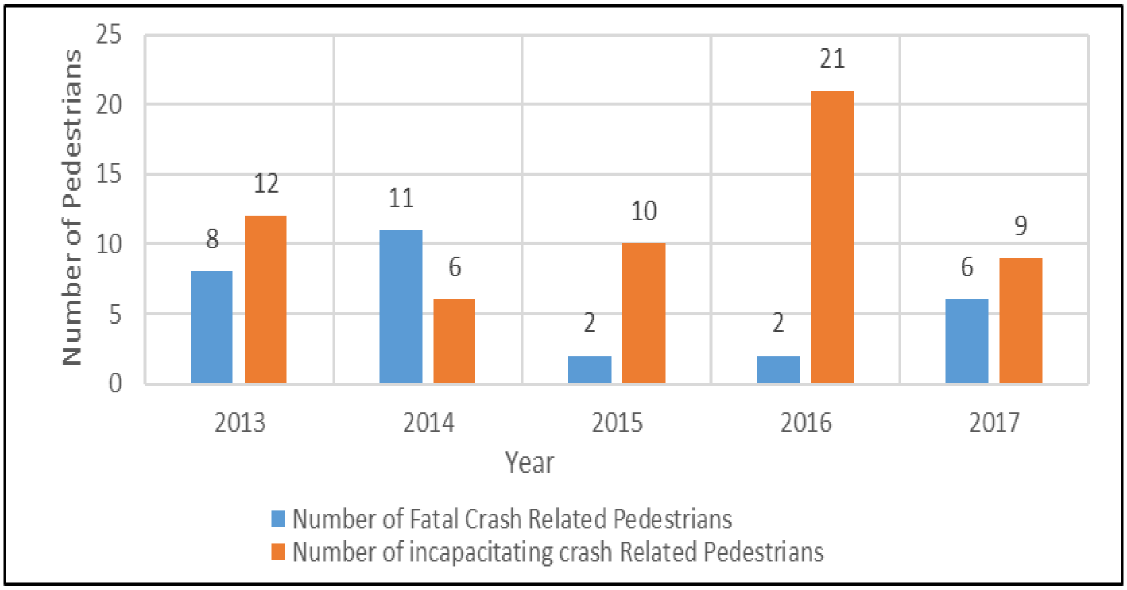

Figure 32. Yearly variation of pedestrians involved in impaired driving K&A crashes•

The spatial distribution of impaired driving related pedestrian crashes is shown in Figure 33. Further analysis suggests that the spatial distribution of the impaired driving related pedestrian crashes occurring during the late-night hours and the alcohol serving establishments are correlated to some degree.

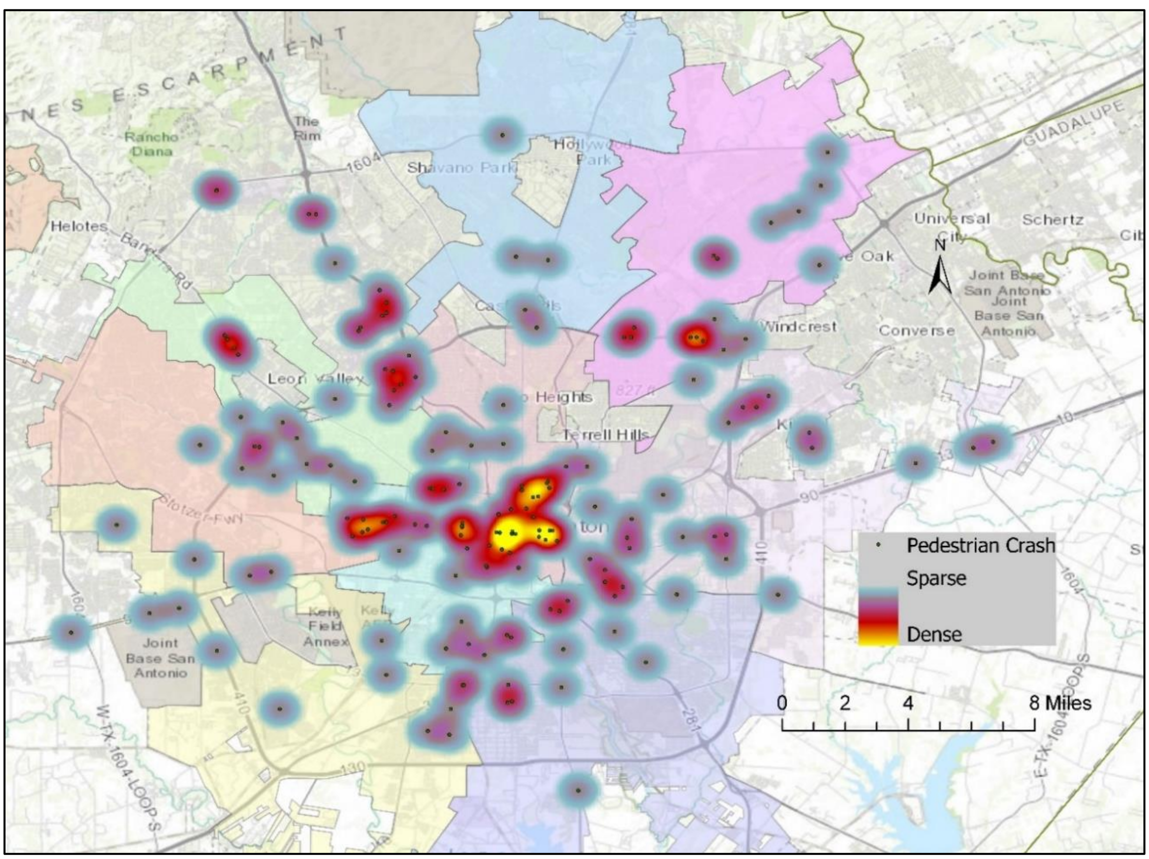

Figure 33. Heat map of pedestrians crashes due to impaired driving•

Lane departure crashes accounted for a total of 38 pedestrian crashes from 2013-2017, a very small percentage of the total pedestrian crashes in San Antonio as shown in Figure 34. These crashes were responsible for 1 fatal pedestrian crash and 6 incapacitating pedestrian crashes.

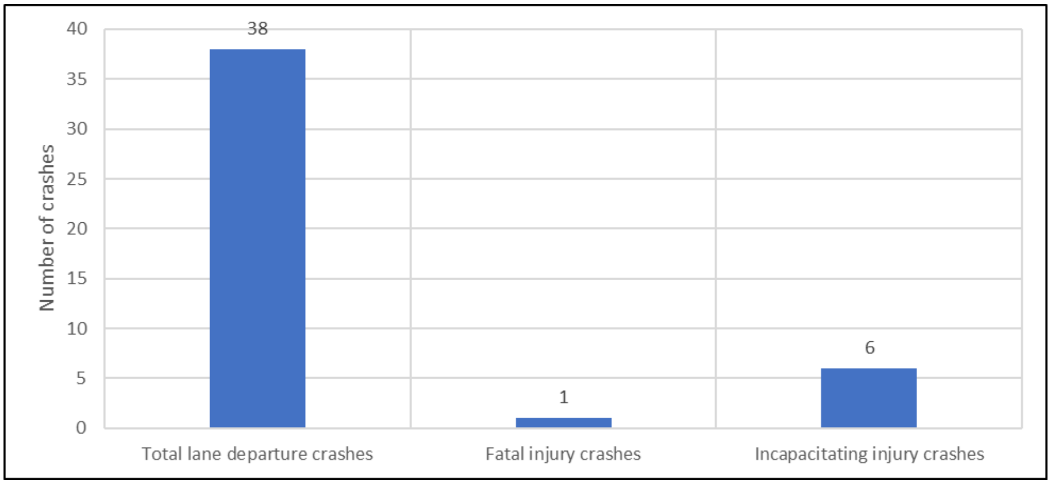

Figure 34. Pedestrian crashes due to lane departure•

The proportion of lane departure related pedestrian crashes is relatively small compared to the proportion of lane departure crashes in total crashes in San Antonio during the study period. Unlike the overall pedestrian crash concentration, lane departure related pedestrian crashes were not concentrated in the city center. However, the North-West part of the city experienced relatively high proportion of lane departure related pedestrian crashes (Figure 35).

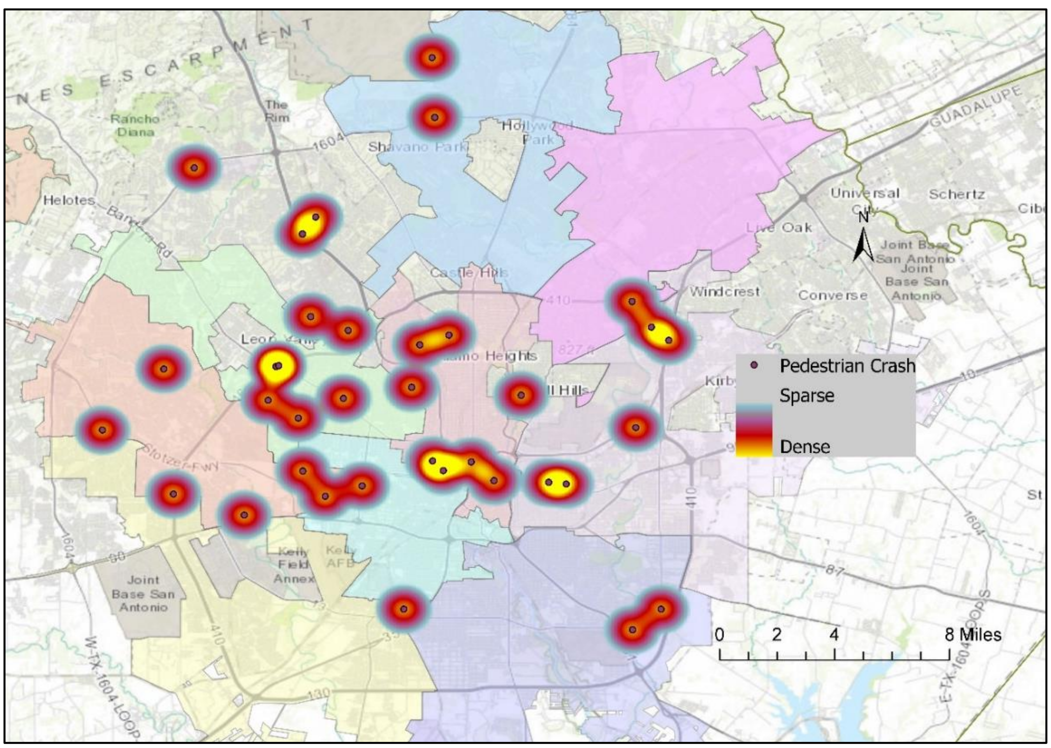

Figure 35. Heat map of pedestrian crashes due to lane departure•

Speeding crashes accounted for a total of 27 pedestrian crashes from 2013-2017, a very small percentage of the total pedestrian crashes in San Antonio as shown in Figure 36. These crashes were responsible for 4 fatal pedestrian crashes and 5 incapacitating pedestrian crashes. When all crashes in San Antonio are considered, 3,193 speeding crashes occurred in San Antonio from 2013-2017, 1.3% of the total crashes. These crashes include 83 fatal crashes (10.8% of all fatal pedestrian crashes) and 137 serious injury crashes (3.4% of all serious injury pedestrian crashes) from 2013 to 2017.

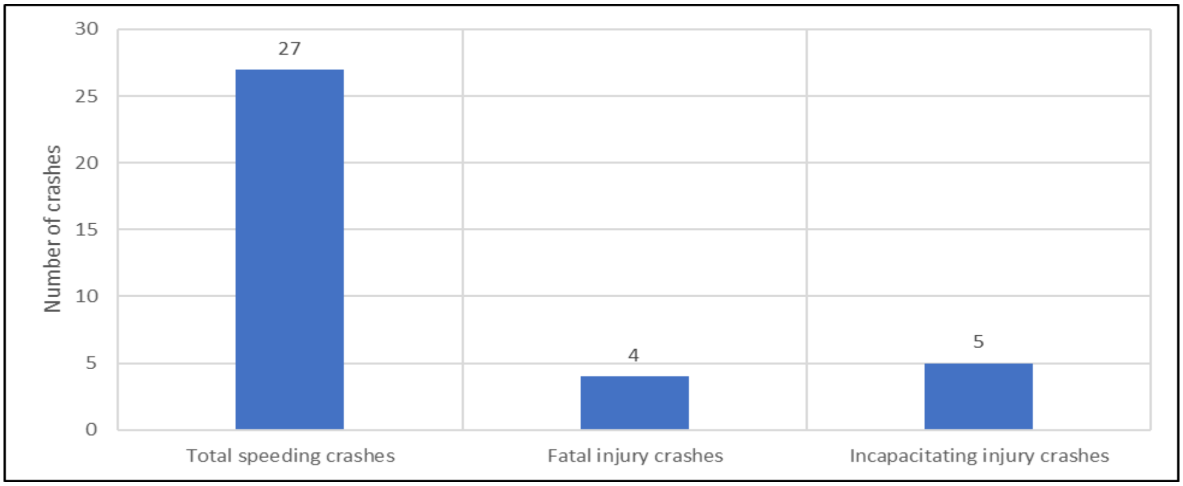

Figure 36. Pedestrian crashes due to speeding•

Speeding related pedestrian crashes were very infrequent and the distribution of these crashes are shown in Figure 37. The spatial distribution of these crashes from the heat map suggests that the crashes were mostly scattered and there were no significant crash clusters.

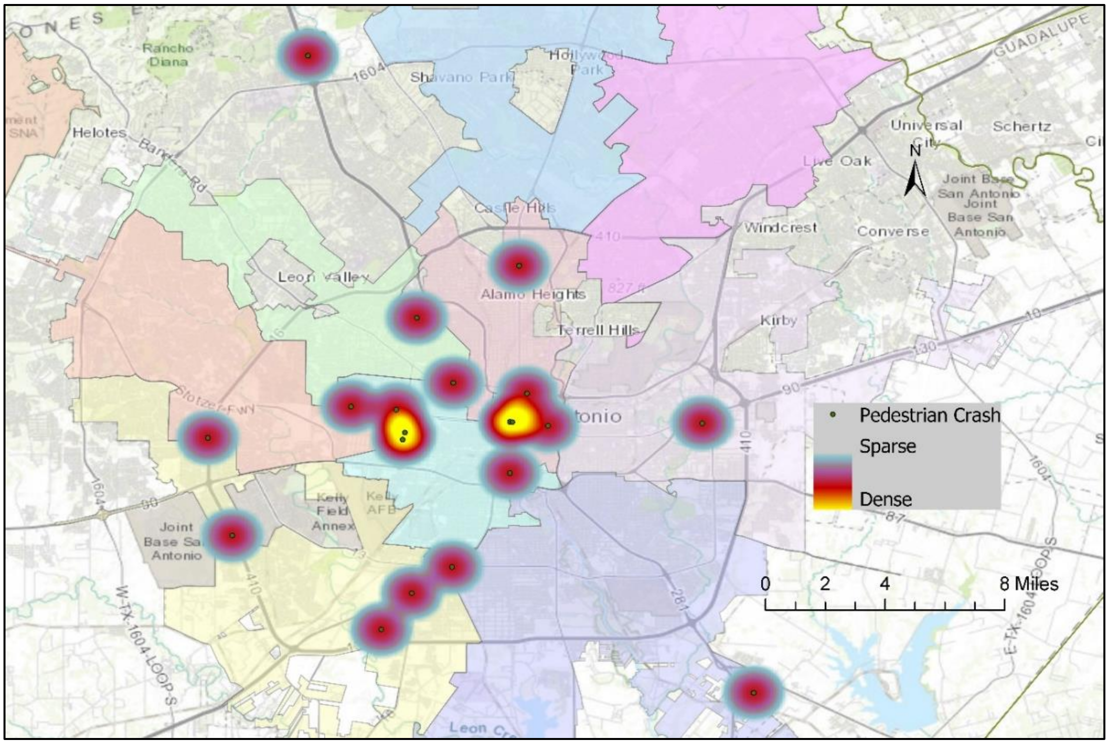

Figure 37. Heat map of pedestrian crashes due to speeding•

5.1.2. Pedestrian-at-Fault Crashes

Pedestrian-at-fault crashes are classified as crashes where pedestrians failed to yield right of way to the vehicles. 1,077 crashes out of the total 4,459 pedestrian crashes were identified as pedestrian-at-fault crashes. Figure 38 expresses the hourly variation of pedestrian-at-fault crashes along primary Y-axis and percentage of pedestrian-at-fault crashes to total pedestrian crashes along secondary Y-axis for 2013-2017. The percentage of pedestrian-at-fault crashes was higher from evening to mid-night (7 p.m. to 12 a.m.) and lower during the day (8 a.m. to 6 p.m.). There was an unusual deviation at 5 a.m. which can be the result of lack of attention of pedestrians at early morning. The frequency of pedestrian-at-fault crashes was high from 7 p.m. to 11 p.m.

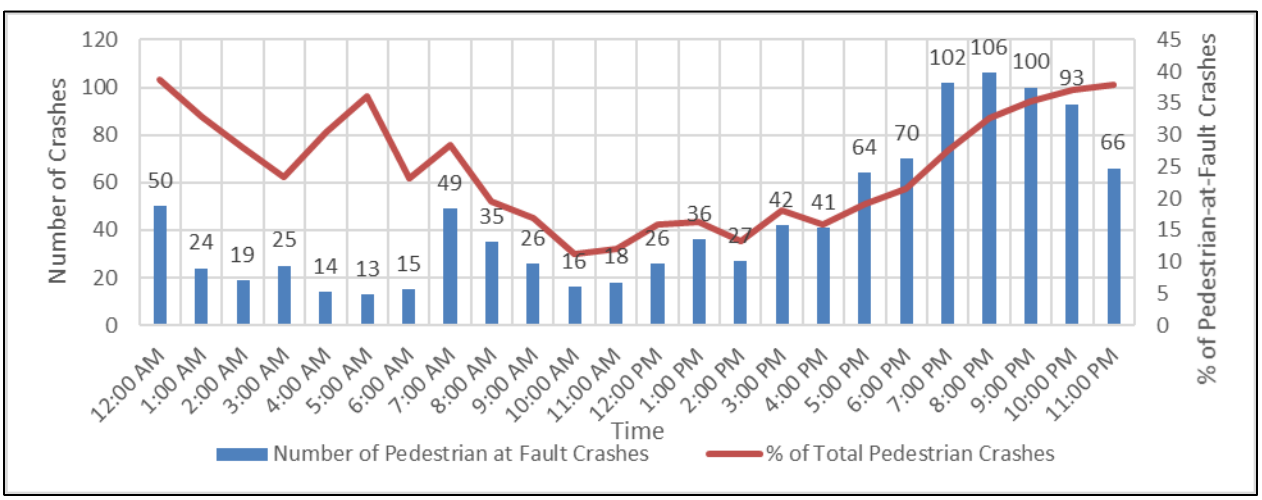

Figure 38. Hourly variation of pedestrian-at-fault crashes and percentage of pedestrian-at-fault crashes to total pedestrian crashes•

As shown in Figure 39, Sunday had considerably lower frequency of pedestrian-at-fault crashes but the highest percentage of pedestrian-at-fault crashes to total pedestrian crashes. Friday had the highest number of pedestrian-at-fault crashes.

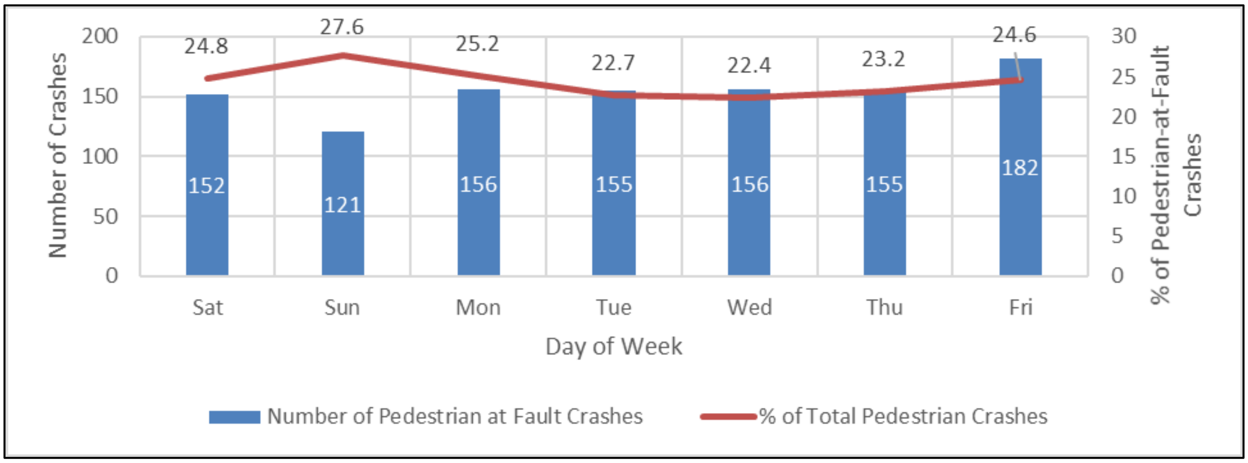

Figure 39. Variation of pedestrian-at-fault crashes by day of week and percentage of pedestrian-at-fault crashes to total pedestrian crashes•

Figure 40 expresses the monthly variation of pedestrian-at-fault crashes along primary Y-axis and percentage of pedestrian-at-fault crashes to total pedestrian crashes along secondary Y-axis for 2013-2017. Crash frequency was lower during summer and higher during fall and early winter. Percentage of pedestrian-at-fault crashes to total pedestrian crashes was comparatively high at the beginning of school year.

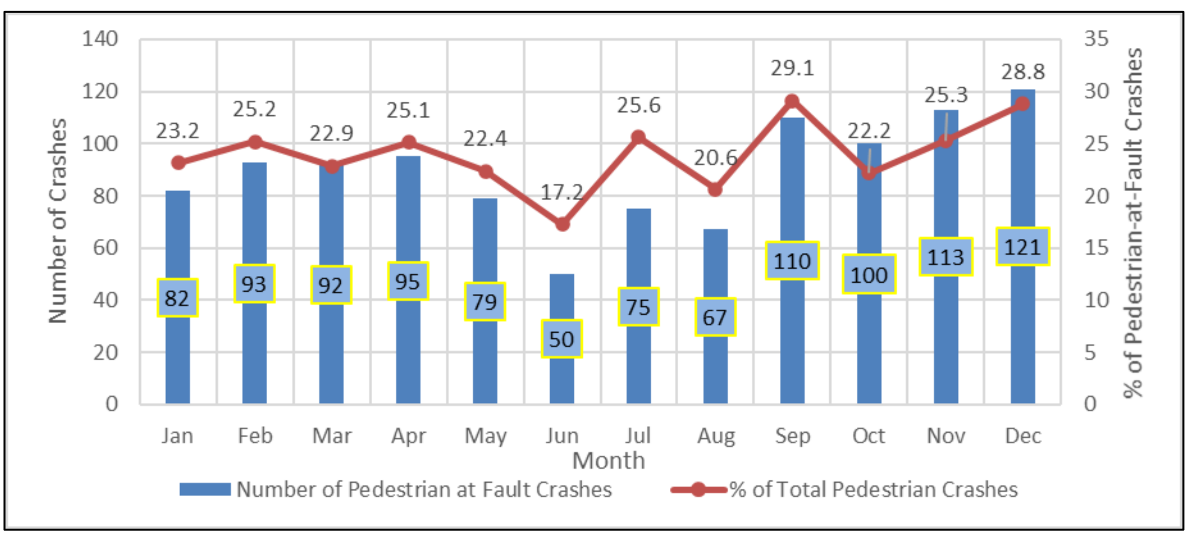

Figure 40. Monthly variation of pedestrian-at-fault crashes and percentage of pedestrian-at-fault crashes to total pedestrian crashes•

A total of 1,121 pedestrians were involved in these 1,077 crashes. Age of 24 pedestrians were unavailable. Among the 1,097 pedestrians with available age, 748 were male and 348 were female.

Gender of 1 pedestrian was unavailable. Crash frequency with respect to age and gender is shown in Figure 41 and frequency was higher for pedestrians of 15-24 age group and 50-59 age group. Male pedestrians were more common victims, especially for the 65-69 age group.

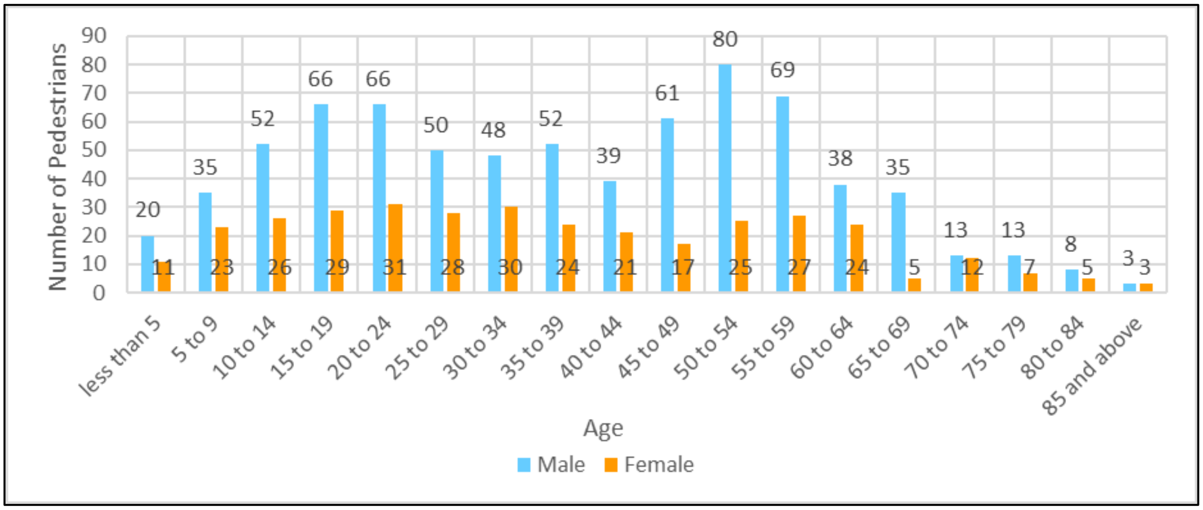

Figure 41. Age and gender distribution of all pedestrians involved in pedestrians-at-fault crashes•

5.2. Bicyclist Safety

Bicyclist crashes accounted for a total of 1,561 crashes from 2013-2017, or 0.63% of the total crashes in San Antonio. In Figure 42, the primary and the secondary Y-axes represent the annual bicyclist crashes and bicyclist crashes as a percentage of total annual crashes, respectively. Bicyclist crashes increased from 2013 to 2014, and then varied little for next 4 years. The percentage of bicyclist crashes in total crashes, however, did not show any specific trend from 2013-2017.

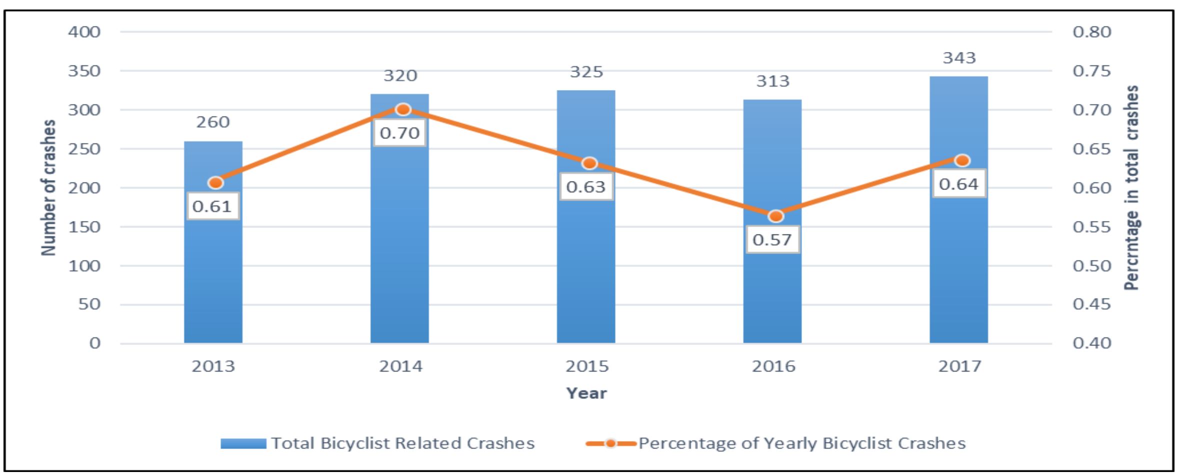

Figure 42. Annual variation of bicyclist of frequencies and percentages of bicyclist crashes•

Bicyclist crashes include 18 fatal crashes (2.3% of all fatal crashes) and 117 serious injury crashes (2.9% of serious injury crashes) from 2013–2017. Fatal and serious injury crash counts by year are shown in Figure 43.

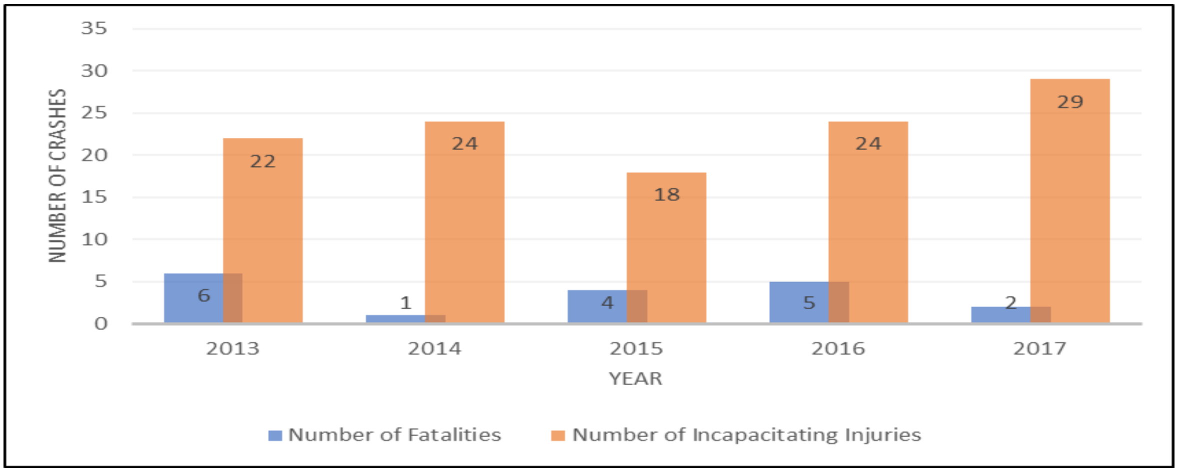

Figure 43. Fatal and serious injury bicyclist crashes•

In Figure 44, fatal and serious injury bicyclist crashes are shown as a percentage of total bicyclist crashes along the secondary Y-axis. The percentage decreased from 2013 to 2015, and then increased.

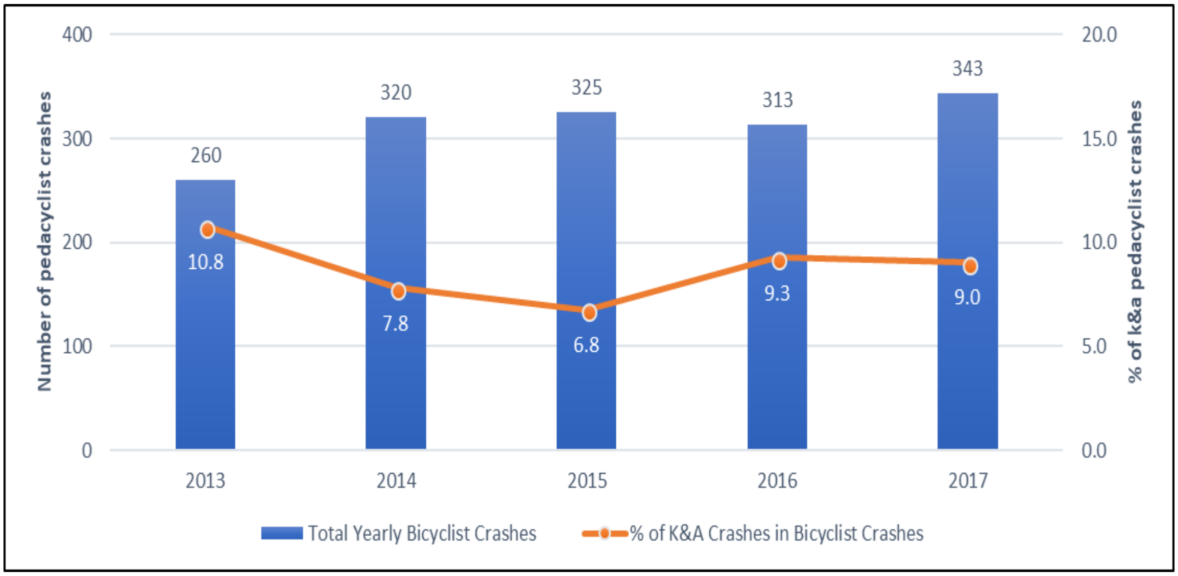

Figure 44. Annual variation of bicyclist crashes and percentage of fatal and serious injury crashes•

A total of 1,575 bicyclists were associated with 1,561 crashes as shown in Figure 45. The ages of 70 bicyclists were unavailable.15-24 age group was associated with highest number of crashes. Older age groups had very few female bicyclists.

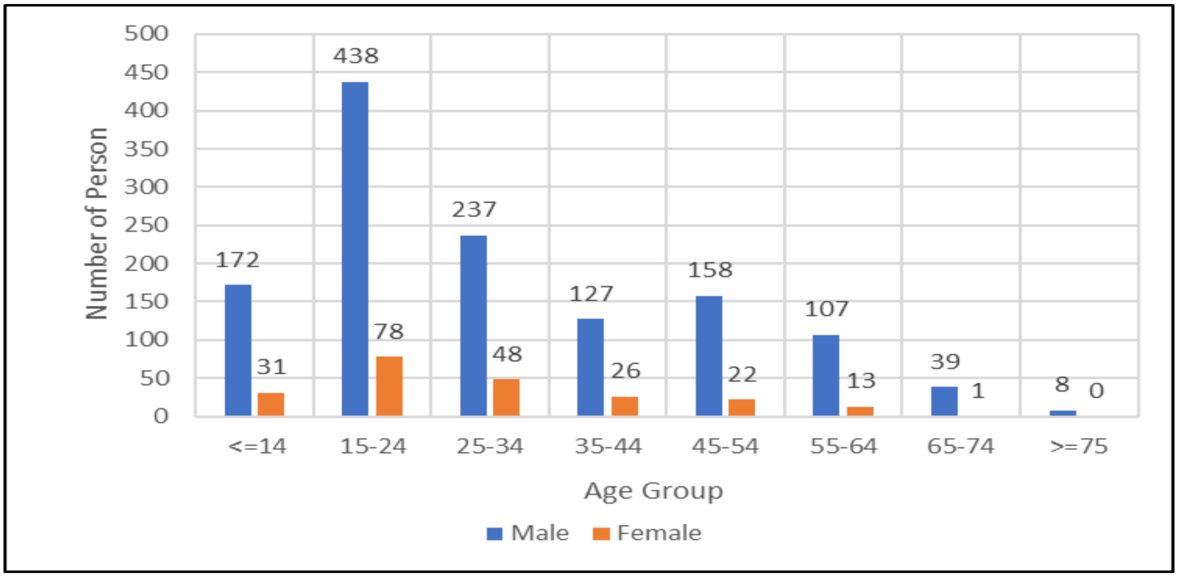

Figure 45. Age and gender distribution of bicyclists involved in crashes•

In Figure 46**,** the variation of bicyclist crash frequency is shown by the day of the week. Tuesday and Thursday experienced relatively high bicyclist crash frequency. Weekend period (Saturday and Sunday) had relatively low bicyclist crash frequency. However, the proportion of fatal and serious bicyclist injury crashes was substantially higher during the weekend period (*66*).

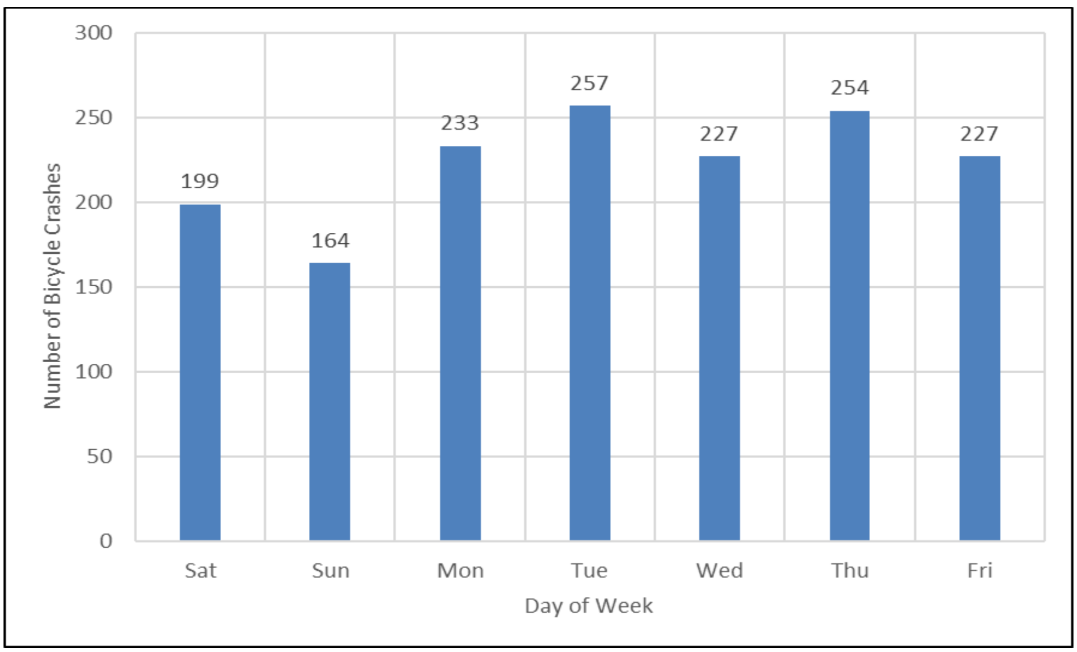

Figure 46. Bicyclist crash frequency by day of the week•

The distribution of bicyclist crash frequency by time of the day is shown in Figure 47. Bicyclist crash frequency gradually increased from the morning, reached the peak at 6:00 p.m., and started to decrease afterwards. Relatively high bicyclist crash frequency at 8:00 a.m. might be related to the increased cycling activity during 7:00-8:00 a.m. period.

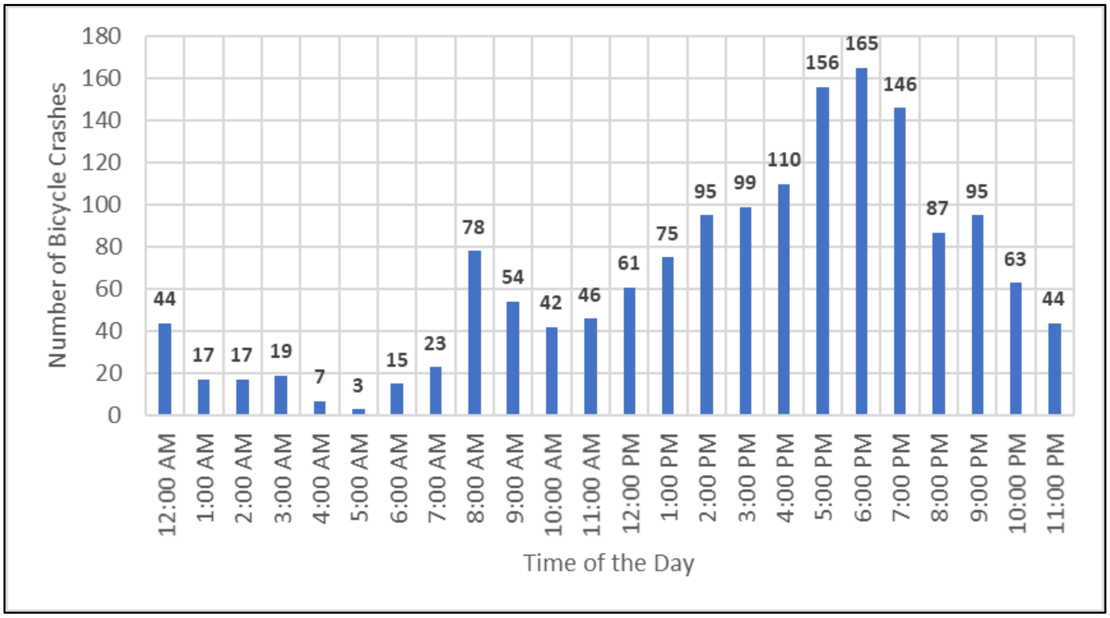

Figure 47. Bicyclist crash frequency by time of the day•

Bicyclist crash frequency by month of crash occurrence is shown in Figure 48. Winter months have relatively lower pedestrian crash frequency. Relatively lesser cycling activities during the winter months might be the reason. Further studies found bicyclist crashes occurring in winter season to be less severe compared to summer season, probably due to clothing practice among other possible reasons (*66*).

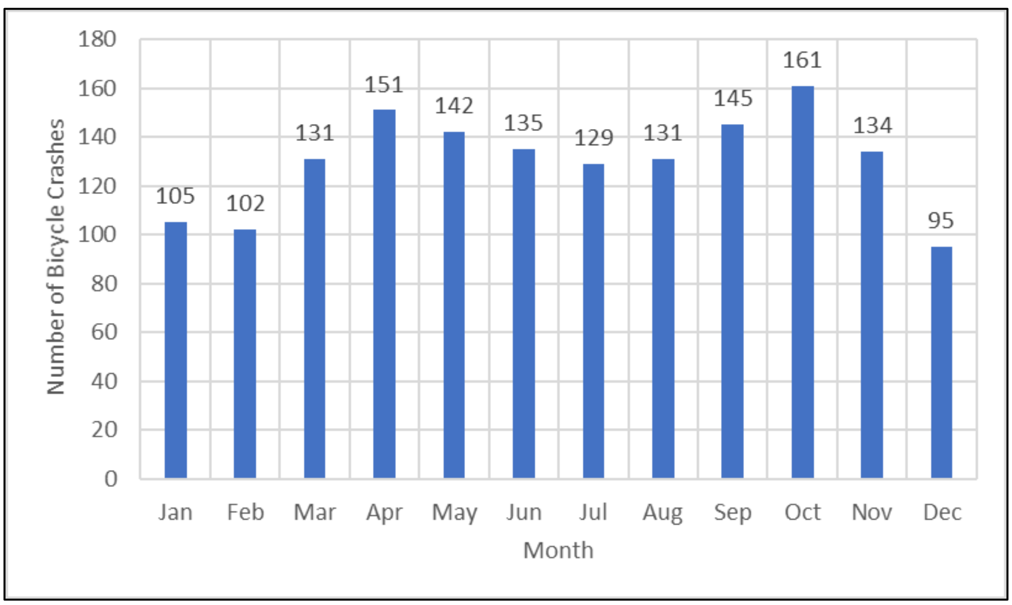

Figure 48. Bicyclist crash frequency by month•

The proportion of bicyclist crash by weather condition is shown in Figure 49**.** Almost 80% of all bicyclist crashes occurred in clear weather condition. Compared to pedestrian crashes, bicyclist crash proportion is higher in clear weather and lower in rainy weather.

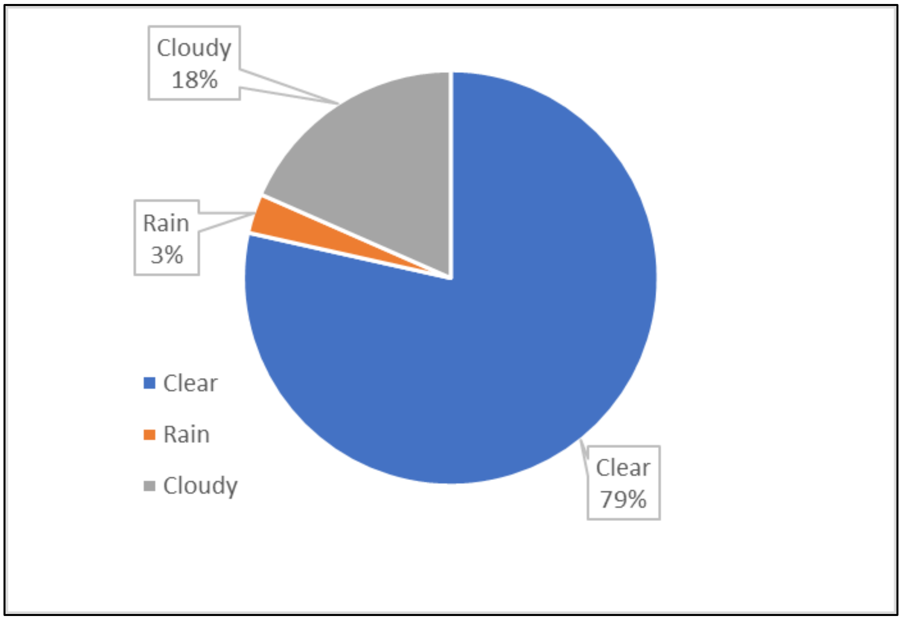

Figure 49. Proportion of bicyclist crash by weather condition•

Bicycle fatal and incapacitating injury crash counts under different weather conditions are shown in Figure 50. No severe bicyclist crash occurred in rainy weather condition.

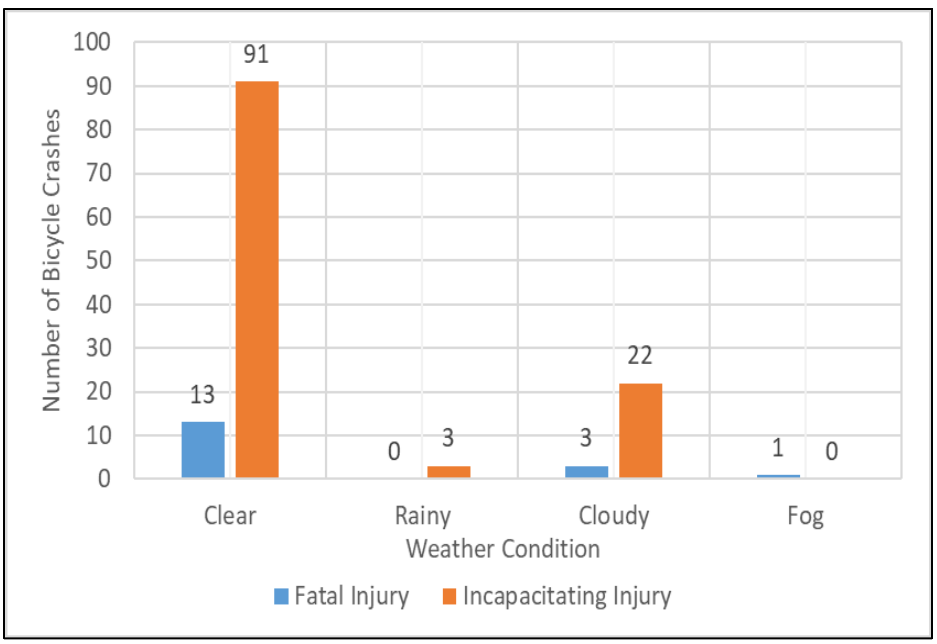

Figure 50. Fatal and incapacitating bicyclist crash frequency by weather condition•

The proportion of bicyclist crashes under different lighting conditions are shown in Figure 51**.** Dark lighting conditions were associated with 27% of all bicyclist crashes. This proportion is relatively low compared to pedestrian crashes where about 41% of all pedestrian crashes were associated with dark lighting conditions.

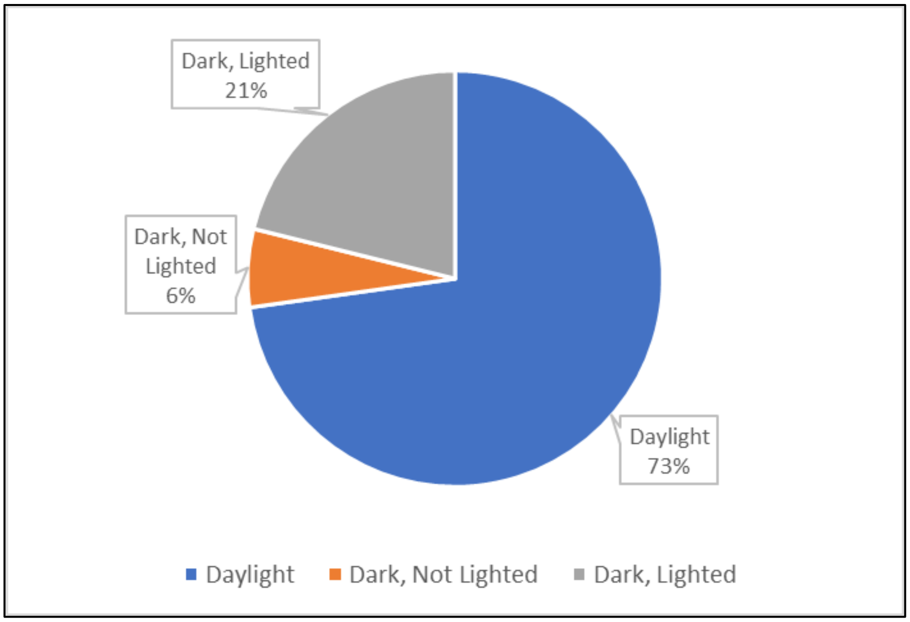

Figure 51. Proportion of bicyclist crashes by lighting condition•

Fatal and incapacitating injury bicyclist crash counts by different lighting conditions are shown in Figure 52. Similar to pedestrian crashes, dark lighting condition was associated with relatively high proportion of bicyclist crashes (especially fatal crashes). Severe bicyclist crashes occurring under "Dark, not lighted" condition were highly likely to be resulted in bicyclist fatalities.

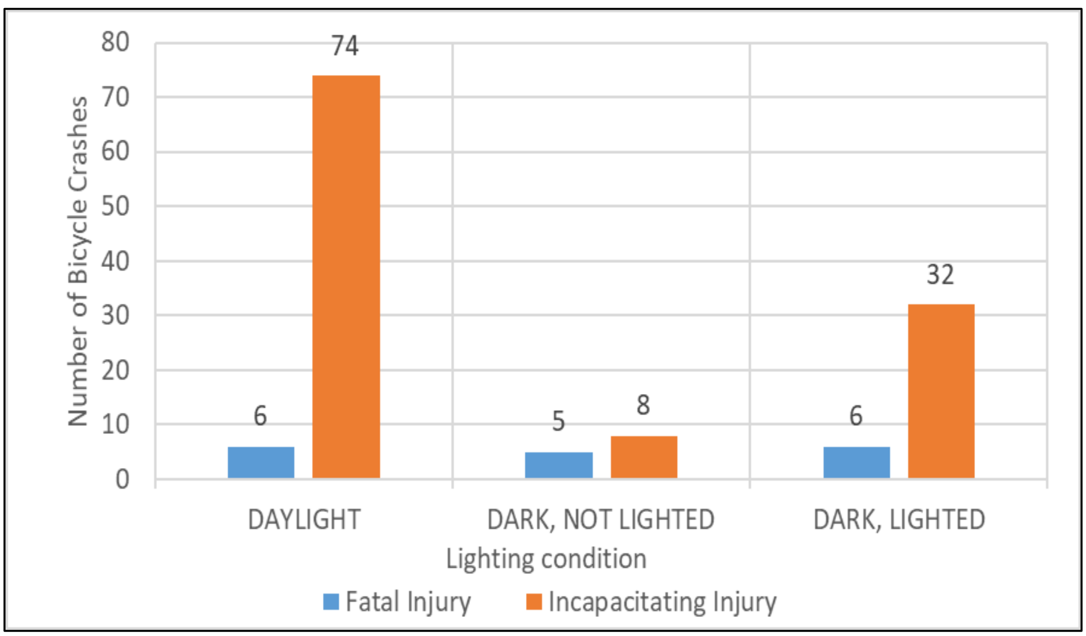

Figure 52. Fatal and incapacitating bicyclist crash frequency by lighting condition•

The proportion of bicyclist crashes on different types of roads are shown in Figure 53. Almost two-third of all bicyclist crashes occurred on city streets. Interstate roads, FM roads, and US & State highways consisted about 20% of all bicyclist crashes altogether.

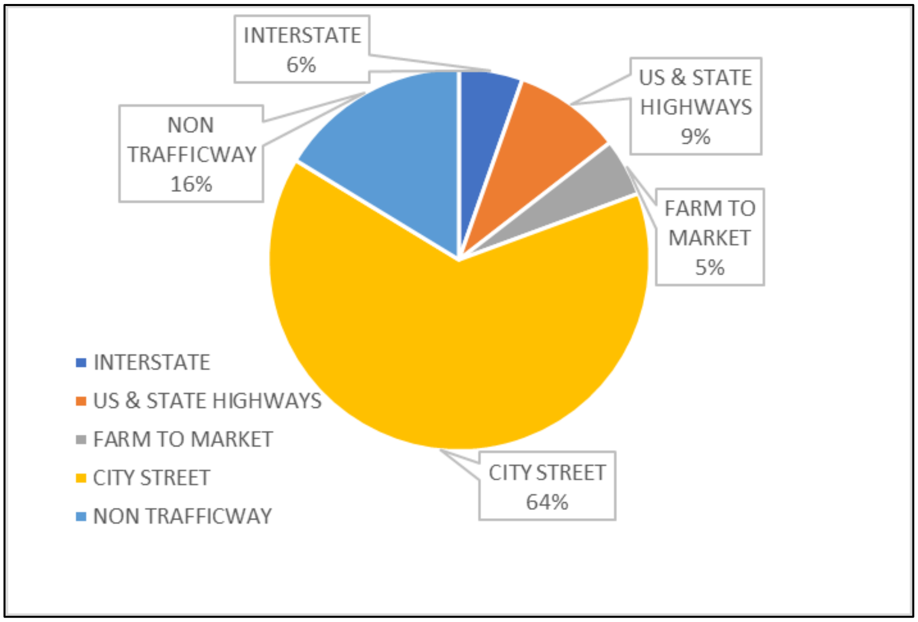

Figure 53. Proportion of bicyclist crashes by road class•

In Figure 54, the frequencies of fatal and incapacitating bicycle injury crashes are shown. Although interstate roads have higher speed limit and are considered to be riskier for vulnerable road users like bicyclists, no fatal crashes occurred on interstate roads. This observation is unlike pedestrian crashes where proportion of fatal pedestrian crashes were substantially high on interstate roads.

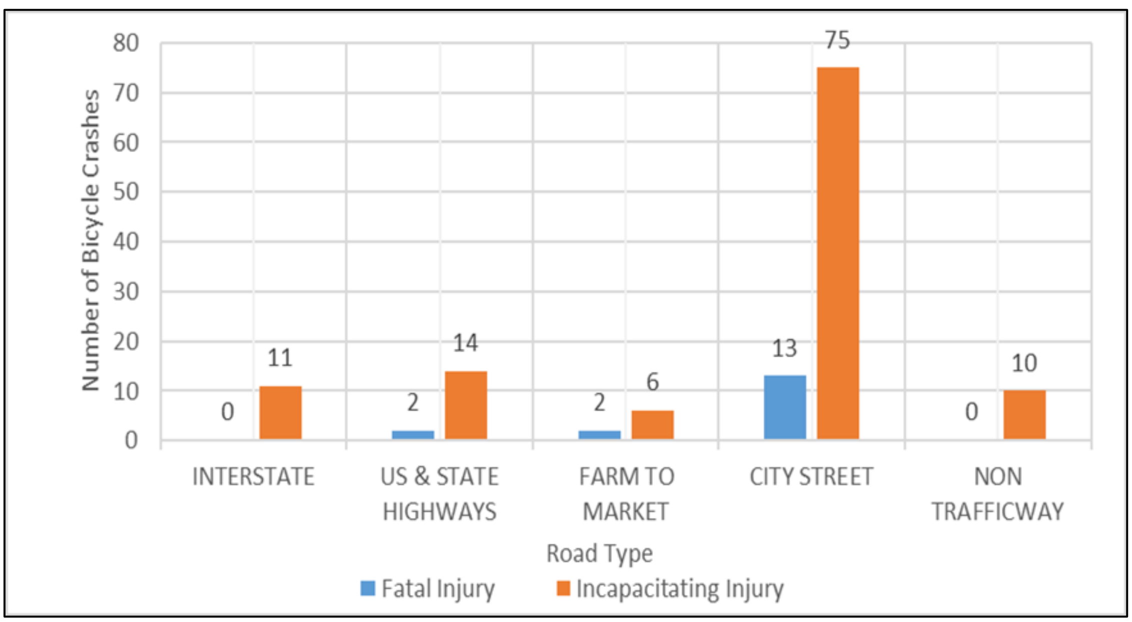

Figure 54. Fatal and incapacitating bicyclist crash frequency by road class•

As shown in Figure 55, more than half of all the bicyclists involved in bicyclist crashes in San Antonio are Hispanic. Asian bicyclists were involved in only 8 bicyclist crashes. The proportions of bicyclists involved in crashes for different ethnicity groups are consistent with their proportion in the overall population in San Antonio.

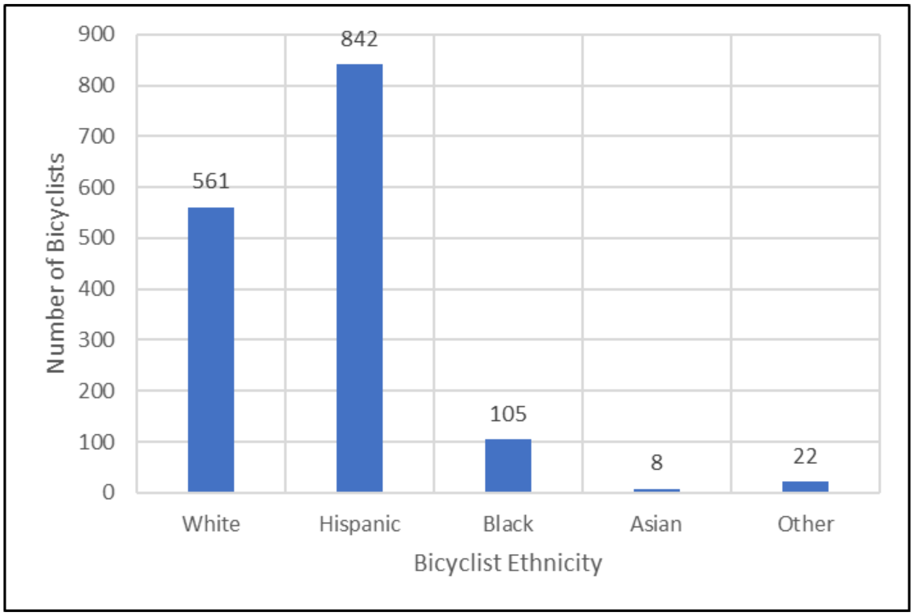

Figure 55. Bicyclist crash frequency by bicyclist ethnicity•

In Figure 56, the numbers of fatal and incapacitating crash involved bicyclists are shown. Although Hispanic bicyclists have greater proportion in overall crash involved bicyclists, White and Black bicyclists were more likely to be involved in severe bicyclist crashes.

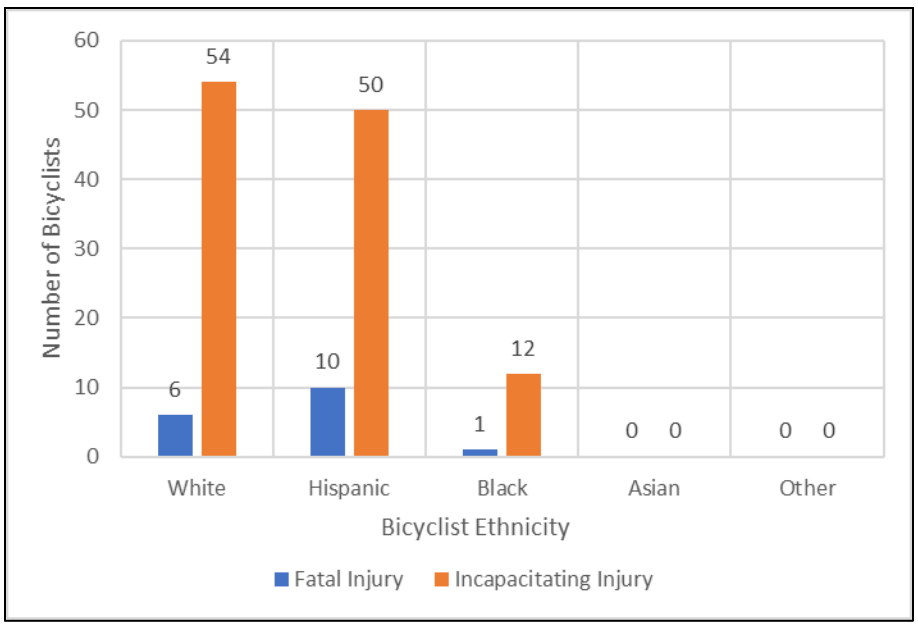

Figure 56. Fatal and incapacitating bicyclist injury count by bicyclist ethnicity•

The proportion of male bicyclists to female bicyclists in San Antonio is shown in Figure 57. Although the proportion of male and female is almost identical in San Antonio, their involvement in cycling is not. That might be reflected in the crash involved bicyclists as almost 86% of all crash involved bicyclists were male.

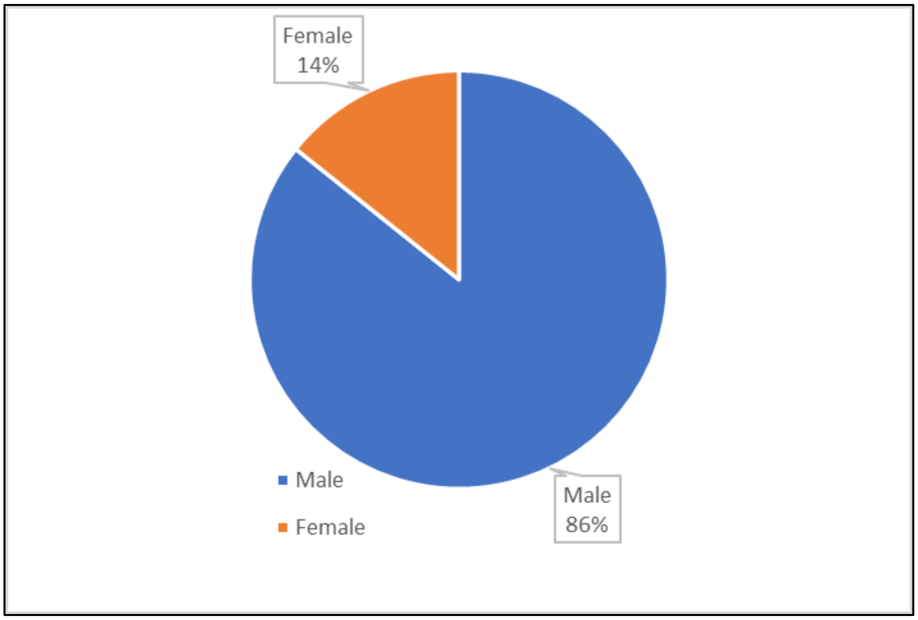

Figure 57. Proportion of bicyclist crash by bicyclist gender•

The number of fatal and incapacitating injury crashes for the crash involved bicyclists by gender in shown in Figure 58. Further analysis suggests that male bicyclists are slightly more likely to be involved in severe crashes compared to their counterparts.

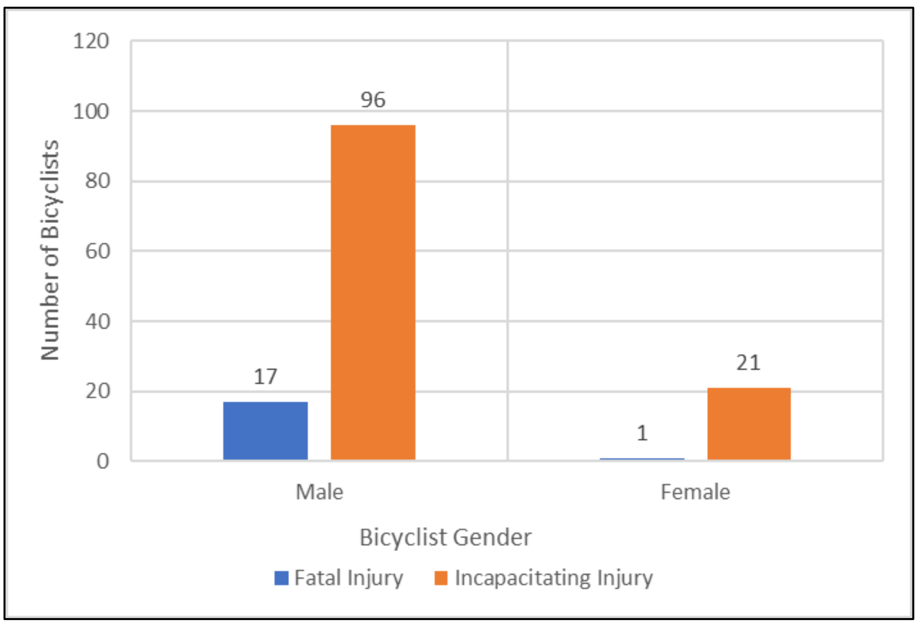

Figure 58. Fatal and incapacitating bicyclist injury count by bicyclist gender•

The proportions shown in Figure 59 suggest that three out of four crash involved bicyclists did not wear helmet. Only 16% of all crash involved bicyclists were wearing helmet. San Antonio do not have mandatory helmet law for bicyclists, which might be one of the reasons behind such helmet wearing practice.

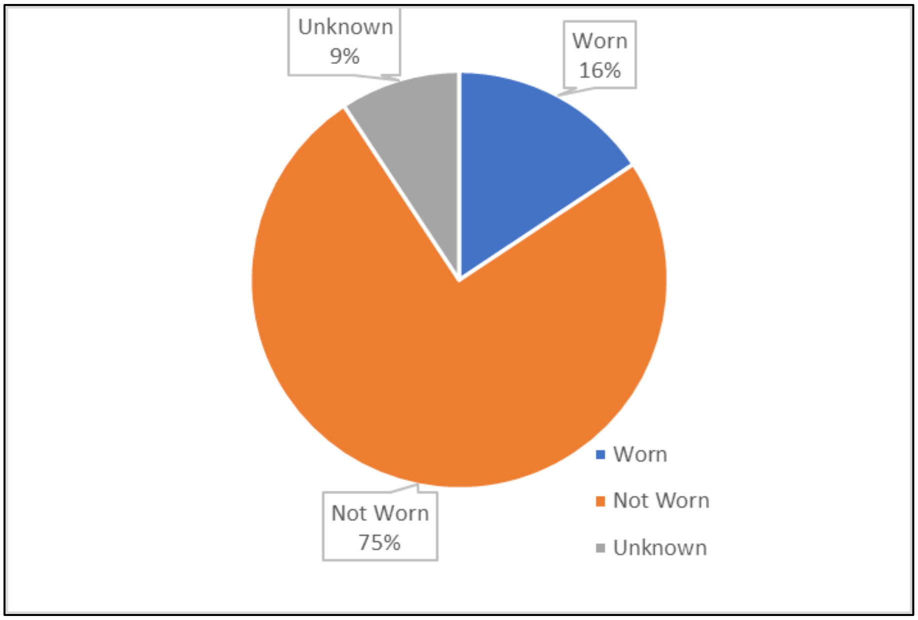

Figure 59. Proportion of bicyclist crashes by bicyclist helmet status•

In Figure 60, the number of fatal and incapacitating injury crashes of crash involved bicyclists is shown. More detailed analysis indicates that use of helmet slightly reduced fatal crash risk (not significant) and significantly reduced incapacitating injury risk.

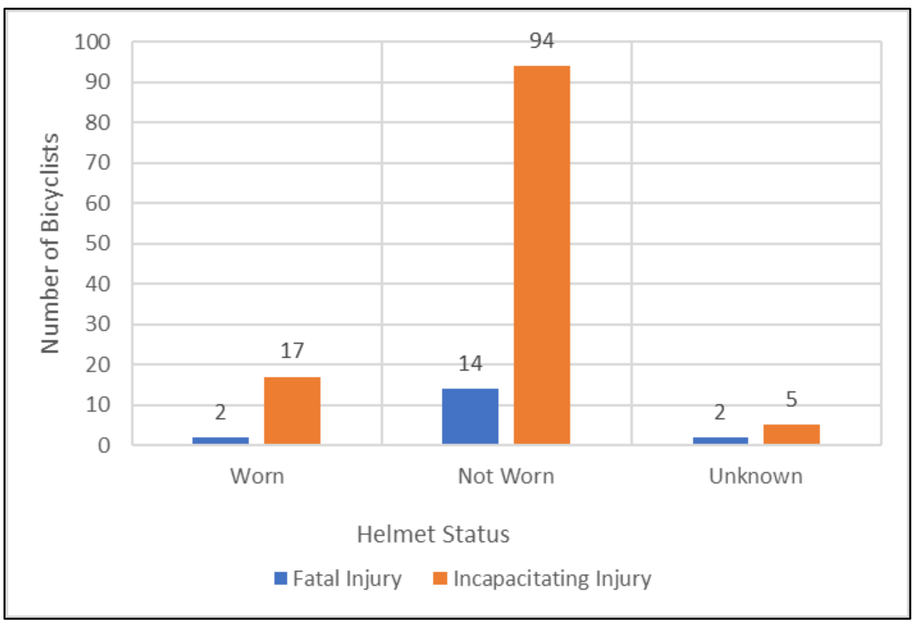

Figure 60. Fatal and incapacitating bicyclist injury count by bicyclist helmet status•

The spatial distribution of all bicyclist crashes in San Antonio is shown in Figure 61. As expected, the highest bicyclist crash density was observed in the downtown area due to higher cycling activities in this area. One of the most critical locations in the City is the intersection at E Houston St and N St Mary's St in terms of bicyclist crash frequency, experiencing 10 bicyclist crashes during the study period. Another location of high crash frequency was the intersection at E Market St and N Alamo St.

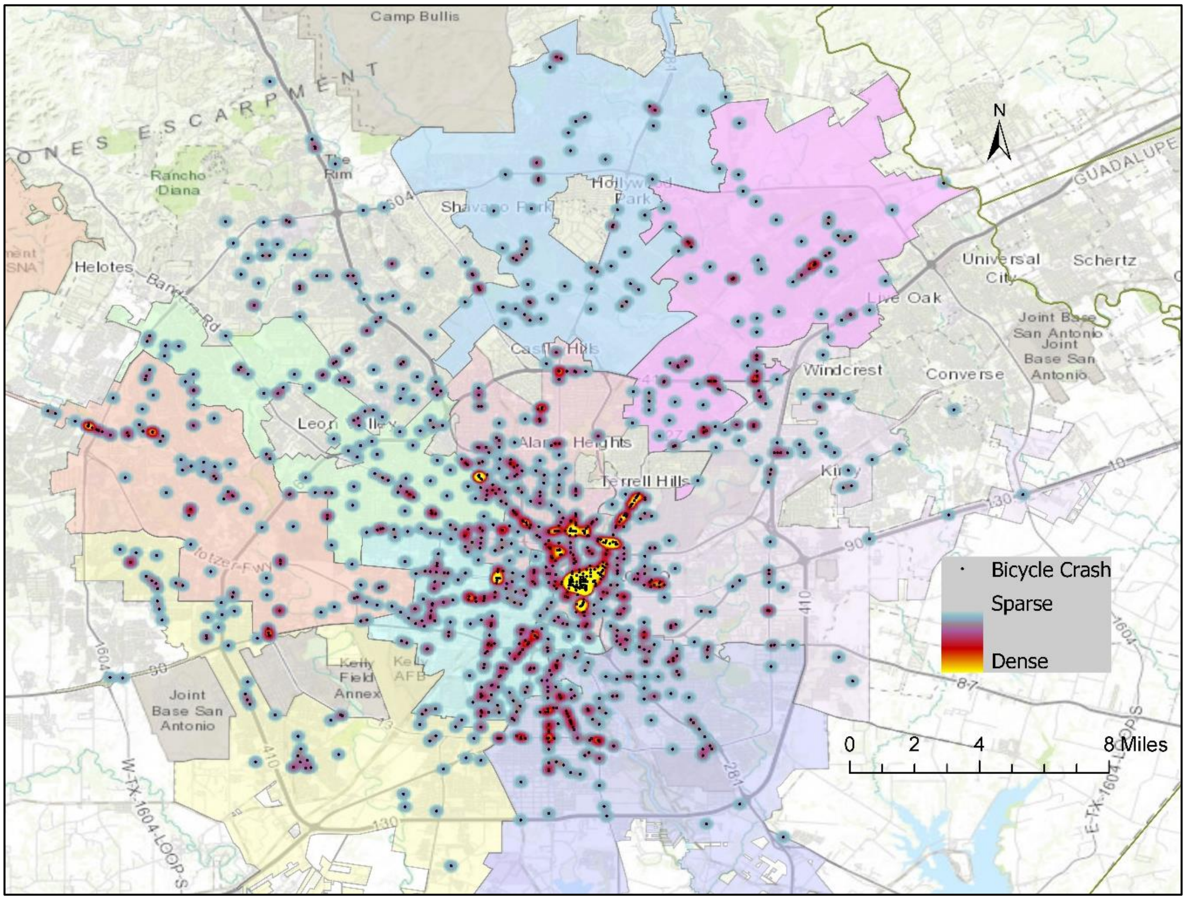

Figure 61. Heat map of all bicyclist crashes•

6. CONCLUSIONS

The practice of walking and cycling is eco-friendly, healthful, and is becoming popular all over the world. However, pedestrians and bicyclists are the most vulnerable road users in terms of crash severity due to their slow speed of movement and unprotected nature. To better understand the characteristics of pedestrian and bicyclist crashes in San Antonio, TX, this study analysed detailed crash data over a five-year period (2013-2017).

Pedestrian and bicyclist crash frequencies showed a slightly increasing trend over the study period. However, this increase is proportional to the overall increase in crash numbers in San Antonio and the proportion of pedestrian and bicyclist crashes in total crashes did not increase during the study period. Although pedestrian and bicyclist crash frequencies were relatively low during the weekend period, they were more likely to result in severe injuries. This calls for an increase in allocation of resources during the weekend period. Pedestrians were more likely to be involved in a crash during the winter season while bicyclists were more likely to be involved in a crash during the summer months. Pedestrian and bicyclist crashes gradually increase throughout the day reaching their peaks in the evening, probably due to higher traffic volumes and reduced visibility in the evening. Pedestrian crashes experience an unusual jump during 2:01-3:00 a.m. hour (which seems to be related to the closure of drinking facilities at 2 a.m.). The use of ride sharing services should be encouraged after drinking alcohol and police patrolling should be increased during this period in addition to ensuring strict punishment to drunk drivers. The fatal and incapacitating injury risk of a pedestrian crashes increased when the pedestrian was at fault in a crash. The proportion of faulty pedestrians in pedestrian crashes was relatively higher during 8:01 p.m.–12:00 a.m. period. Road segments with poor lighting facility and frequent pedestrian crash incidents should be identified and sufficient lighting on those road segments should be ensured. Bicyclist crashes involving non-Hispanic bicyclists resulted in comparatively higher proportion of severe crashes. The use of helmet was scarce in crash involved bicyclists. Although some cities of Texas have implemented an ordinance of mandatory helmet use for bicyclists (*69*) - San Antonio is not one of them. The use of helmet was associated with reduced bicycle injury and introduction of mandatory helmet ordinance is recommended.

Pedestrian and bicyclist crash incidents were more frequent in the downtown area in city center (especially at intersections), which is consistent with the relatively higher pedestrian and bicyclist traffic in that area. However, further study suggests that the pedestrian and bicyclist crashes in the city center are statistically less severe compared to the crashes occurring outside the city center. This might be the result of relatively low vehicle speed and more pedestrian and bicycle facilities at the city center. More pedestrian and bicycle facilities should be provided in the downtown area to reduce pedestrian and bicyclist crash frequency.

6.1. Recommendations

Following are some recommendations to further enhance the safety of pedestrians and bicyclists:

Protected Left-Turn Phase

Left turning movements of motor vehicles are responsible for a high percentage of pedestrian crash. Introducing a protected warranted left-turn phase at pedestrian injury hotspots are recommended.

Right Turn on Red Restrictions

Failure to completely stop and yield to pedestrians or bicyclists prior to turning right on red, especially on roads with wide turning radii, is often observed in motorists. Prohibiting right turn on red (with clear visual instructions) at intersections with high pedestrian/bicycle volumes is recommended.

Illuminated Crossing Marking and High Visibility Crosswalk

Implementation of illuminated crossing markings at locations with higher pedestrian and bicyclist crash frequency during nighttime is recommended. Perpendicular stripes (Zebra/Ladder) provide better viewing angles to drivers and should be adopted for hotspot and crowded crossings.

Rectangular Rapid Flash Beacon

Installation of pedestrian activated (through push button / passive detection) rectangular rapid flash beacons on multi-lane roads or on roads with higher proportion of pedestrians and bicyclists.

Back-in Angle Parking

Back-in angle parking provides better vision of surrounding while exiting the parking space and can help to reduce pedestrian and bicyclist crashes at parking locations.

Crossings Near Transit Stop Location and Pedestrian Crossing Warning Signs

Sufficient pedestrian crossings should be ensured near transit stops with proper lighting and illumination facility. Introducing warning signs with proper visual instructions sufficiently in advance of crossing locations will increase driver awareness.

Crossing Islands, Medians, and Pedestrian Overpass

Crossing islands should be introduced on multi-lane roads with comparatively greater width and busy traffic. Pedestrian overpass could be introduced if warranted at intersections with very high ADT and crash rate. Introducing continuous or intermittent medians on Severe Pedestrian Injury Area (SPIA) corridors might be helpful.

Push Button with Voice and Visual

Should be installed at locations with relatively low volume of pedestrians and bicyclists to aid motor vehicle flow. Push buttons should be equipped with voice instructions and visual indicators.

Mid-block Crosswalks and Signals

Mid-block crosswalks should be installed at mid-block locations experiencing high volume of pedestrians. It should be accompanied with mid-block signals and push button.

Sidewalk Width and Position

Separation of sidewalk from roadway and use of optimal sidewalk width have been found effective in reducing pedestrian and bicyclist crash frequency and severity and are recommended for new sidewalks.

Curb Ramp and Curb Extension

Two curb ramp per corner should be installed in locations with high proportion of older pedestrians, people with disabilities, and bicycle activities. Curb extensions should be installed on downtown streets and residential streets where on-street parking is permitted.

Leading Pedestrian Interval

Green light may be shown to pedestrians 4 to 7 seconds prior to motor vehicles. Pedestrians may start crossing roadway before motor vehicles initiate turning movements, making pedestrians more visible to motorists. Signal controller can be programmed to operate only during peak pedestrian activity hours.

High Speed Limit and Crash Risk

When speed limit is over 40 mph, probability of severe injury of a pedestrian/bicyclist is very high regardless of adopted protective measures. Drivers get lesser reaction time and cone of vision on high-speed roads. High speed roads with high crash frequency should be identified, mid-block crossings on these roads should be discontinued, and medians should be implemented on high-speed roads with pedestrian crossings.

Advanced Stop Line

Line of sight of the driver on the left lane does not get blocked. Vehicles missing the first stop line gets more space to stop vehicle. Bicyclists can be allowed to move beyond first stop line, in the space between stop line and pedestrian crossing, making them more visible to other vehicles.

Raised Crosswalk and Fixed Objects

Raised Crosswalk and Fixed Objects can reduce pedestrian crashes by 45%. They should be installed near school, campus, airports, shopping centers, and transit centers. Placement of bollards, planters, & other fixed objects at the back of curbs on roadways with high pedestrian volume should prevent vehicles from driving onto sidewalk.

Limiting Parking near Crosswalk

Parked vehicles near pedestrian crossings decrease the angle of sight of drivers. Pedestrians also fail to detect the vehicles coming at them due to limited visibility. On high-speed roads, this situation can often cause KA pedestrian crash. On-street parking should be at least 20 feet in advance of crosswalk.

Public Awareness Campaigns

Effectiveness of road safety campaigns vary depending on the targeted type of behavior. Campaigns are more effective when focused on specific groups. Inclusion of community role models in road safety campaigns can help to reach greater population and make deeper impression.

REFERENCES

1. Miller, T.R., Zaloshnja, E., Lawrence, B.A., Crandall J., Ivarsson, J., and Finkelstein A.E. 2004. "Pedestrian and Pedalcyclist Injury Costs in the United States by Age and Injury Severity." Annual Proceedings/Association for the Advancement of Automotive Medicine 48: 265–84.

2. Blincoe, L.J., Seay, A.G., Zaloshnja, E., Miller, T.R., Romano, E.O., Luchter, S., and Spicer, R.S. 2002. The Economic Impact of Motor Vehicle Crashes, 2000, National Highway Traffic Safety Administration.

3. Bureau, US Census. "Fastest-Growing Cities Primarily in the South and West." The United States Census Bureau. Accessed January 27, 2020. https://www.census.gov/newsroom/press-releases/2019/subcounty-population-estimates.html.

4. U.S. Census Bureau QuickFacts: San Antonio City, Texas. Accessed March 1, 2020. https://www.census.gov/quickfacts/fact/table/sanantoniocitytexas/PST045218#PST045218.

5. Royall, Emily. 2018. "Census Data: San Antonio Leads Nation in 2017 Population Growth." Rivard Report. May 24, 2018. https://therivardreport.com/census-data-san-antonio-leads-nation-in-2017-population-growth.

6. McLeod, Ken. 2015. "Where We Ride 2014: Analysis of Bike Commuting." Text. League of American Bicyclists. October 1, 2015. https://www.bikeleague.org/content/where-we-ride-2014- analysis-bike-commuting.

7. City of San Antonio, Office of Sustainability, "2013-2014 Bicycle Counting Report."

8. Walk Score. "List of Cities in Texas on Walk Score." Accessed March 3, 2020. https://www.walkscore.com/TX/.

9. Smart Growth America. "National Complete Streets Coalition." Accessed March 3, 2020. https://smartgrowthamerica.org/program/national-complete-streets-coalition.

10. National Highway Traffic Safety Administration, 2000. Traffic Safety Facts. FARS, available on Internet. http://www.nhtsa.dot.gov/people/ncsa/fars.html.

11. European Transport Safety Council, 1999. Safety of Pedestrians and Cyclists in Urban Areas. Brussels, Belgium.

12. Beck, L.F., Dellinger, A.M., and O'Neil, M.E. 2007. "Motor Vehicle Crash Injury Rates by Mode of Travel, United States: Using Exposure-Based Methods to Quantify Differences." American Journal of Epidemiology 166 (2): 212–18. https://doi.org/10.1093/aje/kwm064.

13. Friede A.M., Azzara C.V., and Gallagher S.S. The epidemiology of injuries to bicycle riders. Pediatr Clin North Am 1985; 32:141e51.

14. Mehan T.J., Gardner R., and Smith G.A. Bicycle-related injuries among children and adolescents in the United States. Clin Pediatr (Phila) 2009; 48:166e73.

15. Schepers P., Agerholm N., Amoros E., Benington R., Bjørnskau T., and Dhondt S. An international review of the frequency of single-bicycle crashes (SBCs) and their relation to bicycle modal share. Inj Prev 2015; 21(e1): e138–43.

16. Stimpson, J.P., Zhu, H., and Wilson, F.A. 2016. "Trends in Bicycle Crashes in California." American Journal of Emergency Medicine 34 (7): 1318–19. https://doi.org/10.1016/j.ajem.2016.04.053.

17. National Highway Traffic Safety Administration, 2018. Traffic Safety Facts 2016: Summary of Motor Vehicle Crashes (DOT HS 812 580), Washington, DC.

18. Wheeler-Martin, K.C., Curry, A.E., Metzger, K.B., and DiMaggio, C.J. 2019. "Trends in School-Age Pedestrian and Pedalcyclist Crashes in the USA: 26 States, 2000–2014." Injury Prevention, September. https://doi.org/10.1136/injuryprev-2019-043239.

19. Fergus, K.B., Sanford, T., Vargo, J., and Breyer, B.N. 2019. "Trends in Bicycle-Related Injuries, Hospital Admissions, and Deaths in the USA 1997–2013." Traffic Injury Prevention 20 (5): 550–55. https://doi.org/10.1080/15389588.2019.1620219.

20. Lee, I.-M., and Buchner, D.M. 2008. The importance of walking to public health. Med. Sci. Sports Exerc. 40 (No. 7 Suppl), S512–518.

21. Mohamed, M.G., Saunier, N., Miranda-Moreno, L.F., and Ukkusuri, S.V. "A clustering regression approach: A comprehensive injury severity analysis of pedestrian–vehicle crashes in New York, US and Montreal, Canada." Safety Science, vol. 54, Apr. 2013, pp. 27–37.

22. Clifton, K.J., Burnier, C.V., and Akar, G., "Severity of injury resulting from pedestrian–vehicle crashes: What can we learn from examining the built environment?" Transportation Research Part D: Transport and Environment, vol. 14, no. 6, Aug. 2009, pp. 425–436.

23. Zhu, M., Zhao, S., Coben, J. H., and Smith, G.S. "Why more male pedestrians die in vehicle-pedestrian collisions than female pedestrians: a decompositional analysis." Traffic Injury Prevention, vol. 19, no. 4, Aug. 2013, pp. 227–231.

24. Henary, B.Y., Ivarsson, J., and Crandall, J.R. "The Influence of Age on the Morbidity and Mortality of Pedestrian Victims." Traffic Injury Prevention, Jan. 2007.

25. Davis, G. "Relating Severity of Pedestrian Injury to Impact Speed in Vehicle-Pedestrian Crashes: Simple Threshold Model." Transportation Research Record: Journal of the Transportation Research Board, vol. 1773, Jan. 2001, pp. 108–113.

26. National Highway Traffic Safety Administration. Traffic Safety Facts 2015 Data – Pedestrians. Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration; 20175. Publication no. DOT-HS-812-375. Available at https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812375. Accessed February 13, 2018.

27. Macinko, J., Silver, D., and Bae, J.Y. 2015. "Age, Period, and Cohort Effects in Motor Vehicle Mortality in the United States, 1980–2010: The Role of Sex, Alcohol Involvement, and

Position in Vehicle." Journal of Safety Research 52 (February): 47–57. https://doi.org/10.1016/j.jsr.2014.12.003.

28. Chang, Dow. 2008. "National Pedestrian Crash Report," June. https://trid.trb.org/view/865004.

29. Plainis, S., Murray, I.J., and Pallikaris, I.G. 2006. "Road Traffic Casualties: Understanding the Night-Time Death Toll." Injury Prevention 12 (2): 125–38. https://doi.org/10.1136/ip.2005.011056.

30. Savolainen, P., and Mannering, F. 2007. "Probabilistic Models of Motorcyclists' Injury Severities in Single- and Multi-Vehicle Crashes." Accident Analysis & Prevention 39 (5): 955–63. https://doi.org/10.1016/j.aap.2006.12.016.

31. Deborah, S., and McIntyre, A. 2018. "Determinants of Pedestrian and Bicyclist Crash Severity by Party at Fault in San Francisco, CA." Accident; Analysis and Prevention 110 (January): 149–60. https://doi.org/10.1016/j.aap.2017.11.007.

32. Ulfarsson, G.F., Sungyop K., and Kathleen M.B. 2010. "Analyzing Fault in Pedestrian-Motor Vehicle Crashes in North Carolina." Accident; Analysis and Prevention 42 (6): 1805–13. https://doi.org/10.1016/j.aap.2010.05.001.

33. Xiaoduan, S., Hu, H., Habib, E., and Magri, D. 2011. "Quantifying Crash Risk under Inclement Weather with Radar Rainfall Data and Matched-Pair Method." Journal of Transportation Safety & Security 3 (1): 1–14. https://doi.org/10.1080/19439962.2010.524348.

34. Federal Highway Administration. (2017). Road weather management program: How do weather events impact roads. Retrieved from https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm (Accessed on 3 July 2021).

35. Khan G., Qin X., and Noyce D.A. 2008. "Spatial Analysis of Weather Crash Patterns." Journal of Transportation Engineering 134 (5): 191–202. https://doi.org/10.1061/(ASCE)0733-947X(2008)134:5(191).

36. Fleiter, J.J., and Watson, B. 2016. "Addressing the Road Trauma Burden in China: Exploring Attitudes, Behaviours, Risk Perceptions and Cultural Uniqueness." Accident Analysis & Prevention, Traffic Safety in China: Challenges and Countermeasures, 95 (October): 326–33. https://doi.org/10.1016/j.aap.2015.07.005.

37. Shakil Mohammad, R., Tay, R., and De Barros, A. 2011. "Effect of Street Pattern on the Severity of Crashes Involving Vulnerable Road Users." Accident Analysis & Prevention 43 (1): 276–83. https://doi.org/10.1016/j.aap.2010.08.024.

38. Tefft, B.C. 2013. "Impact Speed and a Pedestrian's Risk of Severe Injury or Death." Accident; Analysis and Prevention 50 (January): 871–78. https://doi.org/10.1016/j.aap.2012.07.022.

39. Kröyer, H.R.G. 2015. "The Relation between Speed Environment, Age and Injury Outcome for Bicyclists Struck by a Motorized Vehicle - a Comparison with Pedestrians." Accident; Analysis and Prevention 76 (March): 57–63. https://doi.org/10.1016/j.aap.2014.12.023.

40. World Health Organization | Road Traffic Injuries. WHO. Accessed February 1, 2018. http://www.who.int/mediacentre/factsheets/fs358/en/.

41. Hauer, E. (2006). The frequency-severity indeterminacy. Accident Analysis & Prevention, 38(1), 78–83. https://doi.org/10.1016/j.aap.2005.07.001.

42. Hauer, E., & Hakkert, A.S. (1988). Extent and some implications of incomplete accident reporting. Transportation Research Record, 1185, 1-10.

43. Stutts, J.C., and Hunter, W.W. 1999. "Motor Vehicle and Roadway Factors in Pedestrian and Bicyclist Injuries: An Examination Based on Emergency Department Data." Accident Analysis & Prevention 31 (5): 505–14. https://doi.org/10.1016/S0001-4575(99)00007-X.

44. Huang H., Chin H.C., and Haque M.M. Severity of driver injury and vehicle damage in traffic crashes at intersections: a Bayesian hierarchical analysis. Accid Anal Prev. 2008; 40:45–54.

45. Hilakivi, I. 1989. A sixteen-factor personality test for predicting automobile driving accidents of young drivers. Accident Analysis and Prevention 21 (5), 413–418.

46. Behnood, A., and Mannering, F. Determinants of bicyclist injury severities in bicycle-vehicle crashes: A random parameters approach with heterogeneity in means and variances. Anal. Methods Accid. Res. 2017, 16, 35–47.

47. Liu S., and Fan, W. Investigating factors affecting injury severity in bicycle–vehicle crashes: A day-of-week analysis with partial proportional odds logit models. Can. J. Civ. Eng. 2021, 48, 941–947.

48. Zhu, S. Analysis of the severity of vehicle-bicyclist crashes with data mining techniques. J. Saf. Res. 2021, 76, 218–227.

49. Yan, X., Ma, M., Huang, H., Abdel-Aty, M., Wu, C. Motor vehicle–bicyclist crashes in Beijing: Irregular maneuvers, crash patterns, and injury severity. Accid. Anal. Prev. 2011, 43, 1751–1758.

50. Klop, J.R., and Khattak, A. Factors Influencing Bicyclist crash Severity on Two-Lane, Undivided Roadways in North Carolina. Transp. Res. Rec. J. Transp. Res. Board 1999, 1674, 78–85.

51. Pucher, J., Dill, J., and Handy, S. Infrastructure, programs, and policies to increase bicycling: an international review. Prev Med. 2010;50(suppl 1): S106–S125.

52. McKenzie, B. Modes less traveled: commuting by bicycle and walking in the United States, 2008–2012. Available at: https://www.census.gov/prod/2014pubs/acs-25.pdf. Accessed September 3, 2016.

53. Nelson, A., and Allen, D. If you build them, commuters will use them: association between bicycle facilities and bicycle commuting. Transp Res Rec. 1997; 1578:79–83.

54. Dill, J., and Carr, T. Bicycle commuting and facilities in major U.S. cities: if you build them, commuters will use them. Available at: http://www.ltrc.lsu.edu/TRB_82/TRB2003-002134.pdf. Accessed September 3, 2016.

55. Fishman, E., and Schepers, P. Global bike share: what the data tells us about road safety. J Safety Res. 2016; 56:41–45.

56. Hamann, C., and Peek-Asa, C. On-road bicycle facilities and bicycle crashes in Iowa, 2007–2010. Accid Anal Prev. 2013; 56:103–109.

57. Petritsch, T.A., Bruce W.L., Huang, H.F., and Challa, S. 2006. "Sidepath Safety Model: Bicycle Sidepath Design Factors Affecting Crash Rates." Transportation Research Record 1982 (1): 194–201. https://doi.org/10.1177/0361198106198200124.

58. Walker, I. 2007. Drivers overtaking bicyclists: objective data on the effects of riding position, helmet use, vehicle type and apparent gender. Accident Analysis and Prevention 39 (2), 417–425.

59. Hunter, W., Stewart, J., and Stutts, J. 1999. "Study of Bicycle Lanes Versus Wide Curb Lanes." Transportation Research Record 1674 (1): 70–77. https://doi.org/10.3141/1674-10.

60. Environmental Systems Research Institute (ESRI), (2014). ArcGIS Pro Tool Reference. Density Toolset Concept. https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-kernel-density-works.

61. National Center for Statistics and Analysis. Pedestrian: 2016 Data; Traffic Safety Facts. Report No. DOT HS 812 493; National Highway Traffic Safety Administration: Washington, DC, USA, 2018.

62. Da Silva, M.P., Smith, J.D., and Najm, W.G. Analysis of Pedestrian Crashes April. 2003. Available online: https://trid.trb.org/view/678125 (accessed on 18 April 2020).

63. R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

64. Ming, S., Sun, X., and Shan, D. Pedestrian Crash Analysis with Latent Class Clustering Method. Accid. Anal. Prev. **2019**, 124, 50–57, doi:10.1016/j.aap.2018.12.016.

65. Billah, K., Sharif, H.O., and Dessouky, S. Analysis of Pedestrian–Motor Vehicle Crashes in San Antonio, Texas. *Sustainability* **2021**, *13*, 6610. https://doi.org/10.3390/su13126610.

66. Billah, K., Sharif, H.O., and Dessouky, S. Analysis of Bicycle-Motor Vehicle Crashes in San Antonio, Texas. *Int. J. Environ. Res. Public Health* **2021**, *18*, 9220. https://doi.org/10.3390/ijerph18179220.

67. Billah, K., Adegbite, Q., Sharif, H.O., Dessouky, S., and Simcic, L. Analysis of Intersection Traffic Safety in the City of San Antonio, 2013–2017. *Sustainability* **2021**, *13*, 5296. https://doi.org/10.3390/su13095296.

68. Billah, K. 2018. "Pedestrian Crash Analysis for San Antonio." University of Texas at San Antonio.

69. Texas Bicycle Law. Bike DFW. Available online: http://www.bikedfw.org/texas-bicycle-law.html (accessed on 28 June 2021).