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Understanding the Role of Driver, Vehicle, Environment, and Policy Factors in Crash Injury Severity among Older Adults in the United States

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UNDERSTANDING THE ROLE OF DRIVER, VEHICLE, ENVIRONMENT, AND POLICY FACTORS IN CRASH INJURY SEVERITY AMONG OLDER ADULTS IN THE UNITED STATES

A Dissertation Presented

by

Chae Man Lee

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ABSTRACT

UNDERSTANDING THE ROLE OF DRIVER, VEHICLE, ENVIRONMENT, AND POLICY FACTORS IN CRASH INJURY SEVERITY AMONG OLDER ADULTS IN THE UNITED STATES

May 2017

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Driving is related to quality of life and health outcomes. Older drivers involved in car crashes have a higher risk of experiencing a severe injury or fatality. Understanding factors related to injury severity may identify points of intervention to promote road safety. The purpose of this study is to investigate how individual characteristics, vehicle elements, environmental elements, and driving licensing policy are associated with level of injury severity from no injury to fatal injury resulting from car crashes. Furthermore, this dissertation research utilizes the Geographic Information System (GIS) process to visualize the location of crashes and to identify the hot spots of crashes in state of Massachusetts.

This dissertation utilized motor vehicle crash data of 2010 to 2012 from General Estimate System (GES) and Fatality Analysis Reporting System (FARS) administrated by National Highway Traffic Safety Administration (NHTSA). Using the GES crash data, multinomial logistic regression analysis was performed. Results indicated that older drivers (age 65 and older) were more likely to have fatality and severe injury in a crash compared to younger drivers (age 35 to 59). Impaired drivers had a much greater likelihood of fatal and severe injuries compared to drivers with normal conditions. Drivers with sedans compared to pick-up trucks were more likely to have severe injuries. In terms of policy factors, drivers involved in a crash in states with mandatory medical reporting for at a risk driver had decreased risk of fatal and severe injuries. Also, drivers in states requiring the vision test at license renewal had reduced risk of fatal and minor injuries. Using the FARS crash data, results provided an explanation of both the identification and the visual representation of the hot spots of crash locations in MA observed by performing spatial analysis of the GIS application.

In conclusion, among adult drivers involved in crashes, those who are older or impaired (physical or mental) have a significantly greater risk of fatality or serious injury. The results suggest that license renewal policies that limit driving of those risky drivers may be an effective early intervention to enhance safety on the roads.

DEDICATION

I dedicate this dissertation to my parents and my siblings for a long commitment to support and encourage me to finish my work. I also dedicate it to my wife, Eun Hee and my son, Robin for your love, faith, and patience to understand over these many years of schooling and research.

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CHAPTER 1

INTRODUCTION

Background

The U.S. population is aging. In 2014, the number of adults age 65 and older was estimated at 46 million and by 2050 is estimated to be more than 83 million (Ortman, Velkoff, & Hogan, 2014). As the U.S. population ages, research interest in driving fitness among older drivers has grown, due in part, to concerns about public safety. Driving a car is an important mode of transportation for accessing needed goods, services, and social opportunities for independent living (Burkhardt, 2003). Most older persons heavily rely on their automobiles for transportation and prefer to drive to meet their needs (AARP, 2005). The number and proportion of older adults with a license to drive is increasing. In 2011, more than 35 million people age 65 and older had a driver's license, a 21% increase since 2002 (NHTSA, 2013a). By 2020 there will be more than 40 million older adults holding driving licenses (Dellinger, Langlois, & Li, 2002). The annual miles driven by older drivers is increasing. Younger drivers age 35 to 54 increased their annual vehicle miles traveled by 21% between 1995-96 and 2008, whereas older drivers showed much greater increase in annual vehicle miles traveled within same time periods. It was increased by 60% for older drivers age 75 to79 and 51% for older drivers age 80 and

older (Cicchino, 2015; McCartt, 2015). In addition, compared to younger drivers, older drivers were more likely to have severe injuries causing to spend higher health care costs given crashes (Shen & Neyens, 2015).

Older drivers may experience visual, cognitive, or other medical conditions that impact their ability to drive. When impairments are severe, drivers may have to stop or reduce driving (Campbell, Bush, & Hale, 1993; Dellinger, Sehgal, & Barrett-Connor, 2001). Driving cessation or restricted driving tends to be an unwelcome transition and may lead to social isolation, depression, and limitations in daily tasks or activities (Fonda, Wallace, & Herzog, 2001; Ragland, Satariano, & MacLeod, 2005). Driving cessation may negatively influence quality of life and reduce feelings of independence and autonomy. However, driving when no longer safe to do so may lead to adverse events such as car crashes resulting in physical injury or death to drivers, other drivers, passengers, or pedestrians.

Automobile crashes caused by older drivers are often in the mass media and a topic of heated debate on talk radio. In Massachusetts during 2009-2010, the issue was highlighted by a series of destructive crashes, and garnered major media coverage. For example, an 84 year-old woman died when her husband crashed head-on into another car in Woburn, Massachusetts. Another crash involved an 89 year-old woman who hit and fatally injured a 4 year-old child in a crosswalk in Stoughton, MA (Abel, 2009). News coverage of this crash extended well beyond Massachusetts, including extensive coverage in the New York Times. To date the worst and most publicized crash occurred in Santa Monica, CA. An 86 year-old driver (George R. Weller) with multiple chronic conditions

experienced pedal confusion and hit the gas pedal instead of the brake and drove his car through an outdoor market. The crash resulted in 10 fatalities and 62 injuries. The driver was criminally charged with 10 counts of vehicular manslaughter and convicted. Given his advanced age and poor health, he was sentenced to 5 years' probation. It was this crash that sparked intensive public debate about requiring older drivers to be subjected to periodic road tests to maintain a driving license in California (LeDuff, 2004). When crashes like these occur the media reaction can raise awareness of issues surrounding older driver safety, but generally, the media reaction tends to overestimate the actual danger presented by older drivers.

In 2011 there were an estimated 5 million police reported crashes that injured 2 million and caused the death of 30,000 of people (NHTSA, 2013a). Approximately 8% (185,000) of those injured in crashes and 17% (5,288) of all fatalities occur in adults age 65 or older (NHTSA, 2013b). These numbers will increase as the population ages. Due to age-associated health impairments and increasing fragility, older drivers involved in car crashes are at a much greater risk of serious injury, longer hospitalization stays, incomplete recovery, and death compared to younger or middle aged drivers (Braver & Trempel, 2004; Richmond, Kauder, Strumpf, & Meredith, 2002).

Factors that contribute to crashes are varied and include: drivers' individual characteristics, vehicle types, road types, weather conditions, or time of day. For example, two driver characteristics consistently associated with crashes are age and gender. Regarding age, adverse driving events (fatal crashes) seem to follow a U-shaped distribution, where adverse events are highest for the youngest and oldest drivers (Tefft,

2008). Drivers aged 65 and older had a greater rate of fatal car crashes than middle aged drivers based on a measure of vehicle-miles of travel (VMT) (Grabowski & Morrissey, 2001; Li, Braver, & Chen, 2003; Lyman, Ferguson, Braver, & Williams, 2002). Regarding gender, males have higher crash rates for every age. Among drivers age 65 and older, the fatal crash rate for males was 21.7%, whereas females had 6.8% crash rate in 2012 (NHTSA, 2014). Other driver characteristics associated with a risk of unsafe driving include physical limitation and impairments, chronic medical conditions, and cognitive impairments (Zhang, Lindsay, Clarke, Robbins, & Mao, 2000). Older drivers with these characteristics had a higher likelihood of being severely or fatally injured in a crash (Li, Braver, & Chen, 2003; Zhang et al., 2000). Also, older people who had visual impairments (e.g., decline in acuity, contrast sensitivity) were at greater risk for car crashes (Owsley & McGwin, 1999; Owsley, Ball, McGwin, Sloane, Roenker, White, & Overley, 1999).

Research also has shown that type of road (e.g., highway or secondary road), weather, time of day, and level of light are associated with the risk of car crashes among older people. For example, older drivers tend to be involved in fewer crashes on highways than younger drivers (Boufous, Finch, Hayen, & Williamson, 2008). Yet, compared to younger drivers, drivers age 70 and older have a greater risk of being involved in crashes at intersections or driveway locations (Preusser, Williams, Ferguson, Ulmer, & Weinstein, 1998; Stutts, Martell, Staplin, 2009). In terms of weather conditions, the findings are counterintuitive: older drivers had a lower rate of involvement in car crashes during adverse weather conditions such as rain, snow, and fog (McGwin &

Brown, 1999). It is likely that self-regulation or strategic decisions made by older drivers to avoid driving in bad weather may explain this counterintuitive finding.

Policy may also be related to crash risk. Driving is regulated at the state level, and states vary widely in the policies they employ. States which require an in-person license renewal procedure and mandatory vision testing for older adults have fewer fatal car crashes among older people than states that do not implement these policies (Grabowski, Campbell, & Morrisey, 2004; McGwin, Sarrels, Griffin, Owsley, & Rue, 2008; Dugan, Barton, Coyle, & Lee, 2013).

Statement of Purpose

Driving is the preferred means of mobility for many older adults and the number of older drivers is expected to increase dramatically in the next 30 years. Driving safety risks increase with older adults due to both normal age-related changes as well as chronic diseases that occur. As a result, there is an increased risk for their passengers and others on the roadways. In addition, when involved in a crash, older drivers have an increased risk of experiencing a severe injury or fatality.

It is important to identify what factors contribute to severe injury or fatality resulting from car crashes among older drivers. The purpose of this dissertation is to investigate how individual characteristics, vehicle elements, environmental elements, and driving licensing policy are associated with level of injury severity from no injury to fatal injury resulting from car crashes. Further, car crash reports contain geographic information that will be descriptively analyzed. A spatial analysis of the location of car crashes will be mapped by utilizing the Geographic Information System (GIS) process.

Organizational Overview

This dissertation consists of seven chapters. Chapter one presents background information on driving needs and driving safety related to car crashes among older people. The concepts in chapter one also clarifies the purpose of this dissertation. Chapter two reviews the previous studies on risk factors of car crashes resulting in severe injury or fatality. Chapter three introduces a conceptual framework based on the Human Ecology Model that defines relationships between risk factors and injury severity in car crashes. Chapter four establishes research questions and hypotheses that guide the current research. Chapter five describes methodology about data, sample, measurement of variables, and analysis. Chapter six presents the findings of data analyses. Finally, chapter seven provides a discussion of the results, limitations of the study and data, and policy recommendations to improve safety on the roads.

CHAPTER 2

LITERATURE REVIEW

The following chapter will review prominent studies addressing car crashes involving injury or fatality among older people. It provides a detailed summary of the relationships between individual characteristics, vehicle elements, environments, and driving license regulation policy for car crashes involving injury or fatality. The chapter concludes with a summary of gaps in the literature regarding risk factors and injury severity among older drivers.

Current Car Crashes in the United Sates

The NHTSA provides an annual summary report of all car crashes in the United States. Approximately 32,267 people died and 2.22 million people were injured in car crashes in the United States in 2011. As seen in Figure 1, people between the ages of 21 to 24 years old had the highest fatality rates and people between the ages of 16 to 24 years old had the highest injury rates in 2011. In addition, as seen in Figure 1 and 2, people age 65 and older had consistently lower rates for fatality and injury, compared to people between the ages of 16 to 64 years old (NHTSA, 2013b).

Figure 1. Percent of Person Fatality or Injury from Car Crashes by Age Group, 2011, National Highway Traffic Safety Administration

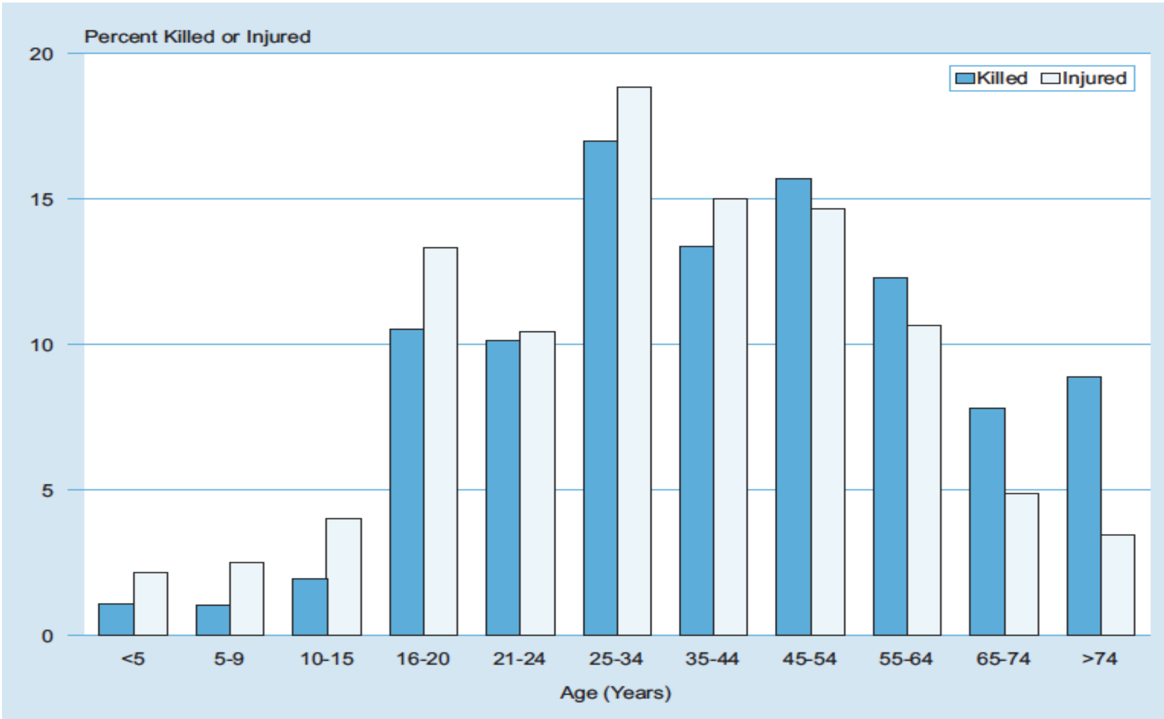


Figure 2. Percent of Person Fatality or Injury from Car Crashes by Age Group, 2011, National Highway Traffic Safety Administration

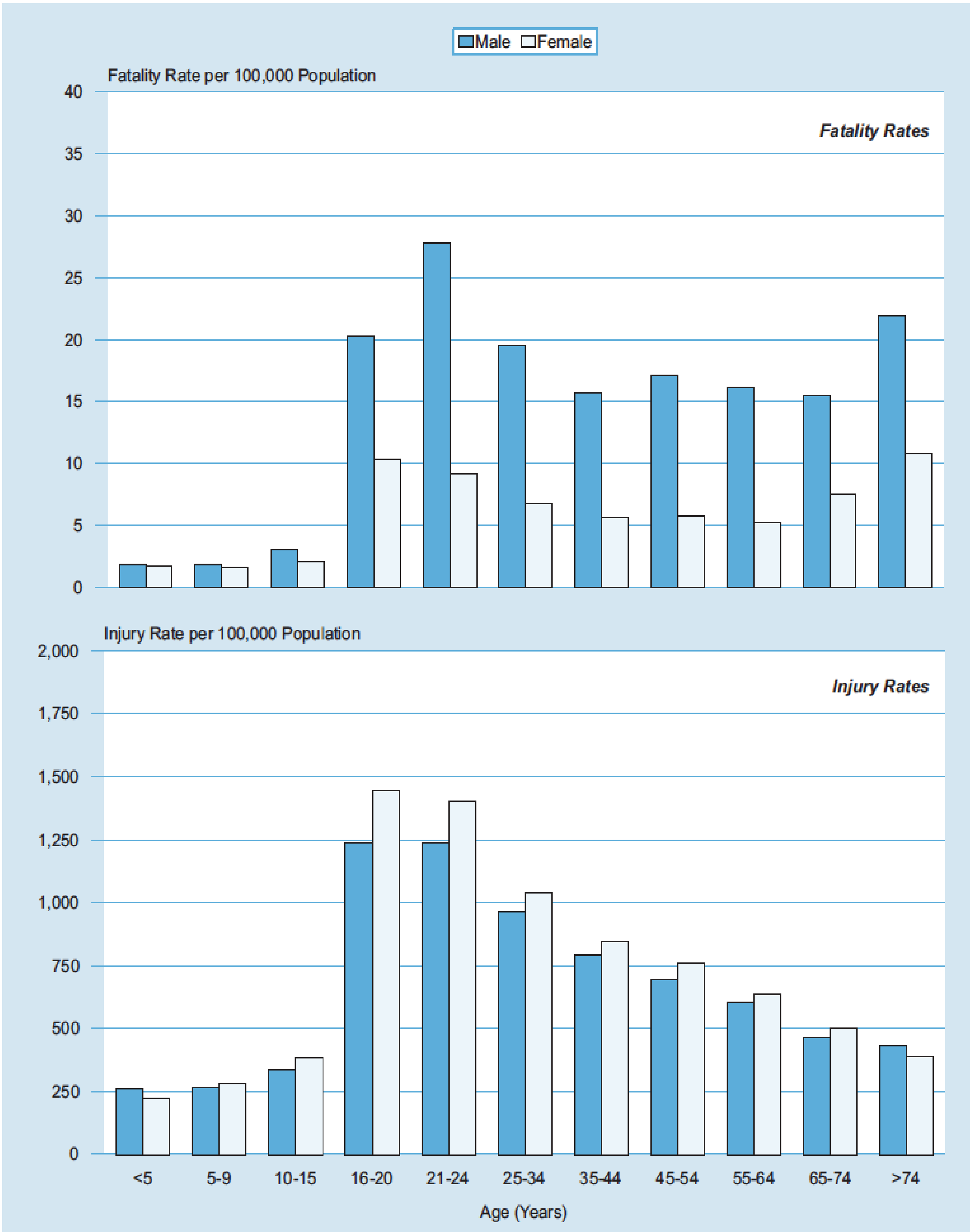


Figure 3. Motor Vehicle Traffic Fatality Rates among Older Population by Age Group, 2002-2011, National Highway Traffic Safety Administration

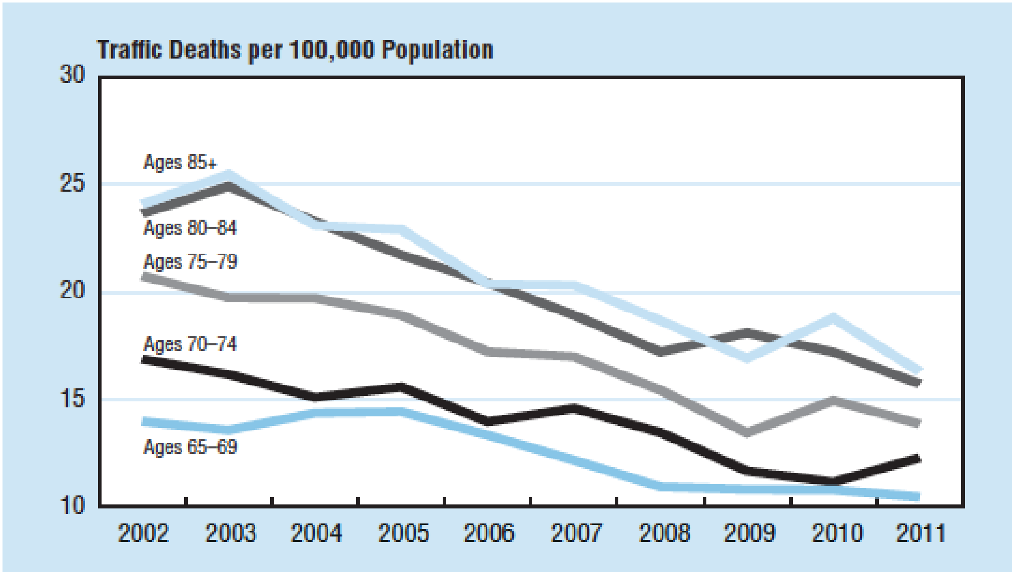
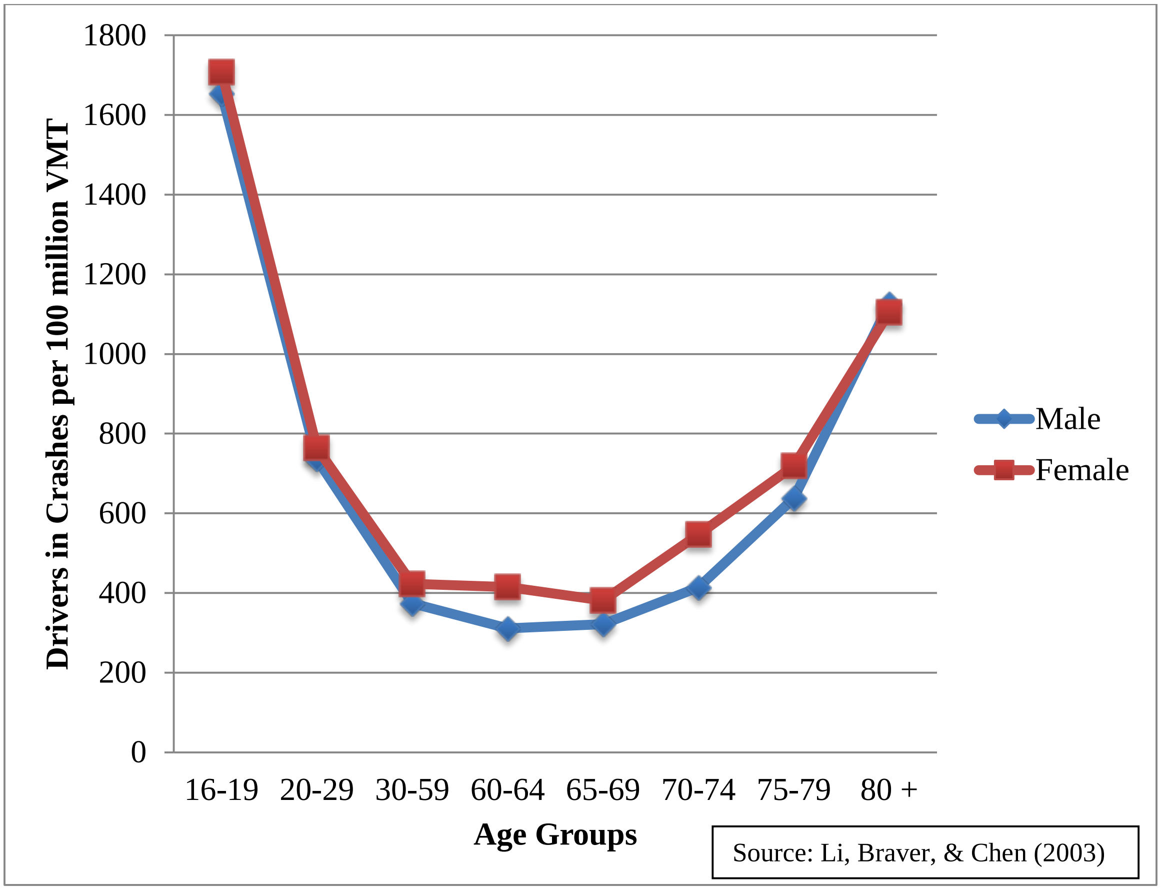


Figure 3 illustrates fatal car crashes involving older people age 65 and older over the last 10 years from 2002 to 2011. Similarly, Cheung and McCartt (2011) looked at trends in rates of fatal car crashes per 100,000 licensed drivers from 1997 to 2008. They compared rates of fatal car crashes among four age groups including drivers age 35 to 54, age 70 to 74, age 75 to 79, and age 80 above by using data from the Fatality Analysis Report System administrated by the NHTSA. They found that fatal car crashes declined between 1997 and 2008 by 16% for drivers age 35 to 54, 20% for age 70 to 74, 28% for age 75 to 79 and 16% for age 80 above (Cheung & McCartt, 2011). In short, older drivers had lower rates of fatal car crashes compared to similar drivers aged 16 to 64. Further, rates of fatal crashes for older drivers age 65 and older have declined over last 10 years. However, crash data involved by older adults show a different trend when considered in terms of VMT.

Figure 4. Drivers in Crashes per 100 million Vehicle-Miles of Travel by Age and Gender



Tefft (2008) examined five years (1999 to 2003) of crash data from the Fatality Analysis Reporting System (FARS) and annual vehicle-miles of travel from the 2001 National Household Travel Survey (NHTS). The number of deaths from crashes was highest for drivers age 19 years, and declines until age 65, and increases rapidly age after 70 per VMT (Tefft, 2008). As seen in Figure 4, depending on VMT and age group, driver involvement rates for all police reported car crashes falls in a U-shaped distribution (Li, Braver, & Chen, 2003; Tefft, 2008). Both younger drivers age 16 to 19 and older drivers age 80 and older have the highest rates for involvement. The rate for car crashes

decreases until it reaches age 60 to 64, but then the rate begins to increase at age 65 to 69. The rate for car crashes of older drivers age 75 to 79 is rapidly increasing based on 100 million of VMT.

Also, crash involvement rates are expected to increase as the older population increases. By using projections of population growth between 1999 and 2030, Lyman and colleagues (2002) investigated crash data from the FARS (1983, 1990, and 1995), the GES (1990 to 1995), and the NPTS (1983, 1990, and 1995) to predict crash involvement rates in 2030 among drivers age 16 and older. Their results showed that fatal crashes would increase by 39% and all police-reported crashes would increase by 34% in 2030. In terms of age differences, older drivers (ages 65 and older) were projected to experience a 155% increase in fatal car crashes and a 178% increases in all police reported car crashes in 2030, whereas younger drivers (ages 16-64) were expected to experience increase by 21% and by 22%, respectively, in 2030 (Lyman, Ferguson, Braver, & Williams, 2002).

By using recent crash data from FARS (1997 to 2012), Cicchino and McCartt (2014) found that fatal crash involvements per 100,000 licensed drivers were higher among older drivers age 70 and older than middle-aged drivers age 35 to 54 during 1997 to 2012. Over all time periods, fatal crash involvements per 100,000 licensed drivers has declined for all drivers age 35 and older. Older drivers age 70 and older had a much greater decline rate than drivers age 35 to 54, 42% to 30% respectively. When considering VMT for fatal crash involvements, a U-shape pattern is observed and suggests both younger drivers and older drivers had greater fatal crash involvements per

100 million VMT than middle-aged drivers (Cicchino & McCartt, 2014).

Further, it is important to understand how the driver's errors are related with crash involvement. By investigating the National Motor Vehicle Crash Causation Survey (NMVCCS) administrated by NHTSA, Cicchino and McCartt (2015) found that inadequate surveillance (33%) and speed misjudgment (6%) were the most prevalent errors for causing car crashes among older drivers age 70 and older. Changes occurring with the aging process in physical ability, vision acuity, and cognitive function could be potentially associated with those driving errors (Cicchino & McCartt, 2015).

As seen above, the rate for car crashes is measured in two different ways. One is to measure the number of fatal crashes occurring within a specific population. The second is to measure the number of fatal crashes occurring within a specific population while considering driving distance. The results vary depending on which measure is used. For example, older people have fewer involvements in car crashes based on number of licensed drivers, but if VMT is used then older people have greater rates of fatal car crashes compared to similar younger drivers. Among older drivers, it is important to note that the errors associated with crash risk are also associated with the aging process (Cicchino & McCartt, 2014; Cicchino & McCartt, 2015; Li, Braver, & Chen, 2003; Tefft, 2008).

Individual Characteristics of Injury Severity in Car Crashes

Previous research has identified a number of individual risk factors related with injury severity resulting from car crashes. Many studies have found that age is positively correlated with incidence of severe injury or fatality from car crashes.

Age: McGwin and Brown (1999) studied car crashes across three age groups: younger drivers age 16 to 34, middle-aged drivers age 35 to 54, and older drivers age 55 and older. They used 1996 Alabama crash data to describe risk factors of individuals, vehicles, and environments. They calculated both measures of crash involvement described above (i.e., rates based on per licensed driver, and VMT). They found that rates for fatal car crashes showed the U-shape pattern suggesting higher fatal rates for both younger drivers and older drivers. Across all age groups, male drivers had higher rates for fatal car crashes per 100 million of travel mileage.

Bédard and colleagues (2002) analyzed the FARS data from 1975 to 1998 to examine how individual and vehicle characteristics were associated with driver's fatality. In a binary analysis, they found that older drivers had a greater proportion of fatal injury than younger drivers. In multivariate logistic regression analyses, they found that older drivers (age 65 and older) had greater odds of fatal injury compared to drivers age 40 to 49. In fact, the odds of fatal injury for older drivers age 80 and older was about 5 times higher than drivers ages 40 to 49 (Bédard, Guyatt, Stones, & Hirdes, 2002).

Dellinger and colleagues (2002) examined two years (1990 and 1995) of GES and FARS crash data to investigate the risk of fatality, risk of crash, and annual average miles driven among drivers age 55 and older. They found older drivers were more likely to have greater fatal crash involvement rates than younger drivers due to the fact that risk of fatality and risk of crash were increased with age (Dellinger, Langlois, & Li, 2002).

Gender: Beyond age differences in car crashes resulting in injury severity, gender is also related to a different likelihood of involvement in car crashes among older

drivers. Bédard and colleagues (2002) studied single vehicle crashes with fixed objects and found male gender was associated with higher fatality odds. Rzeznikiewiz and colleagues (2012) examined fatalities in Ontario Canada. A total of 53,526 vehicles involved in collisions from 2001 to 2006 were analyzed. Results from the multivariate analysis suggest that collisions with older age and male drivers were associated with an increased risk of involving a fatality (Rzeznikiewiz, Tamim, & Macpherson, 2012).

Awadzi and colleagues (2006) utilized a socio-ecological model to determine risk factors related to older drivers' safety. From the point of the socio-ecological model, they focused on the individual, vehicle, and environment domains of the 2003 GES data. The outcome measure, injury severity, was classified as 'no injury', 'possible injury', 'non-incapacitating injury', 'capacitating injury', 'fatal injury', and 'unknown injury severity'. The responses were collapsed into two categories: 'no injury' and 'any kind of injury' in order to perform logistic regression. They found that older male drivers had a greater percentage of car crashes (62%) compared to older female drivers (38%). Conditional on having a crash, older female drivers had about 1.5 times higher odds of having an injury from a car crash compared to older male drivers (Awadzi, Classen, Garvan, & Komaragiri, 2006).

Finison and Dubrow (2002) investigated gender differences in injury severity using the Crash Outcome Data Evaluation System (CODES) for the state of Maine. They also examined the use of emergency medical service, hospital inpatient, and death certification. When comparing three age groups: younger drivers (age 15-24), middle-aged drivers (age 25-64), and older drivers (age 65 and over), they found that older

drivers were more likely to be hospitalized or die from car crashes than middle-aged drivers. Among older drivers, older female drivers were 1.6 times more likely to be hospitalized or die a given car crash compared to older male drivers (Finison & Dubrow, 2002). To summarize gender differences in car crashes and injury severity: older male drivers have a greater proportion of involvement in car crashes than older female drivers, but among those involved in a crash, older female drivers had increased odds of having severe injury or fatality than older male drivers.

Health Status: Prior studies have noted the significant relationships between physical impairments, chronic medical conditions, and risk of unsafe driving. Older people are more likely to suffer from such chronic health conditions as heart diseases, stroke, and arthritis. McGwin and his colleagues (2000) hypothesized that older drivers with chronic medical conditions would have a higher risk of involvement in car crashes. They interviewed 901 older drivers age 65 and older from the Alabama Department of Public Safety driving records in 1997. Based on a logistic regression, they found that older drivers who had heart disease, stroke, or arthritis were at a greater risk of being at fault for car crashes and had significantly reduced ability to safely drive a car, compared to those similar older drivers who had none of these chronic health problems (McGwin, Sims, Pulley, & Roseman, 2000).

Owsley and McGwin (1999), in a review of previous studies about the relationship between visual functions and car crashes, highlighted that visual difficulties such as declines in acuity, glare, contrast sensitivity, or eye diseases (e.g. cataracts or glaucoma) were negatively associated with driving performance and increased risks for

involvements in car crashes among older people (Owsley & McGwin, 1999).

In related work, Owsley and colleagues (1998) examined how visual impairments were associated with involvement in car crashes among older drivers. They followed 294 older drivers age 55 to 87 from 1990 to 1993 in Alabama. They assessed these drivers' visual functions by several tests (visual acuity, contrast sensitivity, stereo acuity, disability glare, peripheral sensitivity, and useful field of view). Older drivers who had reduction in the useful field of view test were 2.2 times more likely to be involved in car crashes compared to their counterparts with unobstructed view (Owsley et al., 1998). The authors found that visual impairments were significantly related to driving problems that increase involvement in car crashes.

Zhang and colleagues (2000) examined the Canadian Traffic Crash Information Databank (1988-1993) to investigate the severity of motor vehicle traffic crashes among older drivers. They found that older drivers age 65 to 69 who had physical impairments had 5 times higher odds of involvement in fatal crash and that drivers age 80 and older with physical impairments had 3.5 times higher odds of involvement in fatal crash compared those drivers of the same age without physical impairments (Zhang et al., 2000).

In summary, prior studies have examined the relationship between individual characteristics deemed risk factors for increased injury severity occurring during car crashes. Most studies reported that older age, gender, and drivers with physical impairments or chronic medical conditions are associated with increased risk of severe injury or fatality at given involvement in a crash. However additional factors, such as

vehicle elements and environment conditions are not as well studied. This dissertation will contribute to the literature by investigating a more comprehensive array of explanatory factors (see Table 2.) related to injury severity from car crashes using multiple years of nationwide crash data and by visualizing locations of car crashes to perform spatial analysis by using GIS application.

Vehicle Elements of Injury Severity in Car Crashes

Research has explored the relationship between vehicle factors (e.g. vehicle types, weight, operation of airbag, or use of seat belt) and crash injury severity level.

Vehicle Weight and Vehicle Type: Farmer, Braver, and Mitter (1997) investigated the National Crash Sampling System Crashworthiness Data System (1981-1993) to determine how vehicle type and weight were associated with injury severity in crashes involving two vehicles. They included passenger cars (sedan, hatchbacks, and wagon) and light trucks (pickup truck). By performing logistic regression analysis, they found that occupants of light weight passenger cars were more likely to have severe injury than occupants of heavier weight passenger vehicles. The odds of severe injury were decreased by 7% for each 1000 pounds increase in weight of the injured person's vehicle (Farmer, Braver, & Mitter, 1997). Similarly, Krull, Khattak, and Council (2000) studied vehicle type and weight and crash outcomes using crash data from Michigan (1994-1996) and Illinois (1993-1995). They estimated three models to explain crash outcomes (a Michigan model, an Illinois model, and a pooled model) and found similar results from all three models. Drivers of passenger vehicles involved in a crash were more likely to have severe injury than drivers of pickup trucks involved in a crash (Krull,

Khattak, & Council, 2000).

More recently, Classen and colleagues (2007) performed a mixed method study of the potential risk factors that reduce driving safety. They included individual characteristics, vehicle elements, and environmental components based on a socio-ecological model. They examined the 2003 FARS data to determine factors related to injury severity (severe or fatal injury vs otherwise). As a result of binary logistic regression, drivers who drove passenger cars (e.g. sedan) had about 2 times higher odds of having severe injury and drivers who drove vans or light trucks had about 23% decrease in odds of having severe injury, compared to drivers who drove sports utility vehicles (Classsen, Lopez, Winter, Awadzi, Ferree, & Garvan, 2007).

Furthermore, Awadzi and colleagues (2008) looked at the same data set of Classen et al's study. They specified three levels of outcome measures including no injury (reference), minor injury, and severe injury or fatality. From their multinomial logistic regression analysis, they found that drivers in passenger cars had about 1.51 times higher odds of having injury than no injury, compare to drivers in sports utility vehicles. Also, drivers in passenger cars had about 2.96 times higher odds of fatality than no injury, compared to drivers in sports utility vehicles (Awadzi et al., 2008). Bédard et al. (2002), Finsion et al. (2002), and Zhang et al. (2000) also examined how vehicle type and weight were related with injury severity in car crashes. Consistent with those above findings, their binary analysis results showed that heavier weight of vehicles reduced the likelihood of severe injury or fatality, and drivers in passenger cars were more likely to have severe injury than drivers in pickup trucks. However, these findings were not significant in

multivariate regression models.

Seatbelt Use: According to the NHTSA report by Liu and colleagues (2007), seat belt use reduced injury severity in car crashes. The authors looked at nationwide crash data from 1993 to 2004. The odds of severe injury for drivers who did not wear a seat belt was about 8 times higher compared to drivers who used a seat belt (Liu, Utter, & Chen, 2007).

Wang and Kockleman (2005) examined the National Automotive Sampling System's Crashworthiness Data System (NASS CDS) from 1998 to 2001. They focused on the relationship between vehicle elements and injury severity of drivers and passengers from car crashes. They distinguished between one-vehicle car crashes and two-vehicle car crashes. Within the two-vehicle model, drivers as well as passengers who used seat belts had a lower probability of injury and fatality (36% and 47%, respectively) compared to similar drivers not using seat belts. The use of seat belts had more significant effects on injury severity within the one-vehicle model. Drivers as well as passengers who used seat belts had about 90% lower probability of injury and about 72% lower probability of fatality than vehicle occupants who did not use seat belts (Wang & Kockleman, 2005).

In summary, with respect to vehicle elements and injury severity, prior studies found that vehicle types (e.g. sedan vs. pickup truck) and vehicle characteristics (e.g. weight of vehicle) were related to injury severity. Drivers with smaller vehicles or lighter weight of vehicles have a greater probability of severe injury or fatal injury from car crashes (Awadzi, et al., 2008; Classen, et al., 2007; Farmer, Braver, & Mitter, 1997;

Krull, Khattak, & Council, 2000). Furthermore, the use of safety equipment such as seat belts is an important role to reduce injury severity from car crashes. Consistent with study findings, people who use seat belts are less likely to experience severe injury during a crash compared to similar people not using seatbelts (Liu, Utter, & Chen, 2007; Wang & Kockleman, 2005). While past studies show that vehicle elements are related to crash outcomes this dissertation will consider a full constellation of factors that contribute to injury severity in crash.

Environmental Elements of Injury Severity in Car Crashes

Environmental elements (e.g. road types, location of crashes, time of day, & weather conditions) may also contribute to injury severity from car crashes.

Road Types: Stutts, Martell, and Staplin (2009) in research for NHTSA investigated what driver, vehicle, roadway and environmental elements are associated with crash outcomes. They explored four years (2002-2006) of FARS and GES data and found that drivers age 70 and older had a high proportion of car crashes occurring at intersection roads (Stutts, Martell, & Staplin, 2009). Similarly, Preusser and colleagues (1998) examined fatal crashes among drivers age 65 and older, compared to drivers age 40 to 49. Overall, they found that the relative risk of fatal crashes increased with age. For example, the relative risk was 1.45 for drivers age 65 to 69 and 5.10 for drivers age 85 and older, compared to similar drivers age 40 to 49. With respect to fatal crashes occurring at intersections, drivers age 65 to 69 had 2.26 times higher risk and drivers age 85 and older had about 10 times a higher relative risk of fatal crashes than drivers age 40 to 49. They also found that the relative risk of fatal crashes for drivers age 65 and older

was lower when a crash occurred at an intersection controlled by traffic signals or stop signs, compared to intersections without traffic control (Preusser et al., 1998).

Relevant findings regarding crashes at intersections were also reported by Mayhew and colleagues (2006). The authors conducted a systematic review of the crash literature occurring after 1990 for older adults and observed persuasive evidence to suggest that older adults have higher proportions crashes involving left-turning maneuvers (Mayhew, Simpson, & Ferguson, 2006).

More recently, Cicchino and McCartt (2014) focused on critical errors made in crashes by older drivers from the NMVCCS crash data. The most prevalent errors were inadequate surveillance (e.g. not seeing other vehicles and failing to see traffic control lights) while driving on the roads among older drivers. The most prominent pre-crash circumstances were acts of turning or crossing intersections among older drivers (Cicchino & McCartt, 2014). Therefore, there is some likelihood that older drivers were making errors at the intersections of roads resulting in crashes.

When analyzing state data rather than national data, similar results are found. Griffin (2004) investigated police reported crash data from Texas in 1975 to 1999 and found that drivers age 65 and older were more likely to have a fatality compared to similar drivers aged 55 to 64. Further, although older drivers had a lower proportion of crashes occurring at intersection-type roads, when a crash occurs the risk for fatality is quite high at intersection roads (Griffin, 2004). However, other research suggests that drivers age 65 and older are more likely to be involved in car crashes at intersections compared to middle aged drivers age 25 to 64 (Finison & Dubrow, 2002; McGwin &

Brown, 1999). Relevant studies in other countries shows similar results. Australian researchers found that drivers age 65 and older were more likely to be involved in car crashes at road intersections than other road types. They also reported that car crashes involving older drivers occurring at road intersections were more likely to result in severe injury or fatality (Boufous et al., 2008; Langford & Koppel, 2006).

Rural vs. Urban: Car crashes resulting in injury severity are also related to geographic location of events (e.g., rural/urban). Brown, Khanna, and Hunt (2000) analyzed car crashes resulting in fatality by using FARS data from 1977 to 1996. They compared rates of fatal car crashes occurring at rural areas with those in urban areas based on two commonly acceptable approaches: per 100 million VMT and per 100,000 populations. In the VMT model, the authors observed a relative risk for fatal car crashes in rural of 3.35 compared to 1.75 in urban areas. In a population-based model, rural areas maintained a higher relative risk (42.71) compared to urban areas (10.43). Both models showed that rural areas had a higher relative risk of fatal car crashes than urban areas (Brown, Khanna, & Hunt, 2000).

Zwerling and colleagues (2005) also provided supportive evidence that car crashes occurring at rural areas were related to severe injury. By examining the 2001 FARS data, they measured 'fatal crash incidence density' by performing the decomposition method with three components such as 'the injury fatality rate' (number of fatal crashes divided by number of crashes with injuries), 'the crash injury rate' (number of crashes with injuries divided by number of all crashes), and 'the crash incidence density' (number of all crashes divided by number of VMT). By comparing the fatal

crash incidence density between rural areas and urban areas, they found that rural areas had approximately two times higher the fatal crash incidence density than those of urban areas. The fatal crash incidence density for both male and female increased sharply when age reached 65 and older (Zwerling, Peek-Asa, Whitten, Choi, Sprince, & Janes, 2005).

Clark (2001) studied how age and population density were related with fatal car crashes. He investigated fatal car crashes from the 1997 FARS data and calculated a county's population density based on the 1995 US Census. Two age groups were created (<65 years and 65 years and older). The rate for fatal car crashes per 100,000 populations was negatively associated with population density. Both younger and older age groups had a greater rate of fatal car crashes per 100,000 populations at rural areas (low population density) than at urban areas (high population density) (Clark, 2001).

Furthermore, with respect to the relationship between injury severity and location of car crashes, Finison and Dubrow (2002), using crash data from Maine, found that older drivers had more car crashes in urban areas than in rural areas, but severe injury were more prevalent in rural areas than urban areas among older drivers in Maine. According to the logistic analysis, older drivers having car crashes in rural areas were about 2 times as likely to be hospitalized or have a fatality compared to older drivers having car crashes in urban areas.

Time of Day: Additional research has explored the relationships between injury severity and light conditions on the roads. Authors suggest that older drivers have greater proportions of fatal car crashes during day light conditions compared to dark, dawn, or dusk conditions (Stutts, Martell, & Staplin, 2009). McGwin and Brown (1999)

investigated crash data from Alabama by comparing three age groups: younger drivers, middle-aged drivers, and older drivers. They found that all age groups had greater proportions of car crashes occurring between 6am to 5pm compared to 6pm to 5am.

Furthermore, given car crashes, the driver's injury severity was associated with the time of events. By examining the 2003 of FARS data, Classen, et al. (2007) found that drivers age 35 and older who were involved in car crashes between 8am to 1pm and between 2pm to 8pm were 28% and 37% respectively less odds to have severe injury compared to similar drivers age 35 and older involved in car crashes occurring between 9pm and 7am. This study reported that driving at daytime was a protective factor for all drivers at given car crashes.

However, there was an interesting finding by interacting drivers' age and time of car crashes. By using the same data set, the 2003 of FARS, Awadzi, et al. (2008) expanded the analysis by adding interaction terms with age groups indicating younger drivers age 35 to 54 and older drivers age 65 and older in a regression model. With regard to the interaction term of age groups, they found that older drivers were about 1.7 times as likely to have a fatal injury from a car crash occurring during day light conditions (between 8am to 8pm) rather than dark conditions (between 9pm to 7am).

Older drivers may avoid driving at nighttime or during other less favorably lighted conditions and prefer driving in daylight (Bauer, Adler, Kuskowski, & Rottunda, 2003; Hakamies-Blomquit & Wahlstroem, 1998). Despite these self-regulating efforts, older drivers may encounter potentially hazardous situations with dense traffic vehicles on the roads during daytime. Higher density traffic may pose risk of car crashes. Those

studies show older drivers have greater proportions of car crashes during daytime compared to driving in nighttime and when involved in a crash are at risk for a severe or fatal injury compared to younger drivers.

Weather: Previous studies have found an association between weather conditions and car crashes. The annual crash report from NHTSA as well as several studies suggest crashes occur in greater proportions in good weather conditions (e.g., clear or dry) than adverse weather conditions (e.g., snowing, raining, fog). Similarly, older drivers were more likely to be involved in crashes during the good weather rather than adverse weather (McGwin & Brown, 1999; Finison & Dubrow, 2002; Stutts, Martell, & Staplin, 2009).

Baker and colleagues (2003) examined FARS data (1982-2001) and found similar results among female drivers age 70 and older who were involved in fatal car crashes. Older female drivers had a greater proportion of fatal car crashes occurring in good weather versus poor (rain, snow, wet) and day hours versus night (Baker, Falb, Voas, & Lacy, 2003). The authors suggest that older drivers avoid driving in bad weather. Self-regulated driving behaviors lower the potential risk for car crashes occurring in adverse situations (Bauer et al., 2003; Hakamies-Blomquit & Wahlstroem, 1998).

Zhang and colleagues (2000) examined Canadian crash data. Older drivers age 65 and older were more likely to have fatal car crashes during a snowy day compared to a clear day. However, research by Wang and Kockleman (2005) and Awadzi et al. (2006) suggest the opposite. First, Wang and Kockleman (2005) observed initial support for a relationship between weather conditions and frequency of severe crashes involving older

adults. According to a two-vehicle crash model, they found that the probability of severe injury and the probability of fatality were decreased by 16.4% and 32.5%, respectively during adverse weather conditions (e.g., snowing). Second, Awadzi et al. (2006) supported these findings in their study by finding that older drivers were less likely to have injury from car crashes on snow-covered road surfaces.

To summarize, numerous prior studies examined how environmental factors influence the risk of car crash involvements and the injury severity from car crashes. First, several studies reported that older people have greater proportions of car crashes at intersections. Second, older people have the higher likelihood of severe injury or fatality when involved in a car crash at intersection roads. Third, based on population density, older people are more likely to be involved in car crashes with severe injury in rural areas than urban areas. Lastly, driving in good weather or daylight conditions is predictive of increased risk for car crashes among older drivers.

State Policy and Injury Severity in Car Crashes

Driving is regulated at the state level. States use two primary policy mechanisms to filter out unsafe drivers: license renewal procedures and medical reporting systems. Research shows that state policy (requiring: in-person renewal, accelerated license renewal cycle, vision test, and medical reporting for at-risk drivers) may also influence crash risk. States vary widely in the policies in use. For example, (see Table 1), some states (e.g., Florida & Indiana) accelerate the renewal cycle for license renewal for older drivers, but other states do not (e.g., Massachusetts & New York). Also, some states (e.g., California & Maryland) require vision tests at license renewal for older drivers, but others

(e.g., Alabama & Connecticut) do not. Researchers have explored whether such policies have any impact on crash fatality rates. Levy, Vernick, and Howard (1995) studied how the vision test as a requirement for the license renewal procedure impacted rates of fatal crashes involving drivers aged 70 and older. They used FARS data (1985-1989) to count fatal crashes in which at least one driver involved was age 70 and older. They found that states that practiced the mandatory vision test for licensure renewal had a 7% reduced rate of fatal crashes among older drivers (Levy, Vernick, & Howard, 1995).

As of January 1, 2004, drivers age 80 and older in Florida were required to pass the vision test in order to renew their driving license. McGwin and colleagues (2008) compared data gathered before and after the vision test became law. The authors found that older drivers age 80 and older were less likely to be involved in fatal crashes after the vision test law went into effect than before the vision test law (McGwin, Sarrels, Griffin, Owsley, & Rue, 2008).

Grabowski, Campbell, and Morrisey (2004) examined how different state policies affected the rate of fatal crashes involving older drivers. In this landmark study of multiple years of data using complex statistical methodology to control for many variables they found that states mandating in-person license renewal procedures were 0.83 odds as likely to be associated with fatal crashes involving drivers age 85 and older, whereas all other license renewal policies were not significant. Tefft (2014) extended this study by examining recent FARS data (1986 to 2011). The finding was consistent that mandatory in-person license renewal reduced fatal crash involvement rates by 31% for drivers age 85 and older, relative to drivers age 40 to 54. Many states required drivers to

pass a vision test during in-person license renewal procedure, but some states required the vision test without doing in-person renewal. The vision test requirement with in-person renewal combined was not significant. The vision test without doing in-person renewal decreased the fatal crash involvements by 36% for drivers age 85 and older, relative to driver age 40 to 54 (Tefft, 2014).

Classen et al. (2007) examined four state licensing policies: age-renewal policies, reduced renewal cycle, in-person renewal, and vision/medical testing. After conducting bivariate analysis, they found that the age-renewal policy and the in-person renewal policy were associated with lower proportions of severe injury among older drivers. However, other renewal policies were not significant in bivariate analysis.

Dugan, Barton, Coyle, and Lee (2013) conducted a systematic review of studies containing state policy and driving outcome data. A total of 29 studies met inclusion criteria. Twenty-two studies investigated license renewal and seven articles examined medical reporting. In-person license renewal requirements were associated with reduced risk for fatal crashes. Restricted licenses were associated with reduced number of miles driven per week. More intensive renewal requirements and being the subject of a medical report to the licensing authority was associated with delicensure.

As noted above, driving license renewal polies are varied with age requirement, length, and foams between one state to other states. It shows that previous studies find similar results. The specific state implementations of license renewal policies regarding as in-person renewal and vision test were associated with reductions of crash involvement rates among older drivers (Classen et al., 2007; Grabowski, Campbell, & Morrisey, 2004;

Levy, Vernick, & Howard, 1995; McGwin, et al., 2008; Tefft, 2014). Further, this dissertation will look at how states' license renewal policies with other individual, vehicle, and environment factors influence car crashes resulting severe injury.

Table 1. Summary of State Driving License Renewal Policy and Age Requirement

State	Accelerated Renewal Cycle	Vision Test at Renewal	In-Person Renewal	Physician reporting for at-risk drivers	Written/Road Test at Renewal
Alabama	No	No	No	No	No
Alaska	No	Yes, Age 69+	Yes, Age 69+	No	No
Arizona	Yes, Age 65+	Yes	Yes	No	No
Arkansas	No	Yes	Yes	No	No
California	No	Yes, Age 70+	Yes, Age 70+	Yes	Yes, Age 70+
Colorado	No	Yes, Age 66+	No	No	No
Connecticut	Yes, Age 65+	No	Yes	No	No
Delaware	No	Yes	Yes	Yes	No
District of Columbia	No	Yes, Age 70+	Yes, Age 70+	Yes, Age 70+	No
Florida	Yes, Age 80+	Yes, Age 80+	No	No	No
Georgia	No	Yes, Age 65+	Yes, Age 64+	No	No
Hawaii	Yes, Age 72+	No	No	No	No
Idaho	Yes, Age 63+	Yes, Age 70+	Yes, Age 70+	No	No
Illinois	Yes, Age 81+	Yes, Age 75+	Yes, Age 75+	No	Yes, Age 75+
Indiana	Yes, Age 75+	Yes, Age 70+	Yes, Age 70+	No	No
Iowa	Yes, Age 72+	Yes, Age 70+	Yes, Age 70+	No	No
Kansas	Yes, Age 65+	Yes	Yes	No	No
Kentucky	No	No	Yes	No	No
Louisiana	No	Yes, Age 70+	Yes, Age 70+	No	No
Maine	Yes, Age 65+	Yes, Age 62+	Yes, Age 62+	No	No
Maryland	No	Yes, Age 40+	No	No	No
Massachusetts	No	Yes, Age 75+	Yes, Age 75+	No	No
Michigan	No	No	No	No	No
Minnesota	No	Yes	Yes	No	No
Mississippi	No	No	No	No	No
Missouri	Yes, Age 70+	Yes	Yes	No	No
Montana	Yes, Age 75+	Yes, Age 75+	Yes, Age 75+	No	No
Nebraska	No	Yes, Age 72+	Yes, Age 72+	No	No
Nevada	Yes, Age 65+	Yes, Age 71+	No	Yes	No

(Table 1 Continued)

Table 1. Summary of State Driving License Renewal Policy and Age Requirement (Continued)

State	Accelerated Renewal Cycle	Vision Test at Renewal	In-Person Renewal	Physician reporting for at-risk drivers	Written/Road Test at Renewal
New Hampshire[1]	No	Yes	No	No	Yes, Age 75+
New Jersey	Yes, Age 70+	Yes, every 10 years	No	Yes	No
New Mexico	Yes, Age 67+	Yes, Age 75+	Yes, Age 75+	No	No
New York	No	Yes	No	No	No
North Carolina	Yes, Age 66+	No	No	No	No
North Dakota	Yes, Age 78+	Yes	Yes	No	No
Ohio	No	Yes	Yes	No	No
Oklahoma	No	No	Yes	No	No
Oregon	No	Yes, Age 50+	Yes	Yes	No
Pennsylvania	No	No	No	Yes	No
Rhode Island	Yes, Age 75+	No	No	No	No
South Carolina	Yes, Age 65+	No	No	No	No
South Dakota	No	Yes, Age 65+	No	No	No
Tennessee	No	No	No	No	No
Texas	Yes, Age 85+	Yes, Age 79+	Yes, Age 79+	No	No
Utah	No	Yes, Age 65+	No	No	No
Vermont	No	No	No	No	No
Virginia	Yes, Age 75+	Yes, Age 75+	Yes, Age 75+	No	No
Washington	No	Yes, Age 70+	Yes, Age 70+	No	No
West Virginia	No	Yes	Yes	No	No
Wisconsin	No	Yes	Yes	No	No
Wyoming	No	No	No	No	No

Note. [1] In New Hampshire, road test was abolished in 2012.

Geographic Information System (GIS) and Car Crashes

Geographic Information Systems (GIS) is a process that includes geo-coding of car crashes that enables the analysis of geographic factors related to crashes. Since 2001, the FARS data provided latitude and longitude information of fatal car crashes. Subramanian (2009) examined the 2006 FARS data to quantify and compare fatal car crashes in rural and urban areas. On the urban layer provided by data from the United States census, Subramanian extended the urban boundary with four more lines representing distances of 2.5 miles, 5 miles, 7.5 miles, and 10 miles. After joining the layers by the GIS application, each fatal crash was distributed within or outside the urban boundary on the map. Subramanian observed that about 44% of fatal car crashes were located within the urban boundary. However, within the extended urban boundary of 2.5 miles, fatal car crashes were increased to 63%. Within 5 miles of the extended urban boundary, the majority (about 75%) of fatal car crashes occurred (Subramanian, 2009). This finding showed that most fatal car crashes occurred in urban areas along with rural areas within 5 mile of the urban boundary. The GIS application is a helpful method to illustrate areas that have high risks of fatal car crash. The GIS application extended the boundary line of urban areas, and showed that high risk fatal car crashes included rural areas that are close to urban areas.

Abdel-Aty, Chundi, and Lee (2007) performed geo-spatial analysis to explore the proportion of crashes involving cars and school-aged children (ages 4-18) as pedestrians or bicyclists. They investigated the 5 years (1999-2003) of crash data in Orange County, Florida from the Florida Department of Highway Safety and Motor Vehicles. GIS

application was adopted with a geo-coding process so that each crash was overlaid on the map of Orange County. Also, GIS application created the ‘school buffer zone’ which was a radius of one half mile surrounding each school. After combining the crash-map and the school buffer zone map, spatial distributions presented that approximately 71% of crashes occurred within the school buffer zone. It was indicated that many school-aged children were involved in crashes near school areas (Abdel-Aty, Chundi, & Lee, 2007). This study also showed that the GIS application can be used as a mapping tool to visualize high risk zones where school-aged children may be involved in car crashes.

Similarly, Prasannakumar and colleagues (2011) utilized the GIS spatial analysis tool to identify how crash locations were clustering together indicating high risk zones or “hot spots”. They selected the study area of Thiruvanathapuram, a city in India. After collecting police reported crash data, they performed the hot spot analysis. Areas with a greater density of crashes are indicated in red on the map. Overall, they found that the red hot spots were concentrated to those areas where study participants were observed to commute (schools, churches) (Prasannakumar, Vijith, Charutha, & Geetha, 2011).

Taken together, GIS applications have been utilized to not only visualize locations of specific crashes but also to identify clusters of crashes known as hotspots. This dissertation also uses the GIS application to identify hotspots yet will further specify high risk areas by a driver’s injury severity in a crash. Based on the differing severity of injury experienced, the hot spots areas may vary.

Gaps in Literature Review

By summarizing the risk factors for car crashes resulting in severe injury or fatality in those previous studies (see Table 2), it is clear that a multitude of factors are related to car crashes and injury severity. The factors include individual characteristics, vehicle elements, environments, and licensing policy for older drivers. A limitation of current knowledge stems from the fact that some studies only focus on individual characteristics (e.g. age, gender, and physical health condition), whereas other studies focus on the vehicle or environment elements. Previous studies have paid little attention to car crashes resulting in severe injury. Thus, there is an opportunity for this dissertation to assess comprehensively a broad range of factors that may contribute to injury severity from car crashes. In addition, many studies predicted the outcomes of crash frequency, crash rates, or involvements of fatal car crashes. This dissertation will focus specifically on injury severity of drivers in vehicles from car crashes.

Car crashes are events that result not only from the interaction of drivers, vehicles, and environments but also as a result of the spatial components of roadways or land use. The GIS application is an excellent tool to visualize the locations of events and to identify hot spots or danger zones on the map by integrating the location of car crashes via latitude and longitude. This dissertation will visualize the locations of car crashes resulting in fatal injury on the map.

The NHTSA provides well-maintained nationwide annual crash data such as GES and FARS in the United States. Most studies done in the United States examined the GES, FARS, or both data to understand crash relevant issues, whereas some studies

explored one individual state crash data. This dissertation will look at three years (2010 to 2012) of both GES and FARS data to examine how multiple factors of individual, vehicle, environment, and licensing policy are related with injury severity resulting from car crashes among drivers. FARS data also provides regional information (e.g. state, county, and city) as well as latitude and longitude of car crashes resulting in at least one fatality given car crashes. This geographic information will be used for visualizing the locations of car crash on the map.

By utilizing nationwide or individual state crash data, most studies have used regression models to predict risk factors on outcomes of crash rates or injury severity. Results of regression models show the relationships between predisposing factors and outcomes of crash rates or injury severity for a given car crash. Furthermore, the GIS application allows a mapping method to display the locations and spatial distribution of car crashes resulting in severe injury. Therefore, this dissertation will conduct the regression model to quantify risks of injury severity among drivers who involved in car crashes and the GIS application allowing visualization of crash locations and the hotspot of crash on the map of Massachusetts.

Table 2. Summary of Studies about Car Crashes and Injury Severity

Author (year)	Crash Data (year)	Analysis	GIS
Lee (2016) [1]	**GES [a] & FARS [b] (2010-2012)**	**MNL [2]**	**Yes**
Abdel-Aty et al. (2007)	Florida (1999-2003)	Spatial & Log-linear	Yes
Awadzi (2006)	GES (2003)	Logistic regression	
Awadzi (2008)	FARS (2003)	Multinomial logistic	
Baker (2003)	FARS (1982-2001)	Descriptive statistics	
Bédard et al. (2002)	FARS (1975-1998)	Logistic regression	
Boufous et al. (2008)	Australia (2000-2001)	Linear regression	
Braver & Trempel (2004)	GES & FARS (1993-1997) NPTS [c] (1995)	Rate ratios	
Brown et al. (2000)	FARS (1977-1996)	Descriptive statistics	
Cheung (2011)	FARS (1997-2008)	Analysis of covariance	
Clark (2001)	FARS (1997)	Descriptive statistics	
Classen (2007)	FARS (2003)	Linear regression	
Dellinger et al. (2002)	FARS & NPTS (1990 & 1995)	Decomposition model	
Farmer et al. (1997)	NASS CDS [d] (1988-1992)	Logistic regression	
Finison & Dubrow (2002)	Main (1996)	Logistic regression	
Grabowski et al. (2004)	FARS (1990-2000)	Negative binomial	
Griffin (2004)	Texas (1975-1999)	Risk ratio	
Krull et al. (2000)	Michigan (1994-1996) & Illinois (1993-1995)	Logistic regression	
Levy et al. (1995)	FARS (1985-1989)	Poisson	
Li et al. (2003)	GES & FARS (1993-1997) & NPTS (1995)	Decomposition model	
Liu et al. (2007)	NASS CDS (1993-2004)	Logistic regression	
Lyman et al. (2002)	GES & NPTS (1990 & 1995), FARS (1993, 1990, & 1995)	Descriptive statistics	
McGwin & Brown (1999)	Alabama (1996)	Descriptive statistics	
McGwin et al. (2000)	Alabama (1991-1995)	Logistic regression	
McGwin et al. (2008)	FARS (2001-2006)	Descriptive statistics	
Preusser et al. (1998)	FARS (1994-1995) & NPTS (1990)	Risk ratio	
Rzeznikiewiz et al. (2012)	Transportation of Ontario (2001-2006)	Logistic regression	
Stutts et al. (2009)	GES & FARS (2002-2006)	Descriptive statistics	
Subramanian (2009)	FARS (2006)	Spatial analysis	Yes
Wang & Kockelman (2005)	NASS CDS (1998-2001)	Ordered logistic	
Zhang et al. (2000)	Canada (1988~1993)	Logistic regression	
Zwerling et al. (2005)	FARS & GES (2001)	Decomposition model	

(Table 2 Continued)

Table 2 Summary of Studies about Car Crashes and Injury Severity (Continued)

Author (year)	Variables	Independent: Factors			
	Dependent	Individual	Vehicle	Environment	Policy
Lee (2016) [1]	**Injury severity**	**Yes**	**Yes**	**Yes**	**Yes**
Abdel-Aty et al. (2007)	Car crash	Yes		Yes	
Awadzi (2006)	Injury severity	Yes	Yes	Yes	
Awadzi (2008)	Injury severity	Yes	Yes	Yes	
Baker (2003)	Fatal crash	Yes	Yes	Yes	
Bédard et al. (2002)	Injury severity	Yes	Yes		
Boufous et al. (2008)	Injury severity	Yes	Yes	Yes	
Braver & Trempel (2004)	Injury severity	Yes			
Brown et al. (2000)	Fatal crash			Yes	
Cheung (2011)	Fatal crash	Yes			
Clark (2001)	Fatal crash	Yes		Yes	
Classen (2007)	Injury severity	Yes	Yes	Yes	Yes
Dellinger et al. (2002)	Fatal crash	Yes			
Farmer et al. (1997)	Injury severity	Yes	Yes		
Finison & Dubrow (2002)	Injury severity	Yes	Yes	Yes	
Grabowski et al. (2004)	Fatal crash	Yes			Yes
Griffin (2004)	Car crash	Yes	Yes	Yes	
Krull et al. (2000)	Injury severity	Yes	Yes		
Levy et al. (1995)	Fatal crash	Yes			Yes
Li et al. (2003)	Fatal crash	Yes			
Liu et al. (2007)	Injury severity	Yes	Yes		
Lyman et al. (2002)	Car crash	Yes			
McGwin & Brown (1999)	Crash rates	Yes	Yes	Yes	
McGwin et al. (2000)	Car crash	Yes			
McGwin et al. (2008)	Fatal crash	Yes			Yes
Preusser et al. (1998)	Fatal crash	Yes		Yes	
Rzeznikiewiz et al. (2012)	Fatal crash	Yes	Yes	Yes	
Stutts et al. (2009)	Crash rates	Yes	Yes	Yes	
Subramanian	Fatal crash			Yes	
Wang & Kockelman (2005)	Injury severity	Yes	Yes	Yes	
Zhang et al. (2000)	Injury severity	Yes	Yes	Yes	
Zwerling et al. (2005)	Fatal crash	Yes		Yes	

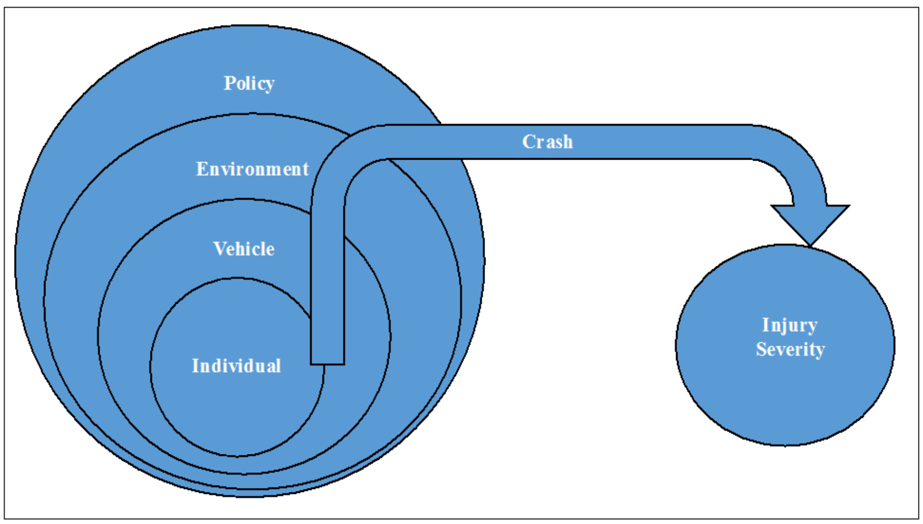
Notes. [1] Representing this current dissertation
[2] Multinomial Logistic Regression
[a] General Estimates System
[b] Fatality Analysis Reporting System
[c] Nationwide Personal Transportation Survey
[d] National Crash Sampling System Crashworthiness Data System
[e] National Highway Traffic Safety Administration

CHAPTER 3

CONCEPTUAL FRAMEWORK

The following chapter will introduce the conceptual framework for this dissertation. This dissertation seeks to examine the effects of multiple factors influencing injury severity in car crashes among older drivers. Figure 5 illustrates the Human Ecology theory with integration of injury severity in car crashes.

Figure 5. Conceptual Frameworks for the Human Ecology Theory



According to the Human Ecology theory first developed by Bronfenbrenner (1979), a human being is part of the nested arrangement of ecosystem including family, neighborhood, community, physical environments, and social cultural environments

(Bubolz & Sontag, 1993). The Human Ecology theory describes a human behavior as reacting from a product of interactions with other individuals in the ecosystem, the physical environment, and the social-cultural environment. For example, driving behavior is influenced by individual driver characteristics as well as interactions with other drivers. Driving behavior is also influenced by perceptions of certain physical environmental conditions, such as when a driver avoids driving in bad weather. An example of socio-cultural norms or policy that influences driving behavior is a driver's tendency to avoid driving after drinking alcoholic beverages.

As noted in the literature review, it is important to understand that there are often multiple and complex causes of car crashes related to injury severity. The Human Ecology theory provides a conceptual framework to develop associations between multiple factors and injury severity in car crashes (See Figure 5). By considering correlates of multiple factors and injury severity in car crashes, the Human Ecology theory consists of four different spheres: individual characteristics, vehicle elements, environmental factors, and policy factors (Awadzi et al., 2008; Classen et al., 2007; Juarez, Schlundt, Goldzweig, & Stinson, 2006).

In defining the individual sphere, the first factor is drivers. Drivers' characteristics such age, gender, and physical impairments are associated with injury severity in car crashes. Individual factors interact with vehicle elements (e.g. vehicle type and vehicle weight) and as the model suggests, these factors interact with a set of environmental factors (e.g. road types, location of rural / urban, light conditions, and weather) that influence injury severity in car crashes. The model also suggests that policy

factors impact injury severity. Licensing regulations for older drivers (e.g. in-person renewal, frequent license renewal cycle, vision test, and medical reporting for at-risk drivers) attempts to cease or restrict driving for risky drivers. Thus, policy factors decrease the likelihood of car crashes involved by risky drivers.

Therefore, to understand injury severity in car crashes among older drivers, the proposed Human Ecology theory stresses the need to consider multiple factors to determine injury severity in car crashes of older people.

CHAPTER 4

RESEARCH QUESTIONS AND HYPOTHESIS

This chapter establishes research questions and hypotheses for this dissertation. The research questions for this dissertation are consisted of a quantitative regression model and a spatial model. Research question #1, #2, #3, and #4 will be answered by analyzing the GES data. Research question #5 will be answered by examining the FARS data.

A strength of this dissertation is the use of two data sources. The NHTSA provides the GES and the FARS data. The GES is a nationally representative probability sample of police reported car crashes occurring while traveling on a public road. The FARS is annual data on traffic crashes resulting in at least one fatality occurring within 30 days after the crash. The FARS is a census database of all fatal car crashes in the United States reflecting national totals of fatal car crashes. Both the GES and the FARS contain detailed information about road users, vehicle, and crash situations.

However, the main difference between the GES and the FARS is that the FARS provides geographical information (e.g. state, county, city, latitude, and longitude) of each fatal car crash, whereas the GES only provides regional information (e.g. northeast, southeast, mid-west, and west) of car crashes. Therefore, the FARS is useful as it

incorporates the GIS application provides latitude and longitude that enables locating car crashes on the map.

Although the FARS provides car crashes, which involved any fatality for all 50 states and Puerto Rico, this dissertation will select events only if they occurred in state of Massachusetts during 2010 to 2012 in order to answer research question #5.

Question 1

How are individual driver factors (e.g. age, gender, and physical impairments) associated with the injury severity in given car crashes?

Previous studies have identified that drivers' characteristics were influential factors on injury severity in car crashes. Compared to middle-aged drivers, older drivers were more likely to sustain severe injury or fatality in given car crashes (Bédard et al., 2002; Cicchino & McCartt, 2014; Cicchino & McCartt, 2015; Dellinger et al., 2002; McGwin & Brown,1999; Tefft, 2008).

With respect to gender differences, older male drivers had a greater percentage of car crash involvements than older female drivers. But, older female drivers had a greater probability of having severe injury or fatality at given car crashes, compared to older male drivers (Awadzi et al., 2006; Bédard et al., 2002; Finison & Dubrow, 2002; Rzeznikiewiz, Tamim, & Macpherson, 2012).

Additionally, drivers with physical impairments were more likely to be involved in car crashes and to have severe injury at given car crashes (McGwin et al., 2000; Owsley & McGwin, 1999; Zhang et al., 2000). Thus, the following hypotheses reflect how driver's factors are related with injury severity in given car crashes.

Hypothesis 1

1) *Older drivers (aged 65 and older) will have a higher likelihood of severe injury outcomes compared to middle aged drivers (aged 35 to 59) in given car crashes.*
2) *Female drivers will have a higher likelihood of severe injury outcomes compared male drivers in given car crashes.*
3) *Drivers with physical impairments will have a higher likelihood of severe injury outcomes compared to drivers without physical impairments in given car crashes.*

Question 2

How are vehicle elements associated with injury severity in given car crashes? Vehicle related elements have been discussed as to how vehicle type or vehicle weight were related with injury severity. Drivers of passenger cars such as a sedan or wagon were more likely to have severe injury than drivers of sports utility vehicle or pickup trucks (Classen et al., 2007; Farmer et al., 1997; Krull et al., 2000). Thus, the following hypothesis reflect vehicle elements on injury severity in given car crashes.

Hypothesis 2

Drivers who drive passenger vehicles will have a higher likelihood of severe injury outcomes in given car crashes, compared to drivers who drive pick-up trucks.

Question 3

How are environmental elements (e.g. road function, road type, light condition, and weather condition) associated with the injury severity in given car crashes?

Previous studies have identified that locations of a roadway and the conditions of light as well as weather were related with the likelihood of car crashes resulting in severe injury or fatality. Older drivers had severe injury or fatality when they were involved in car crashes on intersection related roadways (Boufous et al., 2008; Cicchino & McCartt, 2014; Griffin, 2004; Langford & Koppel, 2006; Mayhew, Simpson, & Ferguson, 2006; Preusser et al., 1998). During darker light conditions or adverse weather conditions, older drivers were less likely to have severe injury in given car crashes (Awadzi et al., 2008; Baker et al., 2003; Wang & Kockleman, 2005). Thus, the following hypothesis reflects how environmental elements are associated with injury severity in given car crashes.

Hypothesis 3

1) *Drivers will have a higher likelihood of severe injury outcomes in given car crashes at the intersection roads.*
2) *Drivers will have a lower likelihood of severe injury outcomes in given car crashes on dark light conditions.*
3) *Drivers will have a lower likelihood of severe injury outcomes in given car crashes on adverse weather conditions.*

Question 4

How are driver licensing policies (e.g. license renewal procedure, restricted licensing, and medical reporting for at-risk drivers) associated with the injury severity in given car crashes?

Mandatory vision tests may be a plausible means of mandating driving cessation or making a referral for appropriate medical care for improving visual functions among people with impaired visual functions. Also, the in-person renewal policy may be linked so that license examiners observe potentially impaired drivers during the license renewal procedure (Morrisey & Grabowski, 2005). These policies have beneficial impacts on reducing car crashes involving impaired drivers. Previous studies found that older people who were required to renew their license in-person and were subjected to a vision test have a lower probability of car crashes resulting in severe injury or fatality (Classen et al., 2007; Grabowski et al., 2004; Levy, 1995; McGwin et al., 2008).

Hypothesis 4

1) *Drivers who hold licenses from states with in-person renewal policy will have less severe injury outcomes in given car crashes, compared to states that do not.*
2) *Drivers who hold licenses from states that require mandatory medical reporting for at-risk drivers will have less severe injury outcomes in given car crashes, compared to states that do not.*

Question 5

How is injury severity in car crashes involving at least one fatality to either a driver or another individual is distributed spatially?

Previous studies have revealed a consistent finding that severe injury in car crashes were more likely to occur in rural areas than urban areas (Brown, Khanna, & Hunt, 2000; Clark, 2001; Finison & Dubrow, 2002; Zwerling, 2005). By using the GIS application, it was shown that the majority of fatal injuries in car crashes occurred in rural areas within 5 miles of the urban boundary (Subramanian, 2009).

Hypothesis 5

Among drivers age 65 and older, fatal injury in car crashes involving at least one fatality to either a driver or another individual will be densely distributed within rural area.

CHAPTER 5

METHODOLOGY

This chapter begins with descriptions of two different sources of crash data. Also, additional data regarding state driver's license policy and GIS shape files, which are required for mapping, are specified. Next, it summarizes how to create an analytical file and clarifies the criteria of samples selection for this dissertation. Then, it determines measurements for dependent and independent variables and presents analytical strategy for this dissertation. Lastly, it describes the human subjects' protections.

Data Sources

With respect to variables related with car crashes and injury severities, this dissertation will use the most available three recent years of GES and FARS data during 2010 to 2012. The NHTSA administers annual crash data of GES and FARS. These data are available at the NHTSA's website: http://www.nhtsa.gov/NCSA.

On one hand, the GES is a nationally representative probability sample of police reported motor vehicle crashes. In order to be included in the GES sample, a police crash report must be completed to collect data for involving at least one motor vehicle traveling on a traffic road. Based on the geography, roadway mileage, population, and traffic density in the United States, the GES collects approximately 50,000 from of random

sample annually from 400 police jurisdictions across the United States. The GES data requires a weighting process and supplies the weighting factor in order to estimate nationwide crashes.

The FARS is a national database about traffic crashes on public roads within the 50 states, the District of Columbia, and Puerto Rico. The FARS is annual data on traffic crashes resulting in at least one fatality occurring within 30 days after the crash. The FARS is a census database of all fatal car crashes in the United States reflecting annual national totals of fatal crashes. The FARS has collected annual data since 1975.

Both the GES and the FARS contain detailed information about road users, vehicle, and crash situations. Both data sets consist of three main files including a crash file, a vehicle file, and a person file. The crash file includes information about each crash situations (e.g. road types, weather conditions, light conditions, time of day, etc.) about each involved crash. The vehicle file has information (e.g. vehicle types, vehicle makers, vehicle weight, driver's zip code, etc.) about all involved vehicles in each crash. The person file contains information about all persons (e.g. age, gender, physical information, drivers as well passengers, pedestrians, injury severity of each person, etc.) who were involved in each crash.

The GES and the FARS are structurally analogous to each other. All the same, there was some difference in data elements between the GES and the FARS. The GES provides the only regional geographic information (e.g. northeast, mid-west, south, and west), whereas the FARS provides more specific geographical information (e.g. state, county, city, latitude, and longitude) of each fatal car crash. This contrast of geographic

information between two data sets illustrates why the FARS is useful to incorporate with GIS application for this dissertation in order to answer research question five. Given the latitude and longitude of events from the FARS data, it allows drawing on the locations of car crashes on the map.

In terms of policy factors of states' license renewal regulations, each state has different license regulations or procedures. In order to get license renewal regulation policy, this dissertation will look at each state website of the Department of Motor Vehicle (DMV), the Insurance Institute for Highway Safety (IIHS), and the American Automobile Association (AAA) Foundation for Traffic Safety database of state laws.

Finally, with respect to the GIS application, this dissertation needs shape files to display roadways, state boundary, and urban/rural boundary. The US Census provides Topologically Integrated Geographic Encoding and Referencing (TIGER/LINE) describing those land attribution of shape files. This dissertation will look at the US Census 2010 to get TIGER/LINE of shape files. It is available at website: https://www.census.gov/geo/maps-data/data/tiger.html. Also, this dissertation will look at the office of Geographic Information to get necessary shape files for the state of Massachusetts (MASS GIS). The MASS GIS website is available at http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/.

Analytical File

As noted above, the crash data of GES and FARS are available to download from the NHTSA website. First, the 2010 year of GES data which is consisted of crash, vehicle, and person files was downloaded. These files contain common variables of crash number, vehicle number, and person number. By using common variables, the STATA 14 merged three files into one complete file of 2010 GES data. The procedure was repeated for the 2011 and 2012 GES data. Finally, the three years of GES data were pooled into one analytical file. The structure of the FARS data is in accord with the GES data. Each year of the FARS data were also pooled into one complete file by following same procedure as the GSA data. However, in order to answer question 5, the FARS data kept car crashes that occurred in Massachusetts only.

Sample Selection

This dissertation focuses on subjects from the 2010 to 2012 of the GES and the FARS. The unit of analysis in this dissertation is a driver who involved in car crash. Thus, the study sample will be restricted to drivers of passenger automobiles (e.g. sedan, mini-van, sport utility vehicle, and pick-up trucks). Pedestrians, passengers, bicyclists, and motorcyclists are excluded. Also, drivers who were driving buses, large trucks, or farming related vehicles are excluded. Finally, the study sample included older drivers age 65 and older and middle-aged drivers age 35 to 59 (reference group).

Although the FARS provides car crash data involving a fatality for all 50 states and Puerto Rico, this dissertation will select only those crashes that occurred in the state of Massachusetts during 2010 to 2012.

Measurements

Dependent variable

Both the GES and the FARS data provide a categorized level of injury severity for vehicle occupants, pedestrians, bike riders, or others who were involved in car crashes by classifying fatal injury (K), incapacitating injury (A), non-incapacitating evident injury (B), possible injury (C), and no injury (O). This KABCO scale represents the degree of injury severity sustained in car crashes. The KABCO scale of injury severity has been used in many transportations related studies. Therefore, the dependent variable in this dissertation is a driver's injury severity measured by KABCO scale at given car crashes.

Independent variables

This dissertation is focused on how individual, vehicle, environment, and policy factors influence injury severity in car crashes. Table 3 presents the list of independent variables for the regression model from GES crash data in this dissertation.

Individual: This dissertation is focused on the driver related factors in regard to individual aspects. **Age** was a continuous value in original datasets. In this dissertation, the driver's age was created by categorical dummy variables resulting in middle aged group (age 35 to 59) serving as a reference group and older age groups (age 65 to 74, age 75 to 84, & age 85 and older). **Gender** was a dichotomous variable coded by 0 for the female driver and 1 for the male driver. **Driver's conditions** were created by the categorical dummy variables consisting of normal conditions (reference group), physically or mentally impaired, asleep, and driving under the influence (DUI). **Number**

of passengers was the dichotomous variable coded by 0 for the only driver in the vehicle and 1 for the driver and at least one or more passengers in the vehicle.

Vehicle: This dissertation was focused on the passenger's cars excluding heavy trucks, bus, and machinery vehicles. **Body types of vehicles** was created by the categorical dummy variables consisting of sedan, mini-van, Sports Utility Vehicle (SUV), and pick-up truck (reference group). The crash data had a significant amount of missing cases for seat belt use and airbag deployment. Instead of excluding those missing cases, this dissertation created missing indicators for seat belt use and airbag deployment. **Seat belt** was created by the categorical dummy variables consisting of none, seat belt use, and missing of seat belt. Also, **airbag deployed** was created by the categorical dummy variables consisting of none, deployed, and missing for airbag. The user guide of the GES and FARS described the vehicles' initial contact points resulting in injury to non-motorists or any occupants in the vehicles. Given this description, **point of collision** was created by the categorical dummy variable consisting of front impact, rear impact, left-side impact, right-side impact, and others (under ride or roll over). Lastly, the GES data provided total numbers of vehicle involved in crash. **Number of vehicles** was created by the categorical dummy variable consisting of one vehicle, two vehicles, three vehicles or more vehicles.

Environment: It attributed the locations and conditions under where/when crashes occurred. **Intersection** was created by the categorical dummy variables including no intersection roads, intersection roads (Four way, T type, or Y type), and other intersection roads (traffic circle, roundabout, drive way, etc.). **Highway** was created by

the dichotomous variable coded by 0 for none highway related and 1 for highway related. The GES recorded land use by specifying population of area where car crashes occurred. **Area** was created by the categorical dummy variables consisting of small city (population between 25,000 to 50,000), mid-city (population between 50,001 to 100,000), large city (population 100,001 and more), and other city (unspecified number of population). **Time of crash** was recorded by the categorical dummy variables consisting of morning (6am to 11:59pm), afternoon (noon to 5:59pm), evening (6pm to 11:59pm), and night (midnight to 5:59am). **Month of crash** was created by the categorical dummy variables regarding as spring (March, April, & May), summer (June, July, & August), Fall (September, October, & November), and winter (December, January, & February). **Weather conditions** was created by the categorical dummy variables including clear, rain, snow, and other weather conditions (fog, smoke, windy, hail, blowing dirt, etc.).

Policy: The GES data did not provide state information for its participants. However, a driver's zip code was available in the data. By using the driver's zip code, state information was identified. Each state mandates different age requirements for driving license renewal policy (See Table 1). Therefore, the licensing policy variables were created by incorporating both state information and the driver's age. **In-person renewal** was created by the dichotomous variable coded by 0 for none and 1 for state required drivers of a certain age to renew their license in-person at every renewal. **Accelerated renewal cycle** was created by the dichotomous variable coded by 0 for none and 1 for state required drivers of a certain age and at every renewal. **Vision test** was created by the dichotomous variable coded by 0 for none and 1 for state required drivers

of a certain age and at every renewal. **Written or road test** was created by the dichotomous variable coded by 0 for none and 1 for state required drivers a certain age and at every renewal. Lastly, **medical reporting for at risk driver** was created by the dichotomous variable coded by 0 for none and 1 for state required for physicians mandatory medical reporting for at risk drivers.

The mandated age for in-person renewal varied by state. As a result, drivers age 70 and older from California were assigned 1 for in-person renewal, whereas drivers younger than 70 years from California were assigned 0. However, there was no age requirement for in-person renewal in the state of Arkansas. So, all drivers in Arkansas were assigned 1 for the in-person renewal. Regarding the accelerated renewal cycle, there were 20 states which required that drivers of certain ages must renew their license more frequently. For example, drivers age 65 and older from Connecticut were assigned 1 for the accelerated renewal cycle, whereas drivers younger than 65 years from Connecticut were assigned 0. Any drivers from a state that did not implement the accelerated renewal cycle was coded 0 all assigned for 0. Coding was similar for policy variables regarding vision and written/road test. For example, drivers from states that were required to submit to the policy were coded as 1, drivers that did not were coded as 0.

Six states (California, Delaware, Nevada, New Jersey, Oregon, & Pennsylvania) mandated physician reporting regardless of a driver's age. All drivers from these states were coded as 1. However, in District of Columbia (DC), mandatory physician reporting is required for drivers age 70 and older. Thus, drivers age 70 and older from DC were assigned 1 for the mandatory physician reporting and drivers younger than 70 years from

DC were assigned 0. Table 1 presents the specific age requirements for each state's renewal policy.

Finally, **latitude and longitude** pertinent to the GIS analysis was collected from the FARS data. Both of them were necessary to create the point of car crash on the map. However, latitude and longitude within a boundary of Massachusetts were only selected and missing values of latitude and longitude were excluded.

Table 3. The List of Independent Variables

Variables	Description of the Variables	Expected Sign
Individual		
Age groups		
Age 35 to 59	If driver’s age was 35 to 59 =1, otherwise=0	Reference
Age 65 to 74	If driver’s age was 65 to 74 =1, otherwise=0	+
Age 75 to 84	If driver’s age was 75 to 84 =1, otherwise=0	+
Age 85 and older	If driver’s age was 85 and older =1, otherwise=0	+
Gender		
Female	If driver was female=1, male=0	+
Drivers’ conditions		
Normal	If driver was normal status=1, otherwise=0	Reference
Impaired	If driver was physically/mentally impaired=1, otherwise=0	+
Asleep	If driver was asleep, otherwise=0	+
Driving Under Influence (DUI)	If driver was DUI status, otherwise=0	+
Having passengers	If driving with at least one passenger=1, otherwise=0	+
Vehicle		
Safety restraints		
No seat belt	If driver without seat belt=1, otherwise=0	Reference
Seat belt use	If driver used seat belt=1, otherwise=0	-
Missing seat belt	If missing seat belt=1, otherwise=0	
Non-deployed airbag	If airbag not deployed=1, otherwise=0	Reference
Deployed airbag	If airbag deployed=1, otherwise=0	-
Missing airbag	If missing airbag=1, otherwise=0	
Body Types		
Sedan	If drove sedan=1, otherwise=0	+
Mini-van	If drove mini-van=1, otherwise=0	+
Sport utility vehicle (SUV)	If drove sport utility vehicle=1, otherwise=0	+
Pick-up truck	If drove pick-up truck=1, otherwise=0	Reference
Point of collision		
Front	If vehicle impacted on front=1, otherwise=0	+
Rear	If vehicle impacted on rear=1, otherwise=0	Reference
Right side	If vehicle impacted on right-side=1, otherwise=0	-
Left side	If vehicle impacted on left-side (driver)=1, otherwise=0	+
Other collisions	If vehicle impacted on other=1, otherwise=0	+
Number of vehicles		
One vehicle	If one vehicle involved=1, otherwise=0	Reference
Two vehicles	If two vehicles involved=1, otherwise=0	+
Three+ vehicles	If three or more vehicles involved=1, otherwise=0	+

Table 3 (Continued)

Table 3. The List of Independent Variables (Continued)

Variables	Description of the Variables	Expected Sign
Environment		
Intersection roads		
No, intersection	If crash on non-intersection related roads=1, otherwise=0	Reference
Yes, intersection	If crash on intersection related roads=1, otherwise=0	+
Other types	If crash on other types of roads=1, otherwise=0	-
Highway roads	If crash on highway roads=1, otherwise=0	+
Crash area of population		
Small city	If crash on area within population 25,000-50,000=1, otherwise=0	-
Mid-city	If crash on area within population 50,001-100,000=1, otherwise=0	Reference
Large city	If crash on area within population >100,000=1, otherwise=0	-
Other city	If crash on area within population unspecified=1, otherwise=0	-
Time of the day		
Morning (06:00-11:59)	If crash occurred at this time=1, otherwise=0	Reference
Afternoon (12:00-17:59)	If crash occurred at this time=1, otherwise=0	-
Evening (18:00-23:59)	If crash occurred at this time=1, otherwise=0	-
Night (00:00-05:59)	If crash occurred at this time=1, otherwise=0	-
Month of crash		
Spring	If crash occurred in March/April//May=1, otherwise=0	Reference
Summer	If crash occurred in June/July/Aug=1, otherwise=0	+
Fall	If crash occurred in September/October/November=1, otherwise=0	+
Winter	If crash occurred in December/January/February=1, otherwise=0	-
Weather conditions		
Clear weather	If crash on clear weather=1, otherwise=0	Reference
Rain	If crash on raining weather=1, otherwise=0	-
Snow	If crash on snowing weather=1, otherwise=0	-
Other weather	If crash on other weather=1, otherwise=0	-
Policy		
In-personal renewal	If driver from state required at every renewal=1, otherwise=0	-
Accelerated renewal cycle	If driver from state required at every renewal=1, otherwise=0	-
Vision test for renewal	If driver from state required at every renewal=1, otherwise=0	-
Written/Road test for renewal	If driver from state required at every renewal=1, otherwise=0	-
Medical reporting for at risk driver	If driver from state required for physician’s medical report=1, otherwise=0	-

Analytic Strategy

This dissertation examines three years of pooled GES and FARS car crash data. This dissertation is based on multivariate analyses that explore the impact of a specific risk factor on driver's injury severity resulting from car crashes. The unit of analysis is a driver who is involved in a car crash between 2010 to 2012 on roadways in Unites States. The outcome variable is a categorized ordered event of drivers' injury severity from car crashes. The ordinal logit (OL) model is an appropriate method of analysis in this dissertation when the outcome variable is ordered. The OL is estimated to determine the relationships between risk factors and injury severity resulting from car crashes. By performing the OL, the odds ratio is calculated to examine the likelihood of injury severity in car crashes.

However, the OL model must satisfy an assumption about the "proportional odds" (also known as parallel line). It assumes that the coefficient of an independent variable is associated with the same marginal effect on the dependent variable from any lower status category to all other higher status outcome categories. For example, it supposes that there is an ordinal outcome measure after a crash with three categories (e.g. no injury, injury, & fatality) and the factor of interest variable such as 'adverse weather'. The proportional odds assumption requires that the increase in the odds of being injured or experiencing fatality from a crash over having no injury is the same as the increase in the odds of fatality over being injured or having no injury (Borooah, 2002).

The STATA 14 performs a pass/fail test of the proportional odds. If the test of proportional odds is failed, this dissertation uses the multinomial logistic (MNL) model with same measurements. When the dependent variable is attributed as nominal category rather than ordinal status, the MNL model is appropriate. This MNL model is not required to test the proportional odds. By performing the MNL, the relative risk ratio is calculated to examine the likelihood of injury severity in car crashes.

Furthermore, the FARS data provides spatial information of crash locations identified by longitude (X) and latitude (Y). The GIS application is a useful tool to transfer spatial information of crash locations on the map. This dissertation utilized the ARCMAP version 10.4 as the GIS application. Figure 6 presented the process for which the spatial analysis was completed for this dissertation. First, given the FARS crash data from 2010 to 2012, crashes occurring only in MA were selected. Information for these drivers regarding injury severity, age, longitude and latitude variables were added into an excel spread sheet.

Second, the GIS application performed the geocoding process to draw the crash locations on the map. There were two common ways to run the geocoding process. The first was by the address geocoding if the exact address of the crash is available. The second was the XY geocoding if longitude and latitude of the crash are available. Since the longitude and latitude were given in the FARS, the XY geocoding was performed. After preforming the geocoding process, the shape file of crash was created.

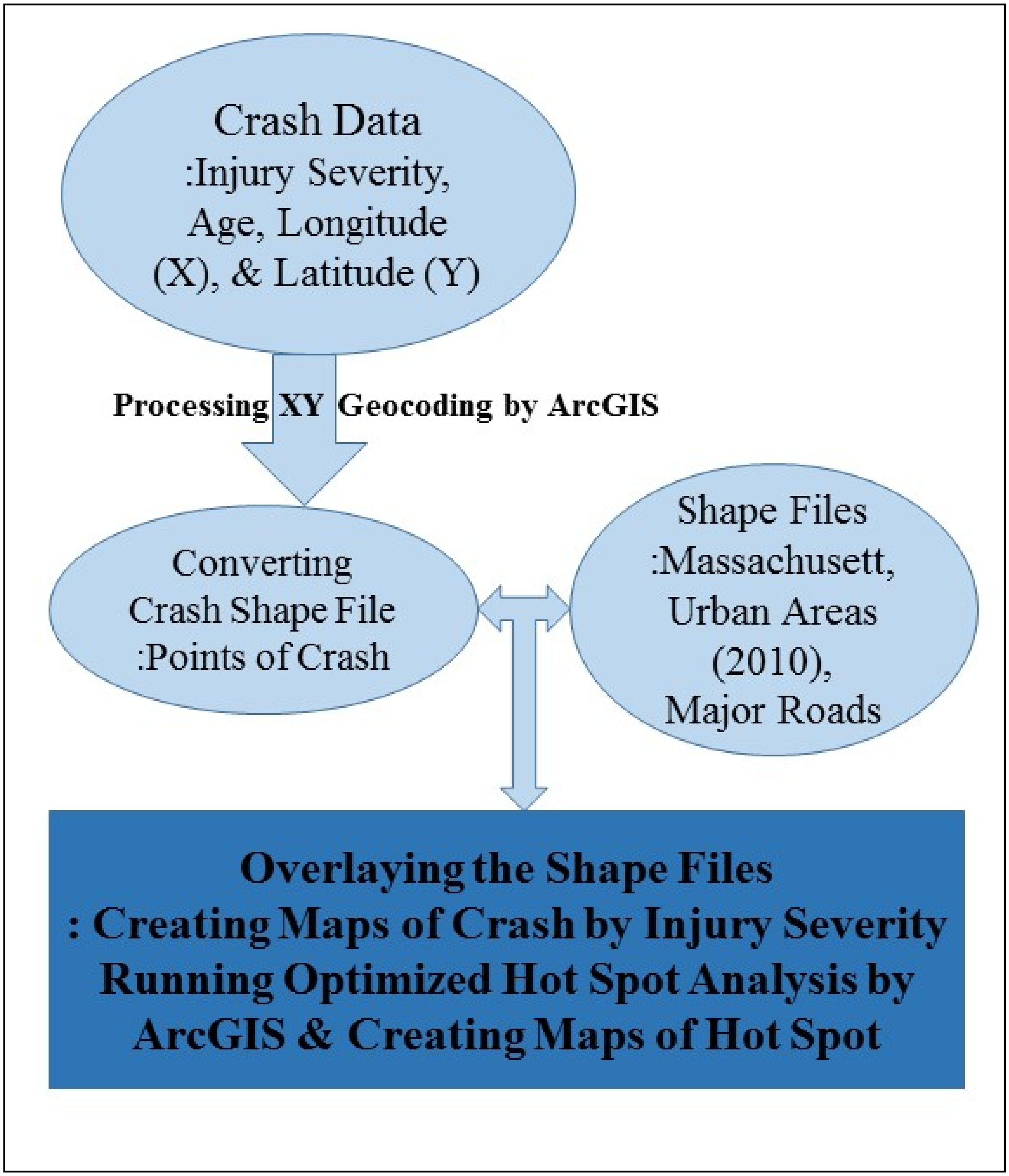
Third, the GIS needed to prepare the study area of shape files including MA state boundary, roads, and urban area of 2010 in MA. Fourth, all the shape files were

overplayed to create one complete map showing points of crashes, urban boundaries, roads, and MA boundaries. Fifth, the GIS application performed the Optimized Hot Spot analysis providing three different functions: 1) aggregating incidents or points in grid ma; 2) aggregating incidents or points in defined areas such as Census block, town, or county; 3) collapsing coincident or nearest neighbor points together to define the hot spot of cluster. This dissertation utilized the third function of the Optimized Hot Spot analysis.

Human Subjects Review

This dissertation uses secondary data, which is available to the public. The NHTSA, administers both the GES and FARS data; the data do not contain any personal identification information and those data are made available to other researchers (e.g. government agencies, universities, institutions, industries, and the general public. Also, this dissertation was submitted to review by the Institutional Review Board from the University of Massachusetts Boston. This dissertation was received exempt status (study #2015101).

Figure 6. Work Flows of Spatial Analysis



CHAPTER 6

RESULTS

Regression

This chapter presents findings from analysis of GES and FARS crash data. Exploration of GES data describes descriptive statistics and results from bivariate and multivariate analyses of a nationally representative sample. It also provides tables and figures with respect to results of relative analyses. By analyzing the FARS data, it presents descriptive statistics and spatial analysis which depicts hot spots of crash locations in the state of Massachusetts. Finally, a sensitivity analysis for this dissertation will be covered in last section of this chapter.

Descriptive Statistics

The sample of this dissertation was described in Table 4 containing the dependent variable and all independent variables used for this dissertation. The description of sample mean and standard deviation for injury severity and covariates is displayed by the driver's age groups in Table 4. After sampling restriction by age and vehicle body types, there were 114,440 drivers without missing data on the dependent variable about injury severity in GES crash data from 2010 to 2012. However, additional 7, 809 (about 6.8%) drivers in GES with missing data on one or more independent variables were dropped.

Thus, the final sample of 106,631 drivers had complete data from GES crash data. Sample means of all variables between the retained 106,631 drivers and the dropped 7,809 drivers were compared. Chi-square tests of those comparison suggested that all the variables except for the 'having passenger' had statistically significant difference between the retained samples and the dropped samples, yet its difference was about +/- 10%. Thus, the dropped sample was less likely to be biased because the overall percentage was low. The results of those comparisons are presented in Table A1 on appendix.

Overall, the majority of respondents (80.9%, n=86,220) was drivers age 35 to59, and followed by drivers age 65 to 74 (11.4%, n=12,209), drivers age 75 to 84 (5.9%, n=6,325), and drivers age 85 and older (1.8%, n=1,877) in a crash. With respect to the dependent variable of injury severity at given crashes, most drivers had no injury (67.8%) compared to possible injury (14.3%), non-incapacitating evident injury (11.1%), incapacitating injury (6.1%), and fatal injury (0.7%). The frequency of injury severity showed a similar distribution indicating a decline rate for severe injury in a crash across the drivers' age groups. Notably, driver's age 85 and older had twice the percentage of fatal injury (2.1% vs about 1%) as well as a greater percentage of the incapacitating injury (8.2% vs about 6%, respectively) and the non-incapacitating evident injury (14.1% vs about 12%, respectively). There were more male drivers (55.2%) than female drivers (44.8%) in a crash. The majority (93.1%) of drivers had no physically or mentally impairing conditions, whereas 3.1% of drivers did drive with these conditions. Drivers age 85 and older had a relatively greater percentage of impaired conditions (5.9%) and a

relatively lower percentage of DUI conditions (0.4%) compared to other age groups of drivers. The majority (75%) of drivers did not have any passengers in the vehicle when occurring crash.

Next, with the vehicle related factors, it showed that the majority (92.8%) of drivers involved in a crash were using a seat belt. Further, approximately 70% of drivers were involved in a crash in which the airbag of their vehicles was not deployed. Four vehicle body types were selected from the GES crash data. Most drivers (55.1%) involved in a crash were driving a sedan type car followed by drivers of SUVs (20.4%), pick-up trucks (16%), and mini-vans (8.6%). Given these vehicle types and age groups of drivers, the data suggests that drivers age 75 to 84 and drivers age 85 and older were more likely to be involved in crashes with the sedan type of vehicles (70.8%, 81.5%, respectively) compared to other types. Most drivers had a frontal collision (49.3%) or rear collision (26.3%) when involved in a crash. The distribution of collision sides on the vehicles were similar among age groups of drivers. The majority (85.2%) of drivers were involved in a crash with more than one vehicles.

In regards to environmental factors at given crashes, approximately 50% of drivers were involved in a crash at the intersection roads. Given this high frequency of intersection related crashes, it was not surprise to find that the majority (88.8%) of drivers were involved in crash on the non-highway roads. By comparing age groups, the data showed that drivers age 35 to 59 had the highest percentage (12.3%) of crashes on the highway, whereas drivers age 85 and older had the lowest percentage (3.1%) of crashes on the highway. Additionally, most drivers exhibited a relatively higher frequency of

crash involvement in areas with higher populations (over 100,000 population). In terms of time and weather conditions, most drivers were involved in crashes during the day time, between 12pm and 5pm (46.5%) and in relatively favorable (clear) weather conditions (73.2%). In fact, only 1% of drivers in age groups 75 to 84 and 85 and older were involved in a crash between 12am and 5 am or during adverse weather conditions (rain, snow). With respect to drivers involved in crashes in particular months, that data suggested that crashes are equally distributed throughout the months of spring, summer, fall and winter.

Finally, driving license renewal polices varied by state. About 25% of drivers were from states that required a vision test during the license renewal process and about 19% of drivers were from states that enforced the in-person renewal policy. Fewer drivers (4%) were from states that implemented the accelerated renewal cycle policy and about 1% of drivers were from states that required the on-road or written test during the license renewal process. These fewer numbers are due in part to the observation that no drivers age 35 to 59 were from states that implemented accelerated, on-road, or written tests. Drivers age 75 and older were more consistently representative of the variety of driving license renewal policies.

Table 4. Descriptive Statistics of the Study Sample from the GES (2010-2012)

Variables	Total (n=106,631)		Age 35-59 (n=86,220)		Age 65-74 (n=12,209)		Age 75-84 (n=6,325)		Age 85+ (n=1,877)	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Dependent variable										
Injury severity										
Fatal injury (K)	0.70%	0.08	0.60%	0.08	1.00%	0.10	1.20%	0.11	2.10%	0.14
Incapacitating (A)	6.10%	0.24	6.00%	0.24	6.10%	0.24	6.70%	0.25	8.20%	0.27
Non-incapacitating (B)	11.10%	0.31	10.80%	0.31	11.50%	0.32	12.70%	0.33	14.10%	0.35
Possible injury (C)	14.30%	0.35	14.40%	0.35	13.90%	0.35	13.90%	0.35	13.40%	0.34
No injury (O)	67.80%	0.47	68.20%	0.47	67.60%	0.47	65.60%	0.48	62.20%	0.48
Independent variables										
Individual										
Age groups										
Age 35 to 59	80.90%	0.39								
Age 65 to 74	11.40%	0.32								
Age 75 to 84	5.90%	0.24								
Age 85 and older	1.80%	0.13								
Gender: Female	44.80%	0.50	45.10%	0.50	43.20%	0.50	44.40%	0.50	43.50%	0.50
Drivers' conditions										
Normal	93.10%	0.25	92.90%	0.26	94.10%	0.24	93.50%	0.25	92.80%	0.26
Impaired	3.10%	0.17	2.80%	0.16	3.80%	0.19	4.90%	0.22	5.90%	0.24
Asleep	0.80%	0.09	0.70%	0.08	0.90%	0.09	1.00%	0.10	0.90%	0.09
DUI	3.10%	0.17	3.60%	0.19	1.20%	0.11	0.60%	0.08	0.40%	0.07
Having passengers	25.00%	0.43	25.40%	0.44	23.80%	0.43	23.60%	0.42	19.30%	0.40
Vehicle										
Safety restraints										
No seat belt	2.20%	0.15	2.30%	0.15	1.90%	0.14	1.50%	0.12	2.10%	0.14
Seat belt use	92.80%	0.26	92.60%	0.26	93.40%	0.25	94.30%	0.23	92.40%	0.26
Missing seat belt	5.00%	0.22	5.00%	0.22	4.70%	0.21	4.10%	0.20	5.40%	0.23
Non-deployed airbag	70.30%	0.46	70.90%	0.45	69.10%	0.46	66.20%	0.47	64.70%	0.48
Deployed airbag	17.20%	0.38	16.90%	0.37	17.00%	0.38	19.70%	0.4	23.50%	0.42
Missing airbag	12.50%	0.33	12.20%	0.33	13.90%	0.35	14.10%	0.35	11.80%	0.32
Body Types										
Sedan	55.10%	0.50	52.70%	0.50	59.60%	0.49	70.80%	0.45	81.50%	0.39
Mini-van	8.60%	0.28	8.90%	0.28	7.80%	0.27	7.10%	0.26	5.00%	0.22
SUV	20.40%	0.40	21.60%	0.41	18.00%	0.38	11.90%	0.32	6.50%	0.25
Pick-up truck	16.00%	0.37	16.80%	0.37	14.60%	0.35	10.10%	0.30	7.00%	0.26
Point of collision										
Front	49.30%	0.50	48.70%	0.50	48.90%	0.50	53.90%	0.50	59.60%	0.49
Rear	26.30%	0.44	27.50%	0.45	24.40%	0.43	17.50%	0.38	11.50%	0.32
Right side	11.10%	0.31	10.50%	0.31	12.90%	0.34	14.60%	0.35	14.00%	0.35
Left side	11.80%	0.32	11.60%	0.32	12.40%	0.33	12.70%	0.33	14.00%	0.35
Other collisions	1.60%	0.13	1.70%	0.13	1.40%	0.12	1.20%	0.11	1.10%	0.10
Number of vehicles										
One vehicle	14.80%	0.36	14.90%	0.36	14.70%	0.35	14.20%	0.35	15.50%	0.36
Two vehicles	67.00%	0.47	66.30%	0.47	68.80%	0.46	71.50%	0.45	72.30%	0.45
Three+ vehicles	18.20%	0.39	18.80%	0.39	16.50%	0.37	14.40%	0.35	12.20%	0.33

(Table 4 Continued)

Table 4. Descriptive Statistics of the Study Sample from the GES (2010-2012) (Continued)

Variables	**Total (n=106,631)**		**Age 35-59 (n=86,220)**		**Age 65-74 (n=12,209)**		**Age 75-84 (n=6,325)**		**Age 85+ (n=1,877)**	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Environment										
Intersection roads										
No, intersection	38.00%	0.49	39.60%	0.49	34.00%	0.47	28.30%	0.45	25.40%	0.44
Yes, intersection	49.90%	0.50	48.60%	0.50	53.40%	0.50	57.90%	0.49	59.10%	0.49
Other types	12.10%	0.33	11.80%	0.32	12.60%	0.33	13.80%	0.34	15.60%	0.36
Highway roads	11.20%	0.32	12.30%	0.33	8.20%	0.27	5.30%	0.22	3.10%	0.17
Crash area of population										
Small city	17.60%	0.38	17.10%	0.38	18.90%	0.39	20.50%	0.40	22.20%	0.42
Mid-city	8.90%	0.28	8.80%	0.28	9.00%	0.29	9.80%	0.30	10.40%	0.31
Large city	41.00%	0.49	41.80%	0.49	38.00%	0.49	37.80%	0.48	34.90%	0.48
Other city	32.50%	0.47	32.30%	0.47	34.10%	0.47	31.90%	0.47	32.60%	0.47
Time of the day										
Morning (06:00-11:59)	29.30%	0.46	28.80%	0.45	30.60%	0.46	33.10%	0.47	33.50%	0.47
Afternoon (12:00-17:59)	46.50%	0.50	45.10%	0.50	51.30%	0.50	53.00%	0.50	55.10%	0.50
Evening (18:00-23:59)	19.20%	0.39	20.40%	0.40	15.80%	0.37	12.60%	0.33	10.00%	0.30
Night (00:00-05:59)	5.00%	0.22	5.70%	0.23	2.20%	0.15	1.30%	0.11	1.40%	0.12
Month of crash										
Spring	24.30%	0.43	24.30%	0.43	24.10%	0.43	24.70%	0.43	23.10%	0.42
Summer	24.30%	0.43	24.20%	0.43	24.50%	0.43	23.70%	0.43	25.00%	0.43
Fall	26.00%	0.44	25.90%	0.44	26.30%	0.44	26.40%	0.44	27.70%	0.45
Winter	25.40%	0.44	25.50%	0.44	25.10%	0.43	25.20%	0.43	24.20%	0.43
Weather conditions										
Clear weather	73.20%	0.44	72.70%	0.45	74.40%	0.44	76.70%	0.42	76.70%	0.42
Rain	8.90%	0.29	9.30%	0.29	7.80%	0.27	6.90%	0.25	6.70%	0.25
Snow	2.40%	0.15	2.50%	0.16	2.00%	0.14	1.40%	0.12	0.90%	0.09
Other weather	15.50%	0.36	15.50%	0.36	15.80%	0.36	15.00%	0.36	15.80%	0.37
Policy										
In-personal renewal	19.40%	0.40	16.70%	0.37	22.20%	0.42	43.00%	0.50	46.60%	0.50
Accelerated renewal cycle	3.80%	0.19	0.00%	0.00	13.10%	0.34	26.70%	0.44	40.60%	0.49
Vision test for renewal	25.20%	0.43	21.10%	0.41	30.90%	0.46	56.70%	0.50	68.40%	0.47
Written/Road test for rene wal	0.90%	0.09	0.00%	0.00	1.90%	0.14	8.80%	0.28	7.90%	0.27
Medical reporting for at risk Driver	11.50%	0.32	11.50%	0.32	11.50%	0.32	12.30%	0.33	12.80%	0.33

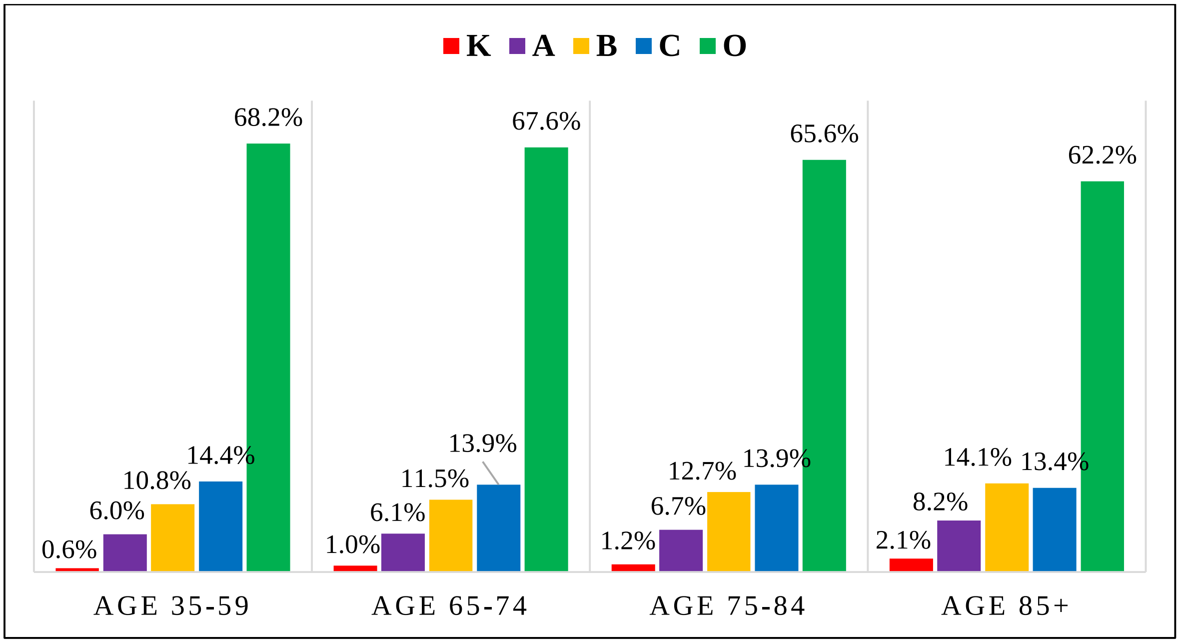
Bivariate Analysis

This section provides an exploration and description of this association between injury severity and independent variables by performing bivariate analysis. The Pearson's chi-square test is used to determine the likelihood of observed relationships between injury severity and exploratory variables occurring by chance (0.05 significant level).

As seen below, Figure 7 through Figure 10 depicts the prevalence of injury severity by individual driver factors. Overall, the chi-square tests suggested that there were significant relationships between injury severity and individual driver factors. The study crash data showed that each driver's age group exhibited a relatively higher frequency of the no injury than other injury types. Notably, drivers' age 85 and older had about 2% of the fatal injury, whereas other age groups of drivers had about 1% of the fatal injury in a crash (see Figure 7). Male drivers compared to female drivers had a greater proportion of the fatal injury (0.9% vs 0.5%) and the no injury (71.6% vs 63.2%) in a crash. In contrast to male drivers, female drivers had greater proportions of the incapacitating, non-incapacitating evident, and possible injuries in a crash (see Figure 8).

With respect to drivers' conditions, drivers with normal conditions peaked in the no injury (69.8%) and had a very low frequency of the fatal injury (0.4%) in a crash. Overall, drivers with normal conditions compared to drivers with other conditions (e.g. impaired, asleep, & DUI) had lower frequencies of the incapacitating, non-incapacitating evident, and possible injury in a crash. However, physically or mentally impaired drivers had relatively higher frequencies of the fatal injury (9.6%) and incapacitating injury (20.4%) compared to other groups of drivers' conditions in a crash (see Figure 9).

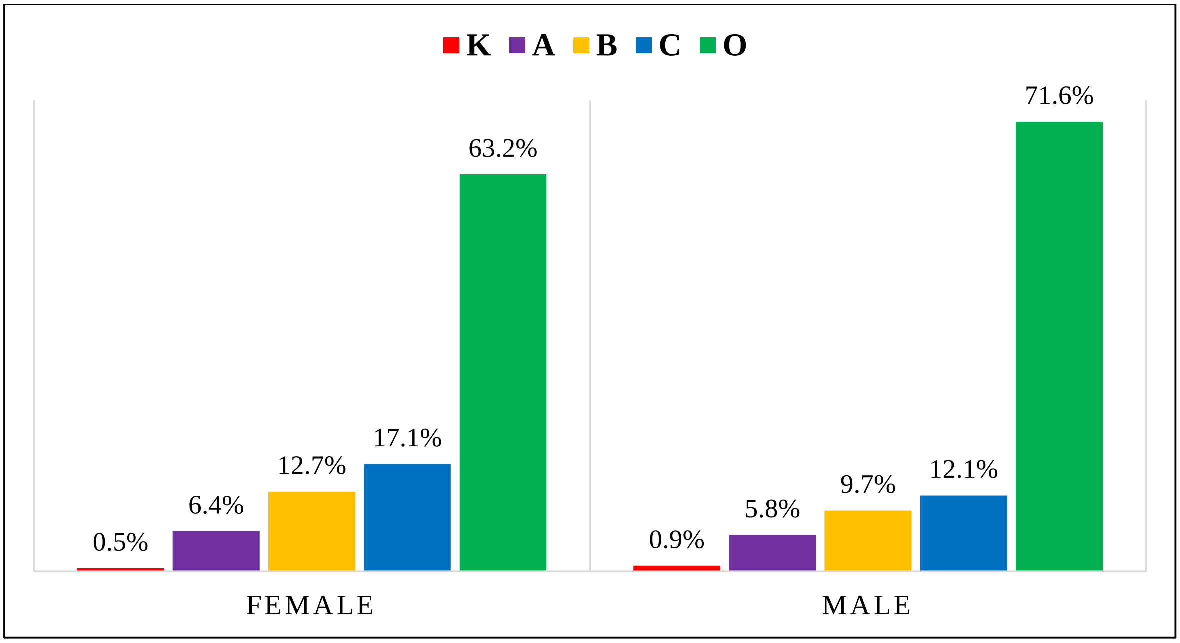
Figure 7. Prevalence of Injury Severity by Drivers' Age Groups from GES



chi-square (df=12, 175.58), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

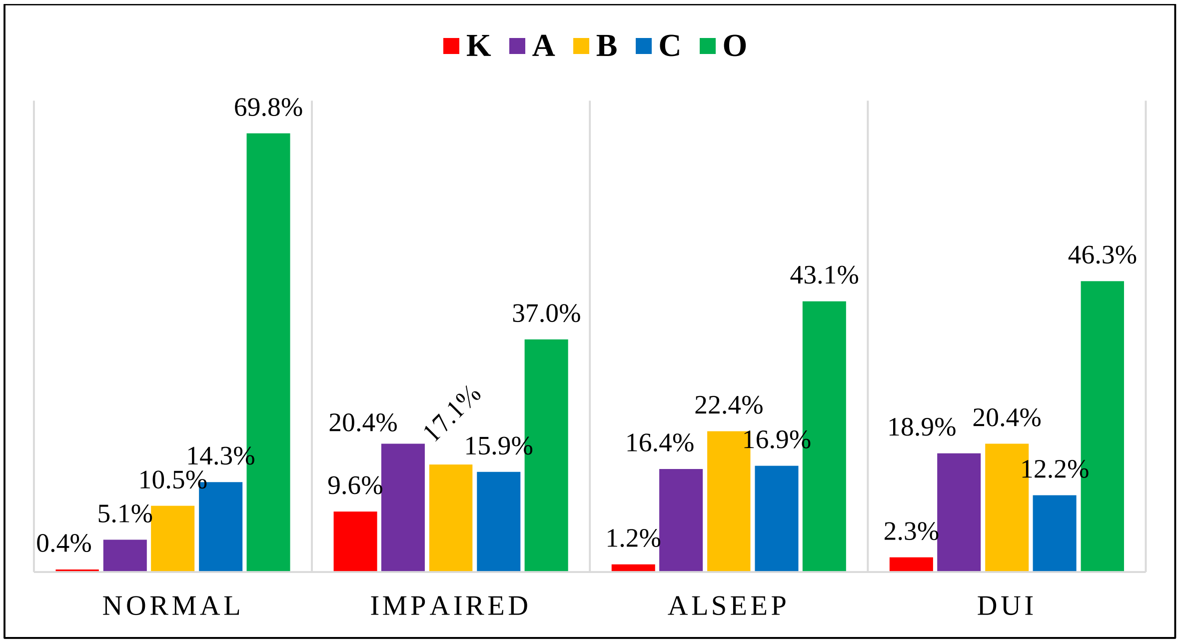
Figure 8. Prevalence of Injury Severity by Drivers' Gender from GES



chi-square (df=4, 1002.88), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

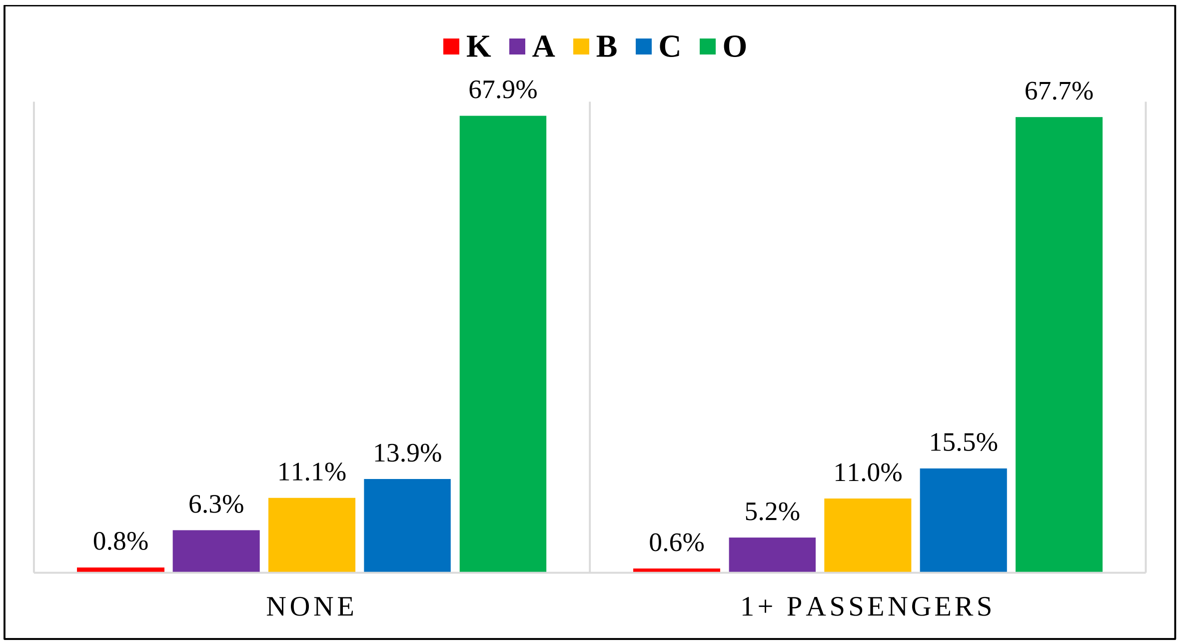
Figure 9. Prevalence of Injury Severity by Drivers' Conditions from GES



chi-square (df=12, 7628.07), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 10. Prevalence of Injury Severity by Having Passengers from GES



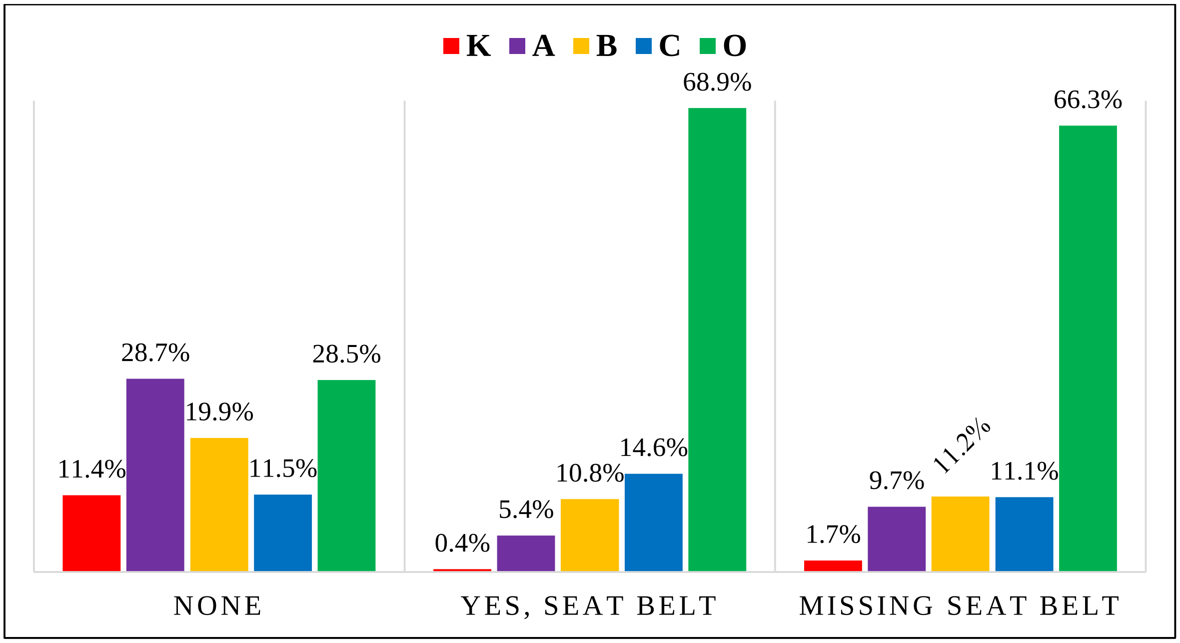
chi-square (df=4, 83.68), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Next, Figure 11 through Figure 15 displays the prevalence of injury severity by vehicle factors. Results of the chi-square tests suggested significant differences in proportions of injury severity.

Drivers who used a seat belt had the greatest percentage of the no injury (68.9%) in a crash. Drivers not using a seat belt had a greater percentage of the fatal injury (11.4%) and incapacitating injury (28.7%) (Figure 11). Drivers involved in crashes where airbags were deployed in the vehicle experienced a greater percentage of the fatal, incapacitating, non-incapacitating evident, and possible injuries compared to similar drivers that did not have their airbags deployed (Figure 12). In terms of vehicle body types, the data suggests that fatal injuries had relatively similar distribution among vehicle body types. However, drivers of sedan types had relatively higher percentages of the incapacitating, non-incapacitating evident, and possible injuries in a crash, compared to drivers with other vehicles (Figure 13). Drivers experiencing collision on the left side of vehicle had slightly higher rates of the fatal, incapacitating, and non-incapacitating evident injuries than when drivers had collision in front, rear, or right side of the vehicle (Figure 14). Considering the number of vehicles involved in crashes, drivers involved in crashes with only one vehicle had higher percentages of the fatal, incapacitating, and non-incapacitating evident injuries compared to drivers involved in crashes with two or more (Figure 15).

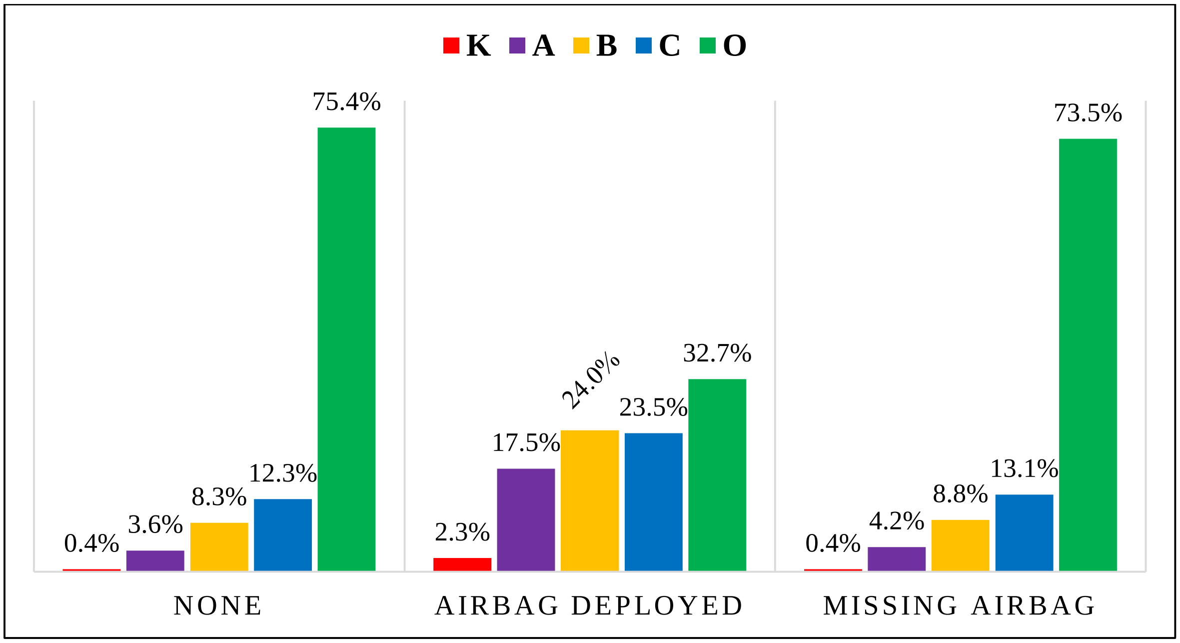
Figure 11. Prevalence of Injury Severity by Seat Belt Use from GES



chi-square (df=8, 7098.73), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

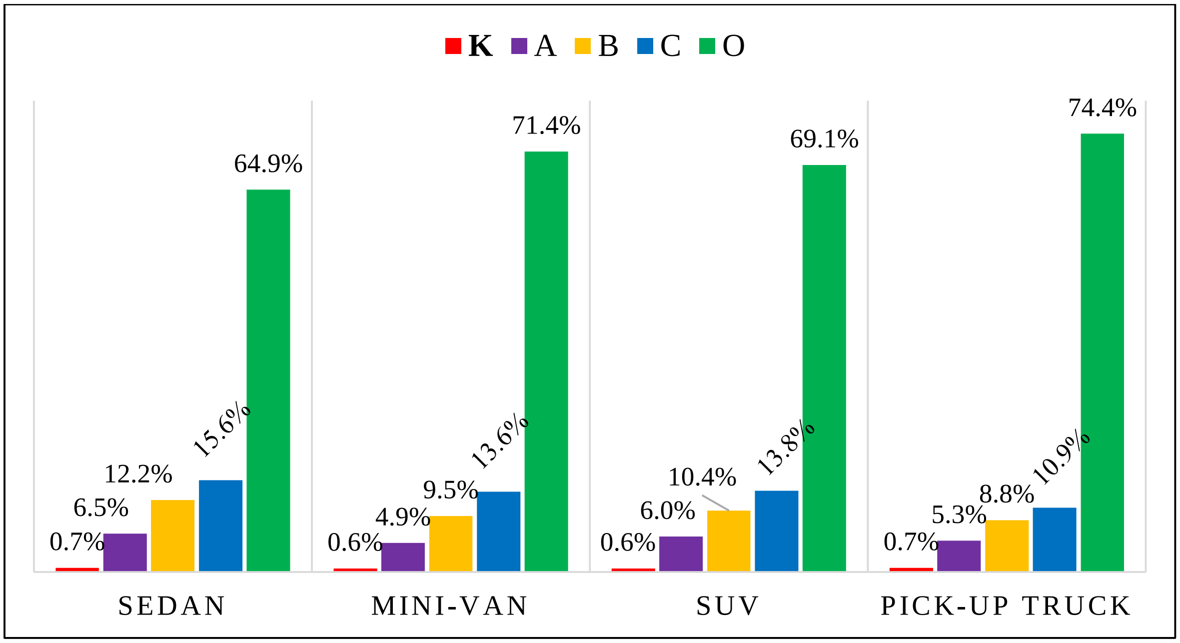
Figure 12. Prevalence of Injury Severity by Deployed of Airbag from GES



chi-square (df=8, 14236.29), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

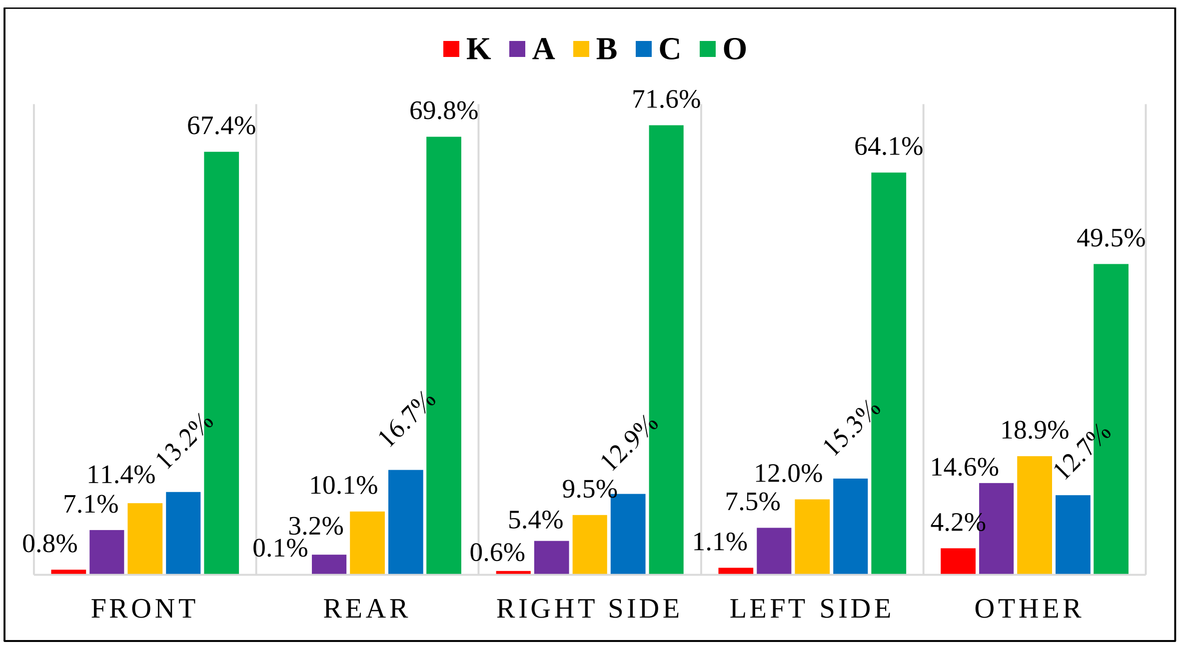
Figure 13. Prevalence of Injury Severity by Vehicle Body Type from GES



chi-square (df=12, 665.07), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

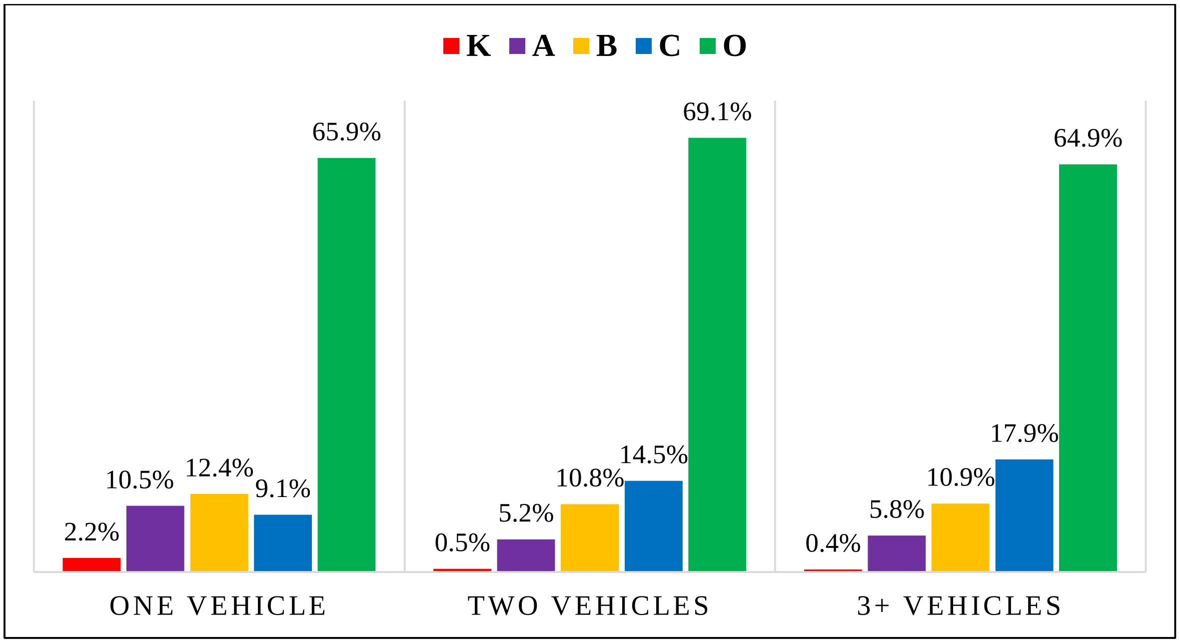
Figure 14. Prevalence of Injury Severity by Point of Collision from GES



chi-square (df=16, 1701.98), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 15. Prevalence of Injury Severity by Number of Involved Vehicle from GES



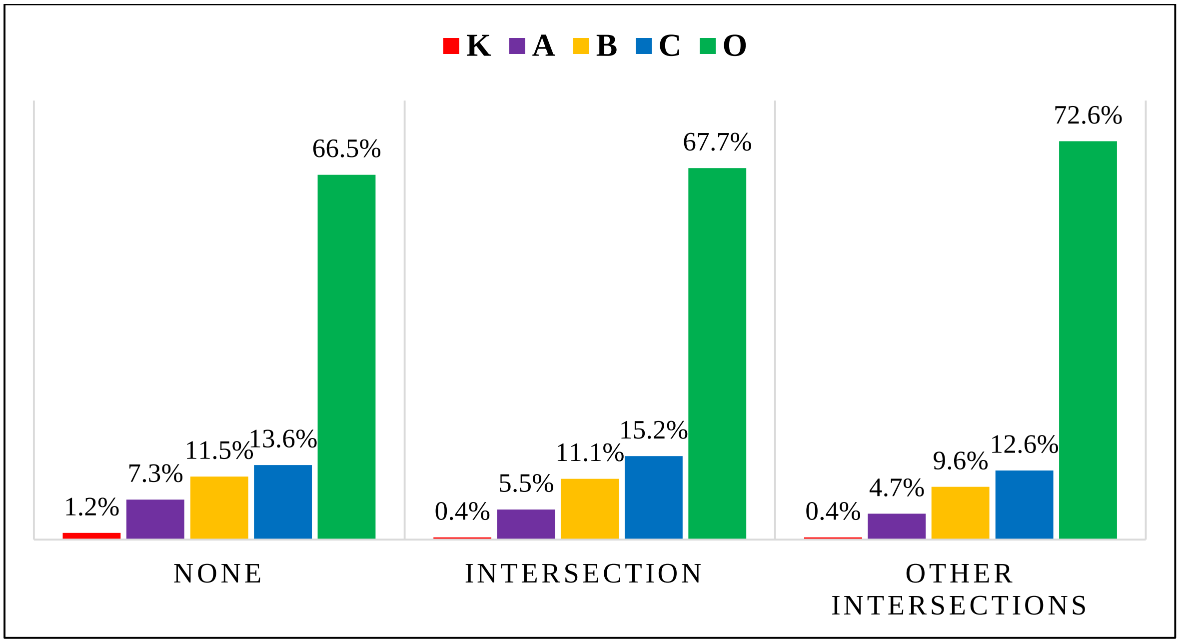
chi-square (df=8, 1724.63), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 16 through Figure 21 presents the proportion of injury severity by environmental factors. The chi-square tests showed the significant differences in proportion of injury severity by environmental factors. When crashes occurred on non-intersection roads, drivers had relatively higher percentages of the fatal, incapacitating, and non-incapacitating evident injuries in comparison to drivers involved in crashes on intersection roads (Figure 16). Also, drivers involved in crashes on highway roads had a lower percentage of O injury and greater percentages of the fatal, incapacitating, and non-incapacitating evident, and possible injuries compared to drivers involved in crashes on non-highway roads (Figure 17). When comparing injury severity by city population, the data suggests that when crashes occurred in the smaller or mid-sized city (populations 25,000-50,000 and 50,001-100,000, respectively) drivers had relatively similar rates of

type of injury severity. When crashes occurred in large cities (population 100,0001 or more), drivers had greater percentages of the fatal, incapacitating, and possible injuries (Figure 18).

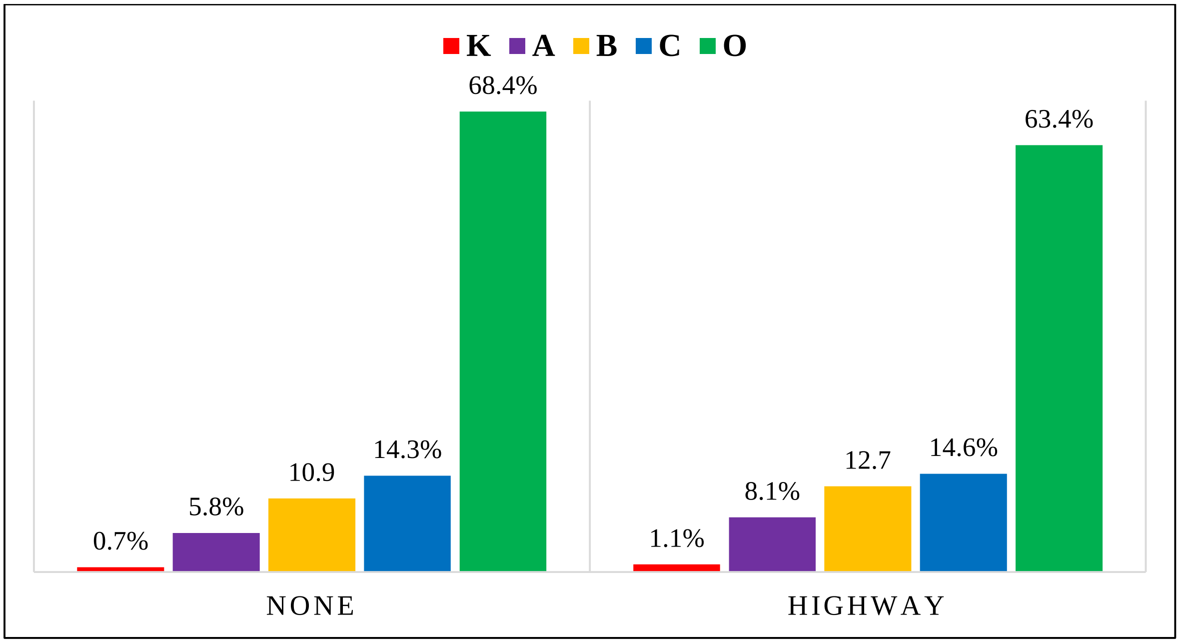
Figure 16. Prevalence of Injury Severity by Intersection Roads from GES



chi-square (df=8, 538.65), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

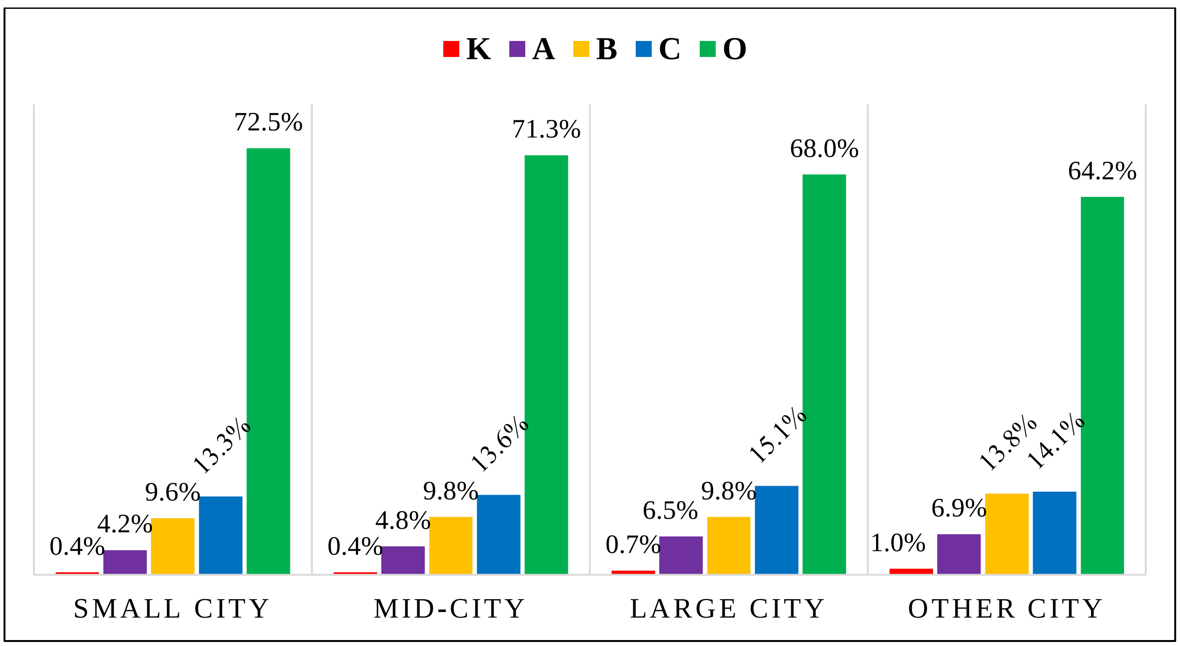
Figure 17. Prevalence of Injury Severity by Highway from GES



chi-square (df=4, 196.87), p <.001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 18. Prevalence of Injury Severity by Crash Area of Population from GES

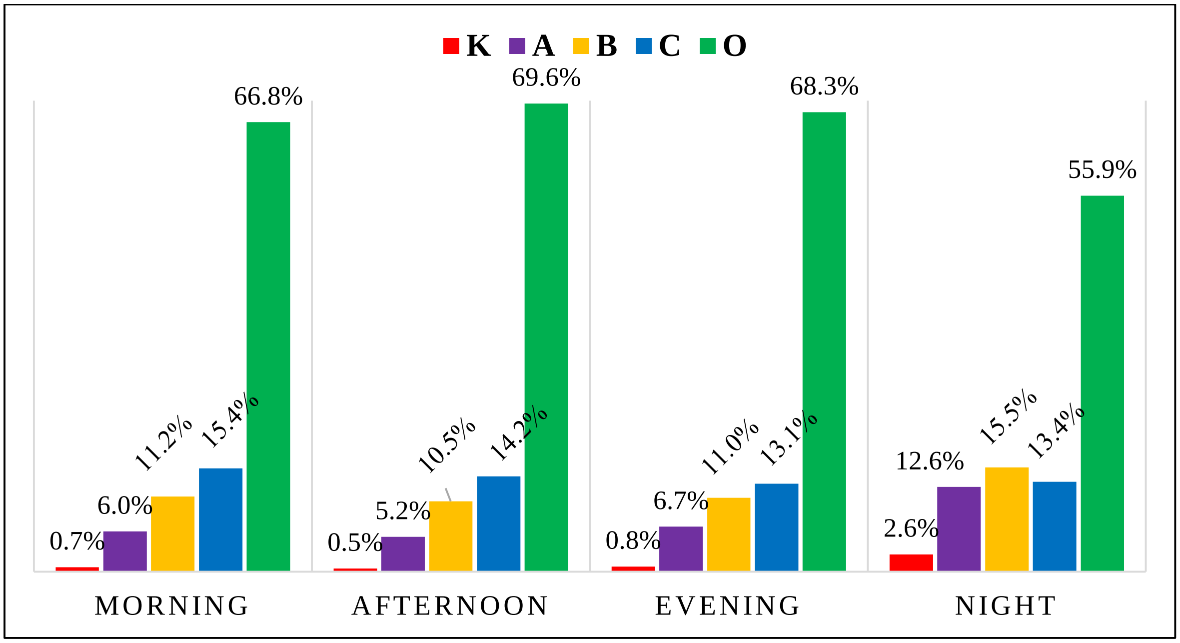


chi-square (df=12, 793.06), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

In regards to the time of day that a crash occurred, drivers involved in crashes between 12am and 5am had relatively higher percentages of the fatal and incapacitating injuries, compared to those involved in crashes during later morning, afternoon, or evening hours (Figure 19). Regarding the month in which a crash occurred, the data showed that drivers had relatively similar proportions of injury severity type during the months of spring, summer, fall and winter (Figure 20). Regarding weather conditions, drivers had a relatively greater percentage of the fatal injury when crashes occurred in clear conditions in comparison to when crashes occurred in rain or snow conditions. When crashes occurred in snow condition, the no injury was greatest (Figure 21).

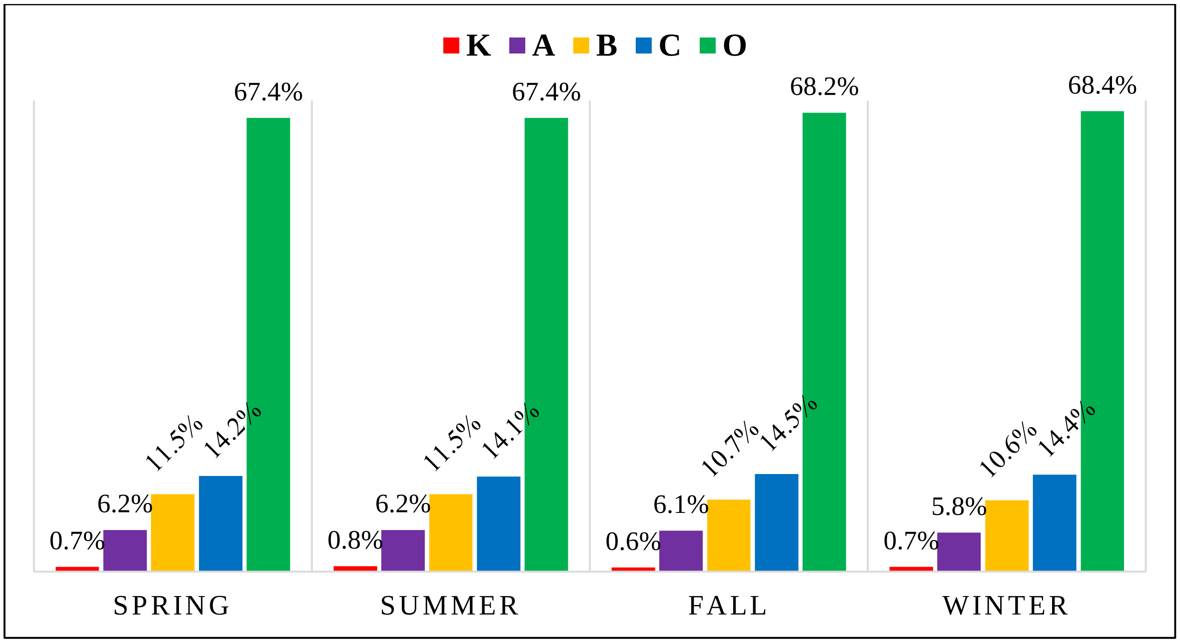
Figure 19. Prevalence of Injury Severity by Crash Time from GES



chi-square (df=12, 1055.53), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

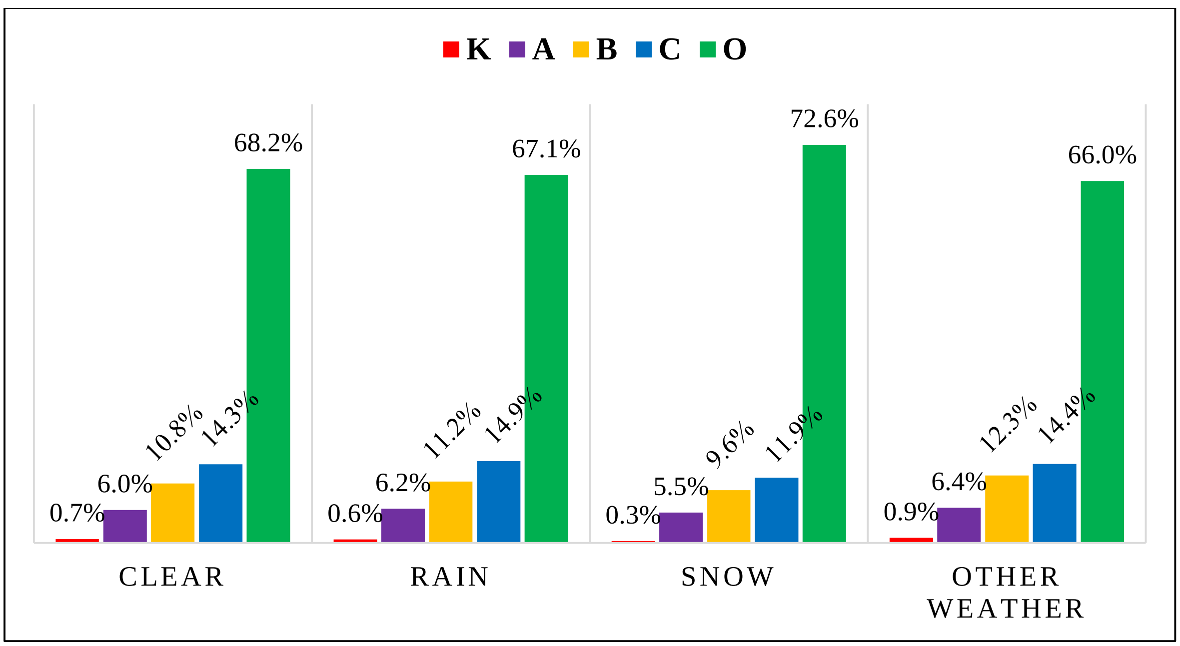
Figure 20. Prevalence of Injury Severity by Crash Month from GES



chi-square (df=12, 34.04), p < .01

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 21. Prevalence of Injury Severity by Weather Conditions from GES



chi-square (df=12, 89.05), p < .001

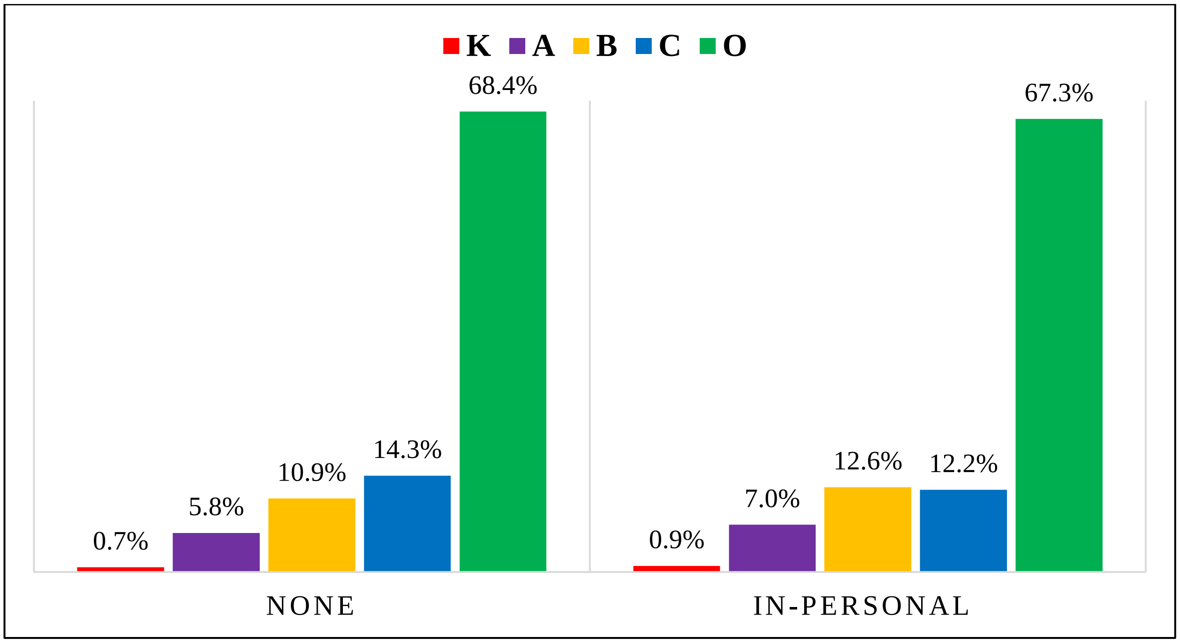
Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Lastly, Figure 22 through Figure 26 depicts the prevalence of injury severity by the type of driving license renewal policy. The chi-square results suggested that there were significant differences between injury severity and the license renewal policies. Drivers from states requiring the in-person license renewal policy had relatively greater percentages of the fatal, incapacitating, and non-incapacitating evident injuries in a crash compared to those not requiring in-personal policy (Figure 22).

Drivers from states implementing the accelerated renewal cycle policy had higher percentages of the fatal and non-incapacitating evident injuries in a crash in comparison to those of not implementing this policy (Figure 23). Also, drivers from states requiring the vision test had relatively higher percentages of the fatal and non-incapacitating evident injuries in a crash compared to those not requiring vision test (Figure 24). However, drivers from states requiring written or road test procedures had a relatively lower percentage of the fatal injury in a crash, compared to those not required to complete these procedures (Figure 25). Also, drivers from states implementing mandatory medical reports for at risk drivers had a relatively lower percentage of the fatal injury in a crash compared to those drivers from states not implementing this policy (Figure 26).

In summary, the bivariate analysis showed statistically significant results that all independent variables in this dissertation were associated with drivers' injury severity in a crash. Therefore, these findings provided valuable information to develop a multivariate regression model by adding those independent variables.

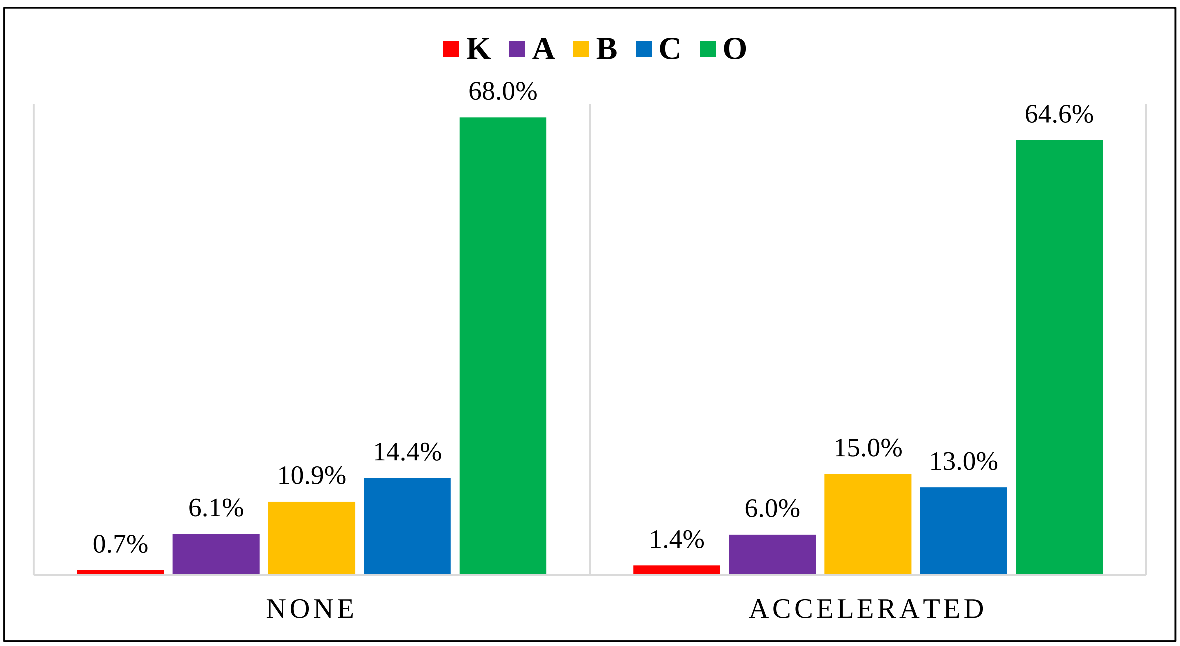
Figure 22. Prevalence of Injury Severity by In-Personal Renewal Policy from GES



chi-square (df=4, 192.06), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

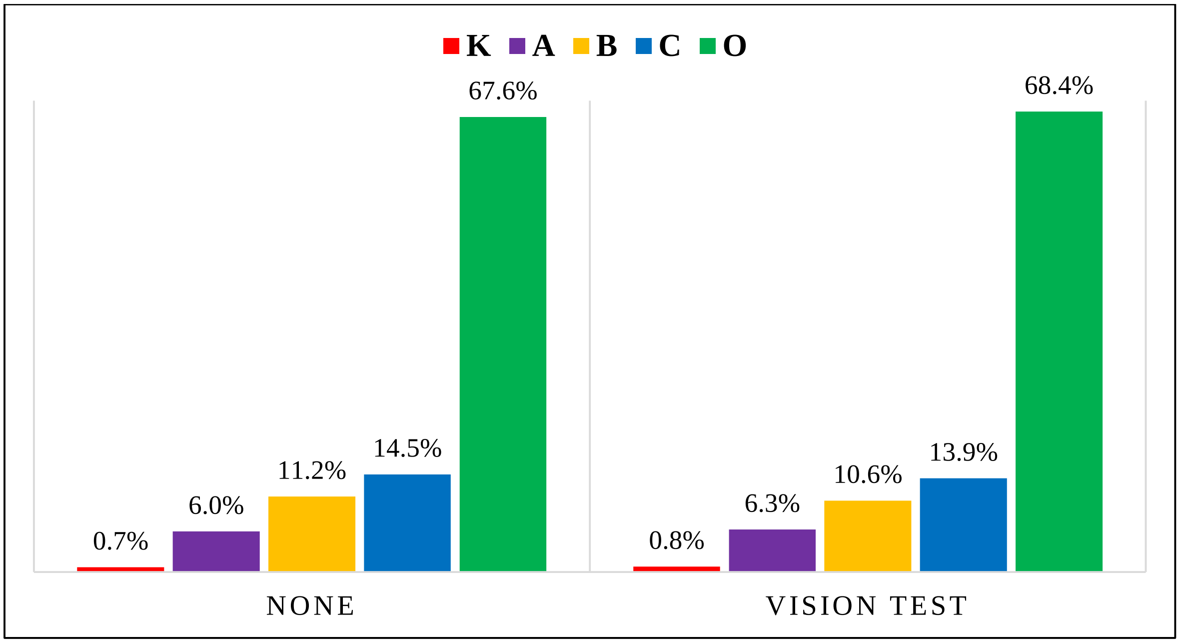
Figure 23. Prevalence of Injury Severity by Accelerated Renewal Cycle Policy from GES



chi-square (df=4, 101.62), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

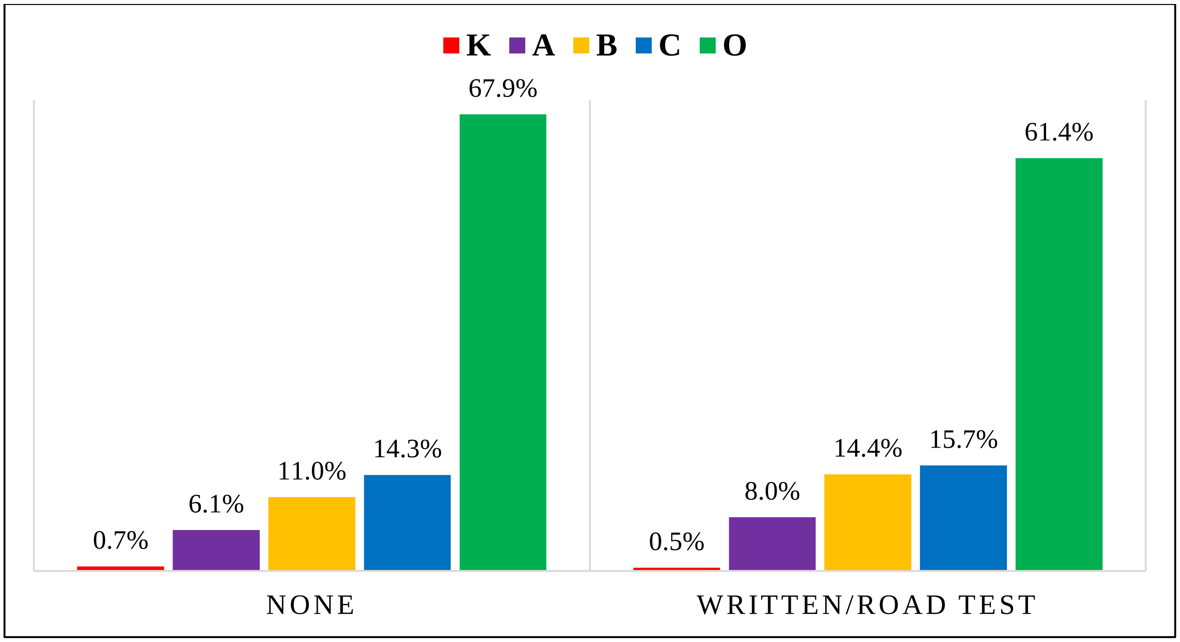
Figure 24. Prevalence of Injury Severity by Vision Test for Renewal Policy from GES



chi-square (df=4, 19.21), p < .01

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

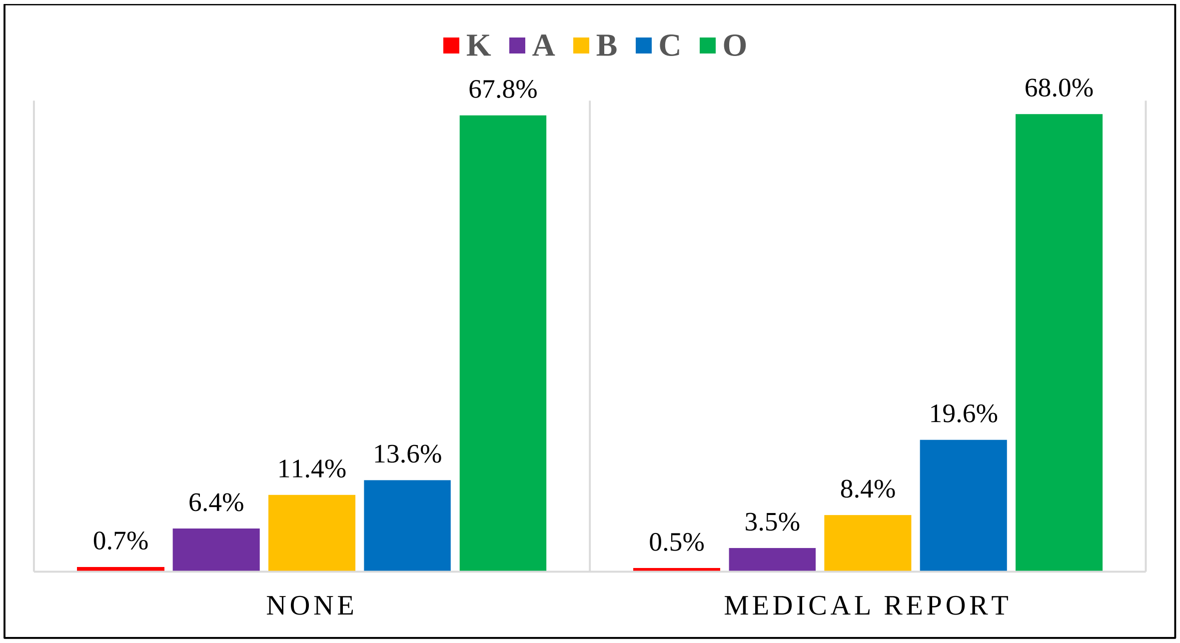
Figure 25. Prevalence of Injury Severity by Written/Road Test for Renewal Policy from GES



chi-square (df=4, 22.83), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 26. Prevalence of Injury Severity by Mandatory Medical Reporting for at Risk Driver Policy from GES



chi-square (df=4, 519.96), p < .001

Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Multinomial Logistic Regression

This section describes results of the MNL model used to predict the probability of injury severity by functioning of individual, vehicle type, and environmental and policy factors. Table 5 presents a summary of the MNL model containing the relative risk (RR) and its 95% confidence interval. As a result of the MNL model, the RR rather than raw coefficients is used to interpret relationships between injury outcomes and independent variables at a 5% significant level. When the RR is greater than one, it suggests that variables tend to increase the likelihood of outcomes. Conversely, when the RR is less than one, it suggests that variables tend to decrease the likelihood of outcomes. The RR is transposed to percent change in increase or decrease by subtracting one from

the RR and multiplying by 100.

Individual: It is expected that compared to drivers age 35 to 59 involved in a crash, drivers age 65 to 74 had 35.5% increased RR of the incapacitating injury (RR=1.355, CI:1.179-1.556) and 15.8% increased RR of the non-incapacitating evident injury (RR=1.158, CI:1.061-1.265) relative to the no injury while all other factors were held constant. Compared to drivers age 35 to 59 involved in a crash, drivers age 75 to 84 had 198% increased RR of the fatal injury (RR=2.978, CI:1.955-4.536), 37.4% increased RR of the incapacitating injury (RR=1.374, CI:1.131-1.669), and 30.5% increased RR of the non-incapacitating evident injury (RR=1.305, CI:1.157-1.471) relative to the no injury. Compared to drivers age 35 to 59 involved in a crash, drivers age 75 to 84 had 14.7% decreased RR of the possible injury (RR=0.853, CI:0.761-0.957) relative to the no injury. Similarly, compared to drivers age 35 to 59 involved in a crash, drivers age 85 and older had 254% increased RR of the fatal injury (RR=3.537, CI:1.591-7.861), 107% increased RR of the incapacitating injury (RR=2.066, CI:1.510-2.827), and 33.3% increased RR of the non-incapacitating evident injury (RR=1.333, CI:1.101-1.614) relative to the no injury.

Regarding gender and injury severity from crashes, female drivers involved in crashes were more likely to have severe injuries than male drivers. The results showed that compared to male drivers involved in a crash, female drivers had 56.6% increased RR of the incapacitating injury (RR=1.566, CI:1.427-1.721), 46.7% increased RR of the non-incapacitating evident injury (RR=1.467, CI: 1.386-1.554), and 61% increased RR of the possible injury (RR=1.610, CI: 1.529-1.696) relative to the no injury.

Compared to physically or mentally normal drivers, drivers with impairments in these areas had a 19 times greater RR of the fatal injury (RR=19.030, CI: 13.446-26.931), 5 times greater RR of the incapacitating injury (RR=4.889, CI: 4.088-5.847), 2.4 times greater RR of the non-incapacitating evident injury (RR=2.437, CI: 2.120-2.802), and 2.1 times greater RR of the possible injury (RR=2.132, CI: 1.837-2.474) relative to the no injury. Compared to physically and mentally normal drivers, those drivers that reported falling asleep or being fatigued behind the wheel had about 3 times greater RR of the incapacitating injury (RR=2.877, CI: 2.045-4.047), 2.7 times greater RR of the non-incapacitating evident injury (RR=2.663, CI: 2.036-3.483), and 2.1 times greater RR of the possible injury (RR=2.131, CI: 1.837-2.474) relative to the no injury. Drivers with a history of DUI had about 2.3 times greater RR of the fatal injury (RR=2.345, CI: 1.325-4.151), 3.1 times greater RR of the incapacitating injury (RR=3.117, CI: 2.532-3.838), and 2.5 times greater RR of the non-incapacitating evident injury (RR=2.504, CI: 2.160-2.903), and 1.4 times greater RR of the possible injury (RR=1.380, CI: 1.170-1.628) relative to the no injury compared to similar drivers with normal conditions.

Finally, compared to drivers without any passengers in their vehicle during a crash, drivers with passengers had 39.2% increased RR of the fatal injury (RR=1.392, CI: 1.006-1.926), 16.4% increased RR of the incapacitating injury (RR=1.164, CI: 1.045-1.296), 10.2% increased RR of the non-incapacitating evident injury (RR=1.102, CI: 1.034-1.175), and 16.7% increased RR of the possible injury (RR=1,167, CI: 1.102-1.235) relative to the no injury.

Vehicle: Drivers that utilize seatbelts can expect an overall decrease in RR of injury. Specifically, compared to drivers not using a seat belt, drivers using a seat belt had 97.8% decreased RR of the fatal injury (RR=0.022, CI: 0.016-0.032), 90.7% decreased RR of the incapacitating injury (RR=0.095, CI: 0.077-0.114), 76% decreased RR of the non-incapacitating evident injury (RR=0.240, CI: 0.203-0.283), and 56.3% decreased RR of the possible injury (RR=0.437, CI: 0.361-0.530) relative to the no injury while all other factors were held constant.

Compared to drivers involved in accidents in which airbags were not deployed, drivers involved in accidents in which airbags were deployed can expect greater risk of injury. In fact, airbag deployment had a 15 times greater RR of the fatal injury (RR=15.786, CI: 11.583-21.515), 14 times greater RR of the incapacitating injury (RR=14.800, CI: 13.333-16.429), 11 times greater RR of the non-incapacitating evident injury (RR=11.839, CI: 11.059-12.675), and 5 times greater RR of possible injury relative to the no injury (RR=5.875, CI: 5.508-6.268).

With respect to the vehicle's body type, the data suggest that when it comes to experiencing severe injury, although a pick-up truck may be a safer ride than a sedan, in fact a mini-van may be the safest ride. Whereas drivers of sedans can expect an increase of approximately 12% of RR of the non-incapacitating evident injury (RR=1.118, CI: 1.027-1.217) and 29.3% increased RR of the possible injury (RR=1.293, CI: 1.197-1.397) relative to the no injury compared to similar pick-up drivers, drivers of mini-vans can expect decreases in relative risks. For instance, drivers of mini-vans can expect a 24.4%

decrease RR of the incapacitating injury (RR=0.756, CI: 0.614-0.931) and 11.8% decrease RR of the non-incapacitating evident injury (RR=0.882, CI: 0.778-0.999) relative to the no injury.

Vehicle impact area (rear, front, left, right) and type of collision were observed to be associated with injury severity. Compared to collisions occurring at the rear, those drivers involved in front-end collisions had about 3.5 times greater RR of the fatal injury (RR=3.495, CI: 1.950-6.263) relative to the no injury, whereas those drivers had 8.2% decreased RR of the B injury (RR=0.918, CI: 0.853-0.988) and 50.9% decreased RR of the possible injury (RR=0.491, CI: 0.461-0.523) relative to the no injury. Drivers involved in a right-side collision had 4.8 times greater RR of the fatal injury (RR=4.849, CI: 2.316-10.154), a 12.6% decreased RR of the non-incapacitating evident injury (RR=0.874, CI: 0.786-0.972), and 48.4% decreased RR of the possible injury (RR=0.516, CI: 0.471-0.565) relative to the no injury compared to similar drivers involved in rear end collisions. Drivers involved in left-side impact accidents had 7.2 times greater RR of the fatal injury (RR=7.201, CI: 3.909-13.266), about 1.7 times greater RR of the incapacitating injury (RR=1.664, CI: 1.415-1.958), and about 1.3 times greater RR of the non-incapacitating evident injury (RR=1.253, CI: 1.1363-1.383) relative to the no injury, whereas those drivers had 35.8% decreased RR of the possible injury (RR=0.642, CI: 0.590-0.700) relative to the no injury compared to similar drivers involved in rear-impact accidents. Compared to drivers involved in rear end accidents, drivers experiencing other types of collisions (e.g. rollover or under ride) had about 35.6 times greater RR of the fatal injury (RR=33.550, CI: 16.364-68.785), about 4 times greater RR of the

incapacitating injury (RR=3.962, CI: 3.043-5.160), and about 3.2 times greater RR of the non-incapacitating evident injury (RR=3.171, CI: 2.540-3.089) relative to the no injury.

Regarding the number of vehicles involved in a crash, compared to drivers with one vehicle involved in a crash, drivers with two vehicles involved in a crash had 10.1% decreased RR of the incapacitating injury (RR=0.809, CI: 0.700-0.934) and 32.2% decreased RR of the non-incapacitating evident injury (RR=0.678, CI: 0.619-0.742) relative to the no injury. However, compared to drivers with one vehicle involved in a crash, drivers with three or more vehicles had about 1.5 times greater RR of the possible injury (RR=1.490, CI: 1.342-1.654) relative to the no injury.

Environment: It is expected that compared to drivers involved in a crash at non-intersection roads, drivers involved in a crash at intersection roads had 49.6% decreased RR of the fatal injury (RR=0.503, CI: 0.353-0.717), 28.9% increased RR of the non-incapacitating evident injury (RR=1.289, CI: 1.207-1.377), and 27.1% increased RR of the possible injury (RR=1.271, CI: 1.196-1.350) relative to the no injury while all other factors were held constant.

Similarly, compared to drivers involved in a crash at non-intersection roads, drivers involved in a crash at other types of intersections (drive way, ramp, or circle way) had 46.6% decreased RR of the fatal injury (RR=0.534, CI: 0.294-0.971) and 20% decreased RR of the incapacitating injury (RR=0.800, CI: 0.678-0.943) relative to the no injury. Furthermore, compared to drivers involved in a crash at non-highway roads, drivers involved in a crash at highway roads had 34.6% increased RR of the incapacitating injury (RR=1.346, CI: 1.173-1.543) and 17.5% increased RR of the non-

incapacitating evident injury (RR=1.175, CI: 1.063-1.298), but 10.2% decreased RR of the possible injury (RR=0.898, CI: 0.813-0.991) relative to the no injury.

Regarding the population of crash areas, compared to drivers involved in a crash in a mid-sized city, drivers involved in a crash in a large city had 28.5% increased RR of the possible injury (RR=1.285, CI: 1.173-1.408) relative to the no injury. Also, compared to drivers involved in a crash in a middle-sized city, drivers involved in a crash in 'other city' (unspecified population) had 192% increased RR of the fatal injury (RR=2.922, CI: 1.680-5.081), 64.4% increased RR of the incapacitating injury (RR=1.644, CI: 1.394-1.938), 67.8% increased RR of the non-incapacitating evident injury (RR=1.678, CI: 1.515-1.858), and 40.6% increased RR of the possible injury (RR=1.406, CI: 1.278-1.547) relative to the no injury.

Compared to drivers involved in a crash between 6am and 11am, drivers involved in a crash between 12pm and 5pm had 37.7% decreased RR of the fatal injury (RR=0.623, CI: 0.448-0.867) and 8.3% decreased RR of the possible injury (RR=0.917, CI: 0.865-0.973) relative to the no injury. Similarly, compared to drivers involved in a crash between 6am and 11am, drivers involved in a crash between 6pm and 11pm had 20.3% decreased RR of the incapacitating injury (RR=0.797, CI: 0.699-0.908) and 14.6% decreased RR of the possible injury (RR=0.854, CI: 0.792-0.920) relative to the no injury. However, compared to drivers involved in a crash between 6am and 11am, drivers involved in a crash between 12am and 5am had 17.8% increased RR of the non-incapacitating evident injury (RR=1.178, CI: 1.028-1.335) relative to the no injury.

With respect to the month of crash, compared to drivers involved in a crash during the Spring months, drivers involved in a crash Fall months had 9.6% decreased RR of the non-incapacitating evident injury (RR=0.904, CI: 0.836-0.977) relative to the no injury. Also, compared to drivers involved in Spring crashes, drivers involved in winter crashes had 15.6% decreased RR of the incapacitating injury (RR=0.844, CI: 0.740-0.962) and 13.8% decreased RR of the non-incapacitating evident injury (RR=0.862, CI: 0.796-0.934) relative to the no injury.

Lastly, compared to drivers involved in a crash in clear weather conditions, drivers involved in a crash in rainy conditions had 13.3% increased RR of the possible injury (RR=1.133, CI: 1.032-1.244) relative to the no injury.

Policy: It is expected that drivers involved in a crash in a state requiring in-person renewal had 33.1% increased RR of the incapacitating injury (RR=1.331, CI: 1.105-1.603) and 45.4% increased RR of the non-incapacitating evident injury (RR=1.454, CI: 1.308-1.615) relative to the no injury while all other factors were held constant. Similarly, drivers involved in a crash in a state with an accelerated renewal cycle had 21.6% increased RR of the non-incapacitating evident injury (RR=1.216, CI: 1.056-1.400) and 17.1% increased RR of the possible injury (RR=1.171, CI: 1.012-1.354) relative to the no injury. Also, drivers involved in a crash in a state requiring a written or road test at every renewal had 31.5% increased RR of the non-incapacitating evident injury (RR=1.315, CI: 0.999-1.729) relative to the no injury. Drivers involved in a crash in a state requiring a vision test at every renewal had 40.6% decreased RR of the fatal injury (RR=0.594, CI: 0.374-0.944) and 21.8% decreased RR of the non-incapacitating

evident injury (RR=0.782, CI: 0.704-0.869) relative to the no injury. Also, drivers involved in a crash in a state with mandatory medical reporting for at risk drivers had 45.7% decreased RR of the fatal injury (RR=0.543, CI: 0.352-0.840), 49.6% decreased RR of the incapacitating injury (RR=0.503, CI: 0.426-0.594) and 11.5% decreased RR of the non-incapacitating evident injury (RR=0.885, CI: 0.801-0.977), but 49.2% increased RR of the possible injury (RR=1.492, CI: 1.387-1.604) relative to the no injury.

Sensitivity Analysis

This dissertation performed several sensitivity analyses. First, in terms of the outcome variable, this dissertation used the 5 categories of injury severity. The GES crash data specified this injury severity as the KABCO scale. This scale is treated as an ordinal variable and as a result, the OL model was utilized, which was an appropriate method for the ordered outcome variable. However, as noted above, the OL model is required to satisfy an assumption regarding the "proportional odds "(also known as parallel line). After running the OL model, the proportional odds assumption was tested by using the test command, 'brant', in STATA version 14. As a result, a significant test statistics provided evidence that the parallel regression assumption had been violated (χ^2 (123, n=106,631) =3325.21, p <.001). According to Long and Freese (2001),

> "In our experience, the parallel regression assumption is frequently violated. When the assumption of parallel regression is rejected, alternative models should be considered that do not impose the constraint of parallel regressions" (p.152).

Therefore, the assumption test failed, the OL model was not deemed appropriate for this analysis.

Second, for modeling purposes, this dissertation tested modifications of the KABCO scale by aggregating the 5 levels into a three and a four-level model. The three category model combined the fatal and incapacitating injuries into a single severe injury category, and combined the non-incapacitating evident and possible injuries into a single minor injury category. The category of no injury was not modified., The four category model combined the fatal and incapacitating injuries into a single severe injury category and did not modify the remaining the categories. Three different models of MNL analysis were performed (3, 4, & 5 category) and likelihood ratio tests were observed. As a result, the 5-category outcome model was selected for ongoing analysis.

Third, according to previous studies, the weight of vehicles was also an important factor for injury severity in a crash. However, the GES crash data do not provide the gross curb weight of vehicles involved in crashes. Only the FARS crash data provide the gross curb weight of vehicles involved in crashes. Both GES and FARS crash data provide information of vehicle model, manufacturer, and year of model, however vehicles of the same model by the same manufacturer have varied weights. For example, there was different gross curb weight observed among Ford Focus' from the year 2007.

Weight fluctuation may be due to independent vehicle options chosen by buyers. These 'options' are not available in the FARS crash data, and as a result, average gross curb weight for the same model, maker, and year were calculated. Finally, this dissertation merged the average gross curb weight from the FARS into the GES by using of model, maker, and year of model.

When this dissertation performed the MNL model after adding the average gross curb weight of vehicle information, the result showed that the variables of vehicle body types were not significant. There was a high correlation between the body types and the average gross curb weight of the vehicle. As a result, average gross curb weight was removed from the MNL model.

Fourth, results from the MNL model suggested that 'deployed airbag' was associated with an increase in severe injury for all drivers in a crash. It was an interesting finding that the deployed airbag in a crash was a risk factor of injury severity. This sensitivity analysis was trying to explore further evidence how interactions of the deployed airbag and age were related with injury severity in a crash. After adding interaction terms between 'deployed airbag' and 'drivers age 65 and older', results suggested the deployed airbag with drivers age 65 and older had 24 times greater RR of the incapacitating injury (RR=24.268, CI: 17.217-34.207), 16 times greater RR of the non-incapacitating evident injury (RR=16.879, CI:13.455-21.175), and 8 times greater RR of the possible injury (RR=8.663, CI:6.929-10.830) relative to no injury. The detailed results regarding with the interaction between the deployed airbag and older drivers age 65 and older is presented in Table A2 on appendix.

Table 5. Multinomial Logistic (MNL) Model for Injury Severity in GES Crash Data (2010-2012)

Variables	Fatal[1]		Incapacitating[1]	
	RR	95% CI	RR	95% CI
Individual				
Age groups				
Age 35 to 59 (Ref.)				
Age 65 to 74	1.477	(0.984-2.218)	1.355***	(1.179-1.556)
Age 75 to 84	2.978***	(1.955-4.536)	1.374**	(1.131-1.669)
Age 85 and older	3.537**	(1.591-7.861)	2.066***	(1.510-2.827)
Gender				
Female	0.94	(0.699-1.263)	1.566***	(1.427-1.720)
Driver's conditions				
Normal (Ref.)				
Impaired	19.030***	(13.446-26.931)	4.889***	(4.088-5.847)
Asleep	2.016	(0.761-5.343)	2.877***	(2.045-4.047)
DUI	2.345**	(1.325-4.151)	3.117***	(2.532-3.838)
Number of passengers				
Having passengers	1.392*	(1.006-1.926)	1.164**	(1.045-1.296)
Vehicle				
Safety restraints				
No seat belt (Ref.)				
Seat belt use	0.022***	(0.016-0.032)	0.093***	(0.077-0.114)
Missing seat belt	0.060***	(0.036-0.101)	0.126***	(0.098-0.161)
Non-deployed airbag (Ref.)				
Deployed airbag	15.786***	(11.583-21.515)	14.800***	(13.333-16.429)
Missing airbag	0.773	(0.419-1.426)	1.171	(0.967-1.417)
Body Types				
Sedan	0.916	(0.621-1.350)	0.905	(0.792-1.034)
Mini-van	0.804	(0.451-1.432)	0.756**	(0.614-0.931)
SUV	1.011	(0.656-1.557)	0.936	(0.803-1.092)
Pick-up truck (Ref.)				
Point of collision				
Front	3.495***	(1.950-6.263)	1.034	(0.904-1.181)
Rear (Ref.)				
Right side	4.849***	(2.316-10.154)	0.958	(0.801-1.146)
Left side	7.201***	(3.909-13.266)	1.664***	(1.415-1.958)
Other collisions	33.550***	(16.364-68.785)	3.962***	(3.043-5.160)
Number of vehicles				
One vehicle (Ref.)				
Two vehicles	0.981	(0.693-1.388)	0.809**	(0.700-0.934)
Three+ vehicles	1.177	(0.638-2.171)	1.103	(0.934-1.303)

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

(Table 5 Continued)

Table 5. Multinomial Logistic (MNL) Model for Injury Severity in GES Crash Data (2010-2012) (Continued)

Variables	Fatal[1]		Incapacitating[1]	
	RR	95% CI	RR	95%CI
Environment				
Intersection roads				
No, intersection (Ref.)				
Yes, intersection	0.503***	(0.353-0.717)	1.008	(0.906-1.123)
Other types	0.534*	(0.294-0.971)	0.800**	(0.678-0.943)
Highway roads	1.337	(0.945-1.892)	1.346***	(1.173-1.543)
Crash area of population				
Small city	1.324	(0.691-2.536)	1.051	(0.873-1.356)
Mid-city (Ref.)				
Large city	1.556	(0.884-2.739)	1.15	(0.975-1.356)
Other city	2.922***	(1.680-5.081)	1.644***	(1.394-1.938)
Time of the day				
Morning (06:00-11:59) Ref.				
Afternoon (12:00-17:59)	0.623**	(0.448-0.867)	0.928	(0.834-1.033)
Evening (18:00-23:59)	0.888	(0.604-1.305)	0.797***	(0.699-0.908)
Night (00:00-05:59)	1.29	(0.825-2.015)	1.181	(0.965-1.446)
Month of crash				
Spring (Ref.)				
Summer	1.081	(0.753-1.552)	1.085	(0.955-1.232)
Fall	0.802	(0.533-1.206)	0.977	(0.863-1.106)
Winter	0.882	(0.613-1.269)	0.844*	(0.740-0.962)
Weather conditions				
Clear weather (Ref.)				
Rain	1.396	(0.837-2.328)	0.911	(0.777-1.067)
Snow	0.372	(0.124-1.118)	0.731	(0.530-1.008)
Other weather	1.412	(0.968-2.059)	1.033	(0.915-1.166)
Policy				
In-person renewal	1.516	(0.905-2.541)	1.331**	(1.105-1.603)
Accelerated renewal cycle	1.651	(0.900-3.026)	0.942	(0.729-1.218)
Vision test for renewal	0.594*	(0.374-0.944)	0.847	(0.705-1.018)
Written/road test for renewal	0.456	(0.134-1.553)	1.225	(0.758-1.980)
Medical reporting for at risk driver	0.543**	(0.352-0.840)	0.503***	(0.426-0.594)
Constant	0.003***	(0.001-0.009)	0.044***	(0.031-0.062)
Pseudo R Square	**0.11**			

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

(Table 5 Continued)

Table 5. Multinomial Logistic (MNL) Model for Injury Severity in GES Crash Data (2010-2012) (Continued)

Variables	Non-incapacitating[1]		Possible[1]	
	RR	95% CI	RR	95% CI
Individual				
Age groups				
Age 35 to 59 (Ref.)				
Age 65 to 74	1.158**	(1.061-1.265)	0.951	(0.872-1.038)
Age 75 to 84	1.305***	(1.157-1.471)	0.853**	(0.761-0.957)
Age 85 and older	1.333**	(1.101-1.614)	0.936	(0.770-1.137)
Gender				
Female	1.467***	(1.386-1.554)	1.610***	(1.529-1.696)
Driver's conditions				
Normal (Ref.)				
Impaired	2.437***	(2.120-2.802)	2.132***	(1.837-2.474)
Asleep	2.663***	(2.036-3.483)	1.848***	(1.402-2.435)
DUI	2.504***	(2.160-2.903)	1.380***	(1.170-1.628)
Number of passengers				
Having passengers	1.102**	(1.034-1.175)	1.167***	(1.102-1.235)
Vehicle				
Safety restraints				
No seat belt (Ref.)				
Seat belt use	0.240***	(0.203-0.283)	0.437***	(0.361-0.530)
Missing seat belt	0.265***	(0.215-0.327)	0.417***	(0.332-0.523)
Non-deployed airbag (Ref.)				
Deployed airbag	11.839***	(11.059-12.675)	5.875***	(5.508-6.268)
Missing airbag	1.204***	(1.085-1.336)	1.007	(0.923-1.098)
Body Types				
Sedan	1.118*	(1.027-1.217)	1.293***	(1.197-1.397)
Mini-van	0.882*	(0.778-0.999)	1.043	(0.933-1.166)
SUV	1.051	(0.954-1.159)	1.069	(0.977-1.170)
Pick-up truck (Ref.)				
Point of collision				
Front	0.918*	(0.853-0.988)	0.491***	(0.461-0.523)
Rear (Ref.)				
Right side	0.874*	(0.786-0.972)	0.516***	(0.471-0.565)
Left side	1.253***	(1.136-1.383)	0.642***	(0.590-0.700)
Other collisions	3.171***	(2.640-3.809)	1.223	(0.995-1.503)
Number of vehicles				
One vehicle (Ref.)				
Two vehicles	0.678***	(0.619-0.742)	1.078	(0.986-1.180)
Three+ vehicles	1.106	(0.990-1.234)	1.490***	(1.342-1.654)

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

(Table 5 Continued)

Table 5. Multinomial Logistic (MNL) Model for Injury Severity in GES Crash Data (2010-2012) (Continued)

Variables	**Non-incapacitating**[1]		**Possible**[1]	
	RR	**95% CI**	**RR**	**95% CI**
Environment				
Intersection roads				
No, intersection (Ref.)				
Yes, intersection	1.289***	(1.207-1.377)	1.271***	(1.196-1.350)
Other types	1.032	(0.938-1.135)	0.949	(0.869-1.036)
Highway roads	1.175**	(1.063-1.298)	0.898*	(0.813-0.991)
Crash area of population				
Small city	1.084	(0.969-1.213)	1.085	(0.981-1.200)
Mid-city (Ref.)				
Large city	1.08	(0.976-1.196)	1.285***	(1.173-1.408)
Other city	1.678***	(1.515-1.858)	1.406***	(1.278-1.547)
Time of the day				
Morning (06:00-11:59) Ref.				
Afternoon (12:00-17:59)	0.96	(0.900-1.024)	0.917**	(0.865-0.973)
Evening (18:00-23:59)	0.961	(0.886-1.043)	0.854***	(0.792-0.920)
Night (00:00-05:59)	1.178*	(1.028-1.335)	0.995	(0.872-1.135)
Month of crash				
Spring (Ref.)				
Summer	1.079	(0.998-1.166)	1.039	(0.966-1.118)
Fall	0.904*	(0.836-0.977)	1.041	(0.971-1.117)
Winter	0.862***	(0.796-0.934)	0.978	(0.911-1.050)
Weather conditions				
Clear weather (Ref.)				
Rain	1.015	(0.918-1.122)	1.133**	(1.032-1.244)
Snow	0.847	(0.697-1.028)	0.931	(0.782-1.108)
Other weather	1.078	(0.999-1.164)	1.066	(0.993-1.144)
Policy				
In-person renewal	1.454***	(1.308-1.615)	0.946	(0.848-1.055)
Accelerated renewal cycle	1.216**	(1.056-1.400)	1.171*	(1.012-1.354)
Vision test for renewal	0.782***	(0.704-0.869)	1.035	(0.936-1.144)
Written/road test for renewal	1.315*	(1.001-1.729)	1.055	(0.809-1.376)
Medical reporting for at risk driver	0.885*	(0.801-0.977)	1.492***	(1.387-1.604)
Constant	0.081***	(0.064-0.103)	0.140***	(0.109-0.178)
Pseudo R Square		**0.11**		

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

Spatial Analysis

In this section, the results of an analysis of the FARS data are presented. Descriptive and spatial analysis of the FARS allows for identification of ‘hot spots’ of crash locations in the state of Massachusetts. In contrast to the analysis of the GES data for the MNL model, the spatial analysis of the FARS data does not include vehicle, environmental, or policy factors. The goal of this spatial analysis is to identify and display the hot spots of crash locations in MA rather than finding risk factors of crash. It is important to note that a crash in FARS data includes at least one fatality. As a result of the spatial analysis, crash maps of hot spots are provided based on the observed crash locations in MA.

Descriptive Statistics

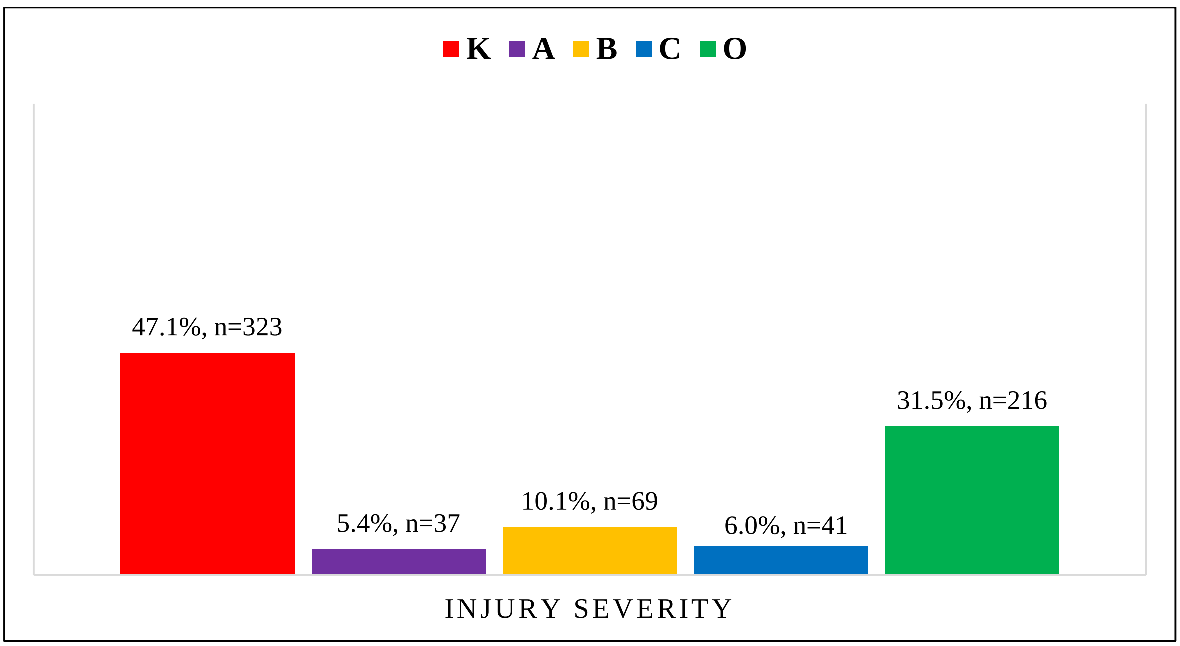
Regarding with the sampling criteria of drivers’ age groups in FARS data, there were initially 734 drivers involved in a crash resulting in at least one fatality in MA from FARS 2010 to 2012. Data regarding longitude and latitude of crash location was not available for 48 drivers and these drivers were dropped from the analysis. Therefore, the final sample of the spatial analysis based on the FARS included complete data for 686 drivers from MA.

Overall, the majority of respondents was drivers age 35 to 59 (72.6%, n=498) and drivers age 65 and older (27.4%, n=188) in a crash resulting in at least one fatality. Drivers involved in accidents that involved at least one fatality had relatively high frequencies of the fatal injury (47.1%, n=323) and no injury (31.5%, n=216), compared to other injury types: incapacitating injury (5.4%, n=37), non-incapacitating evident

injury (10.1%, n=69), and possible injury (6.0%, n=41). The greater number of fatal versus other injury type observed was probably associated with the specialty of FARS data including at least one fatality from a crash (See Figure 27).

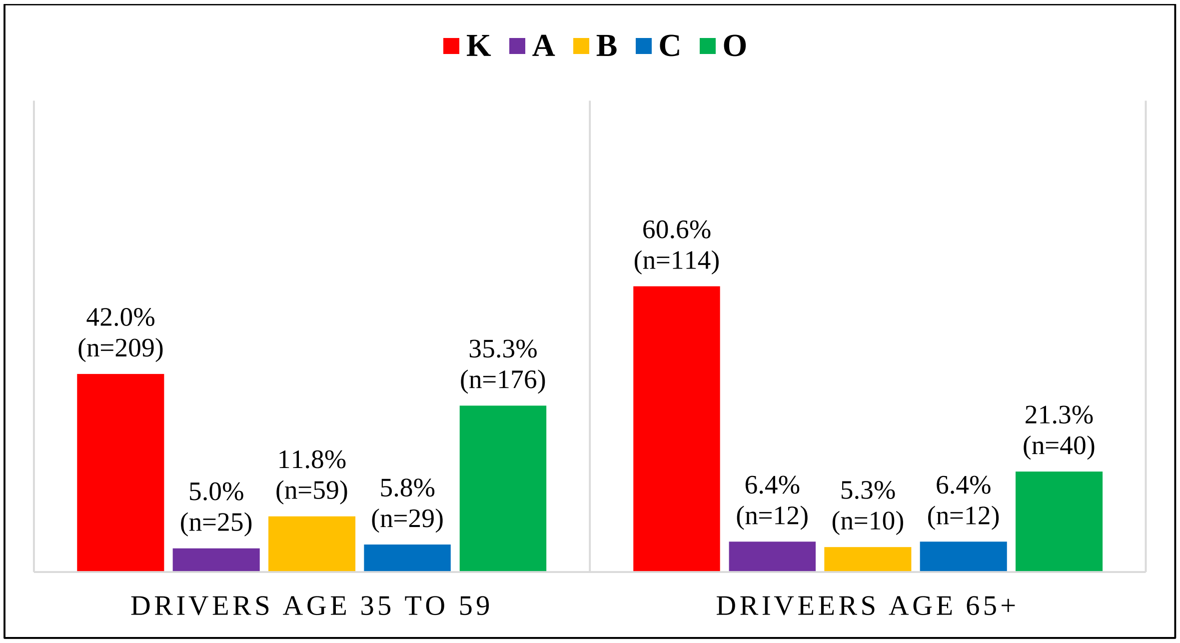
Also, in relation to age groups and injury severity, the data suggests that drivers age 35 to 59 and drivers age 65 and older had similar distributions of injury severity that indicated relatively high frequencies of the fatal injury (42.0% & 60.6%, respectively) and no injury (35.3% & 21.3%, respectively) (See Figure 28).

Figure 27. Prevalence of Injury Severity from FARS in MA



Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Figure 28. Prevalence of Injury Severity by Drivers' Age Group from FARS in MA



Note. K: Fatal, A: Incapacitating. B: Non-incapacitating evident, C: Possible, O: None

Hot Spots Analysis

Results in this section offer an explanation of both the identification and the visual representation of the hot spots of crash locations in MA observed by performing spatial analysis of the GIS application. Crash sites for 686 drivers were plotted on a map and color-coded for injury severity. Overlays with MA state boundaries and major road lines were added. As seen Figure 29, the greater cluster of points (crash sites by severity) are located along major roads in MA. Also, the clusters of points are observed regionally as well. For instance, points are clustered in the Greater Boston area and town of Fall River, MA, New Bedford, MA, Springfield, MA, and Worcester, MA. The maps with entire names of town in MA is presented in the Appendix B (Figure B1 through B10).

Maps were also created that presented the density of population age 35 to 59 and the density of population age 65 and older by towns in MA based on the US Census,

2010. When the maps were overlaid, a visual representation of crash location by population density was observed. As seen in Figure 30, the overlay suggested there was a relatively lower density of population age 35 to 59 in the area of Boston, Springfield, and Worcester, yet crash location points of these drivers were highly clustered in those areas. Additionally, as seen Figure 31, a higher density of population age 65 and older was observed in area of western MA (Berkshire county) and Cape Cod, yet crash location of points for these drivers clustered around the area of Boston and Springfield despite the lower density of population age 65 and older.

The GIS application also provides a tool which is able to distinguish areas with high numbers of crashes effectively. By performing the Optimized Hot Spots Spatial analysis, a cluster of the original points (by severity) were transferred to a "heated map". A heated map shows a high density of points as red, suggesting higher numbers of crashed occurred, and it shows a low density of point as blue, suggesting lower number of crashes occurred. A map overlay of the urban boundaries was used to observe hot spots occurring within urban boundaries by severity type. According to the US Census 2010, they were 21 specified urban areas in MA. When viewing these maps, the purple lines represent the urban boundary of MA.

Results are presented in a series of maps (Figures 32-38) based on both injury severity and age group. Based on the GIS application tool, it required at least 60 points of crash locations to perform the Optimized Hot Spot analysis. Therefore, drivers with the incapacitating, non-incapacitating evident, or possible injuries were not enough sample to run the Optimized Hot Spot analysis. Thus, the incapacitating, non-incapacitating

evident, or possible injuries were aggregated to one category of the injury, making over 60 cases. Overall, the red spots on the map were located within the urban boundaries in MA. Also, the red spots were located in the areas where the major roads were crossing over each other.

The Optimized Hot Spot analysis utilized the function of collapsing nearest points as a point. It provided the z-score indicating whether the collapsed points were clustered as hot spots significantly or not. In terms of the fatal injury (Figure 32), the clustered points (Red pins on the map) of the fatal injury among all drivers involved in a crash were located near Boston area of within urban boundaries. When considering driver's age and the fatal injury, it showed that drivers age 35 to 59 had two specific hot spots areas near Boston and one hot spot out of Boston (near Fall River in MA), whereas drivers age 65 and older had five different hot spots along with the boundary of greater Boston (Figure 33 & Figure 34).

However, there was no significant collapsed points of the incapacitating, non-incapacitating evident, or possible injuries (Figure 35 & Figure 36). Finally, in terms of the no injury, the most collapsed points of the hot spots were located near Boston area and two other collapsed points were in Berkshire county of the western MA and in New Bedford MA among all drivers (Figure 37). But, it showed that drivers age 35 to 59 had the hot spots of the no injury were located near Boston and in Fall River (Figure 38). Among divers age 65 and older, the incapacitating, non-incapacitating evident, possible, and no injuries were not able to perform the Optimized Hot Spot analysis to identify the hot spot because the cases were less than 60.

Figure 29. Distribution of Crash Locations by Injury Severity among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

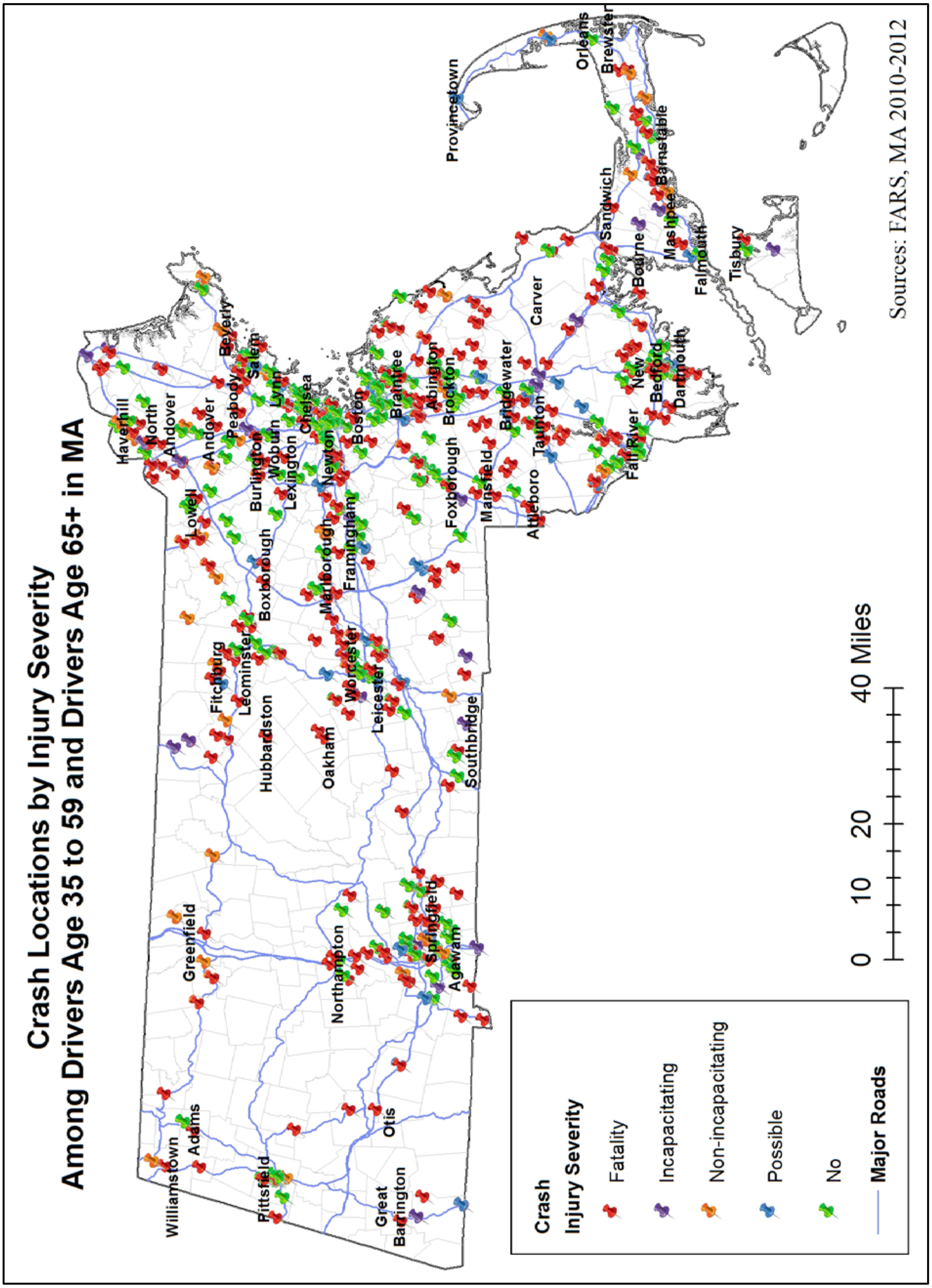


Figure 30. Injury Severity with Density of Population Age 35 to 59 in MA from FARS 2010-2012

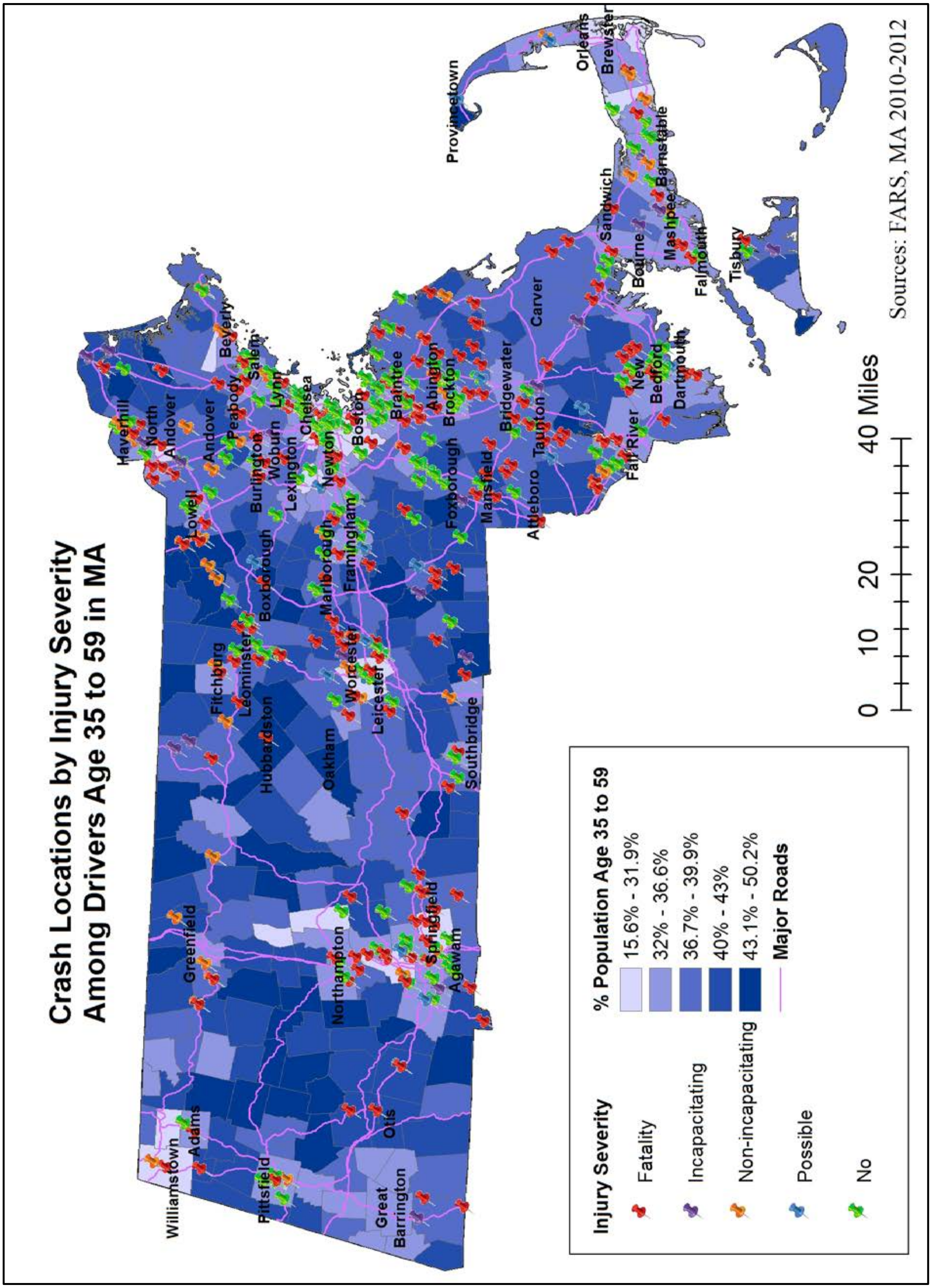


Figure 31. Injury Severity with Density of Population Age 65 and Older in MA from FARS 2010-2012

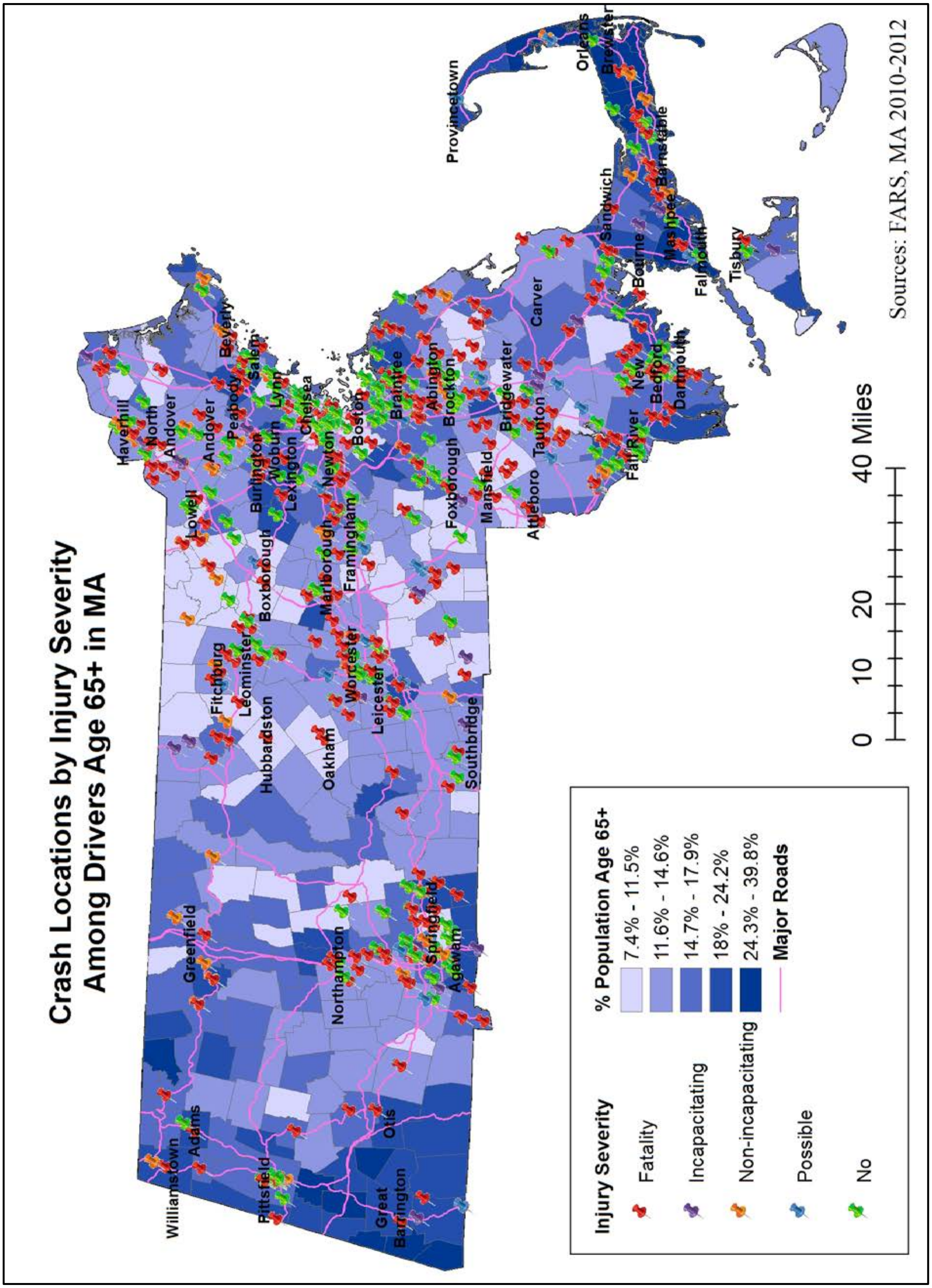


Figure 32. The Hot Spots of Crash Locations by the Fatal Injury
among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

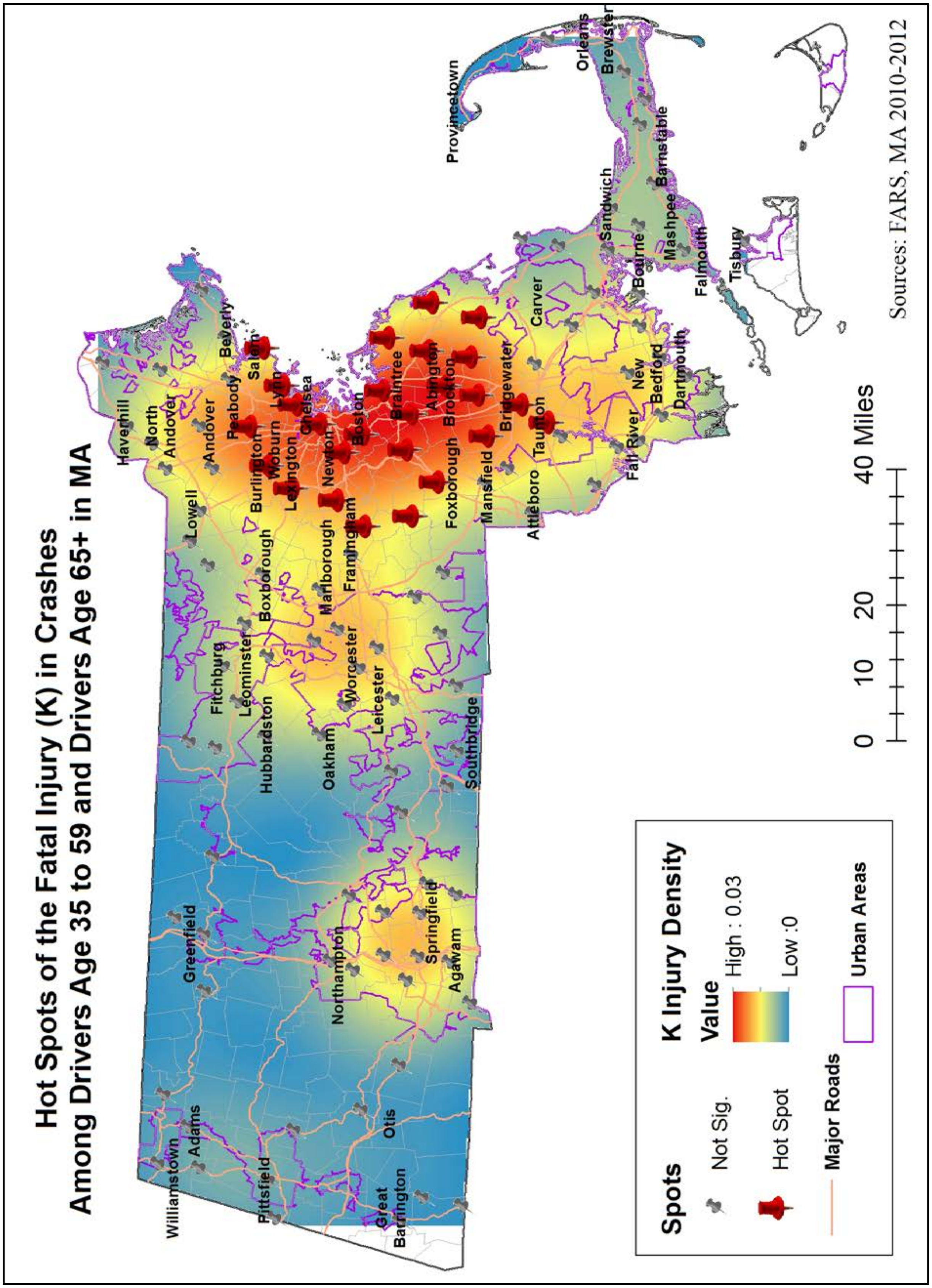


Figure 33. The Hot Spots of Crash Locations by the Fatal Injury among Drivers Age 35 to59 in MA from FARS 2010-2012

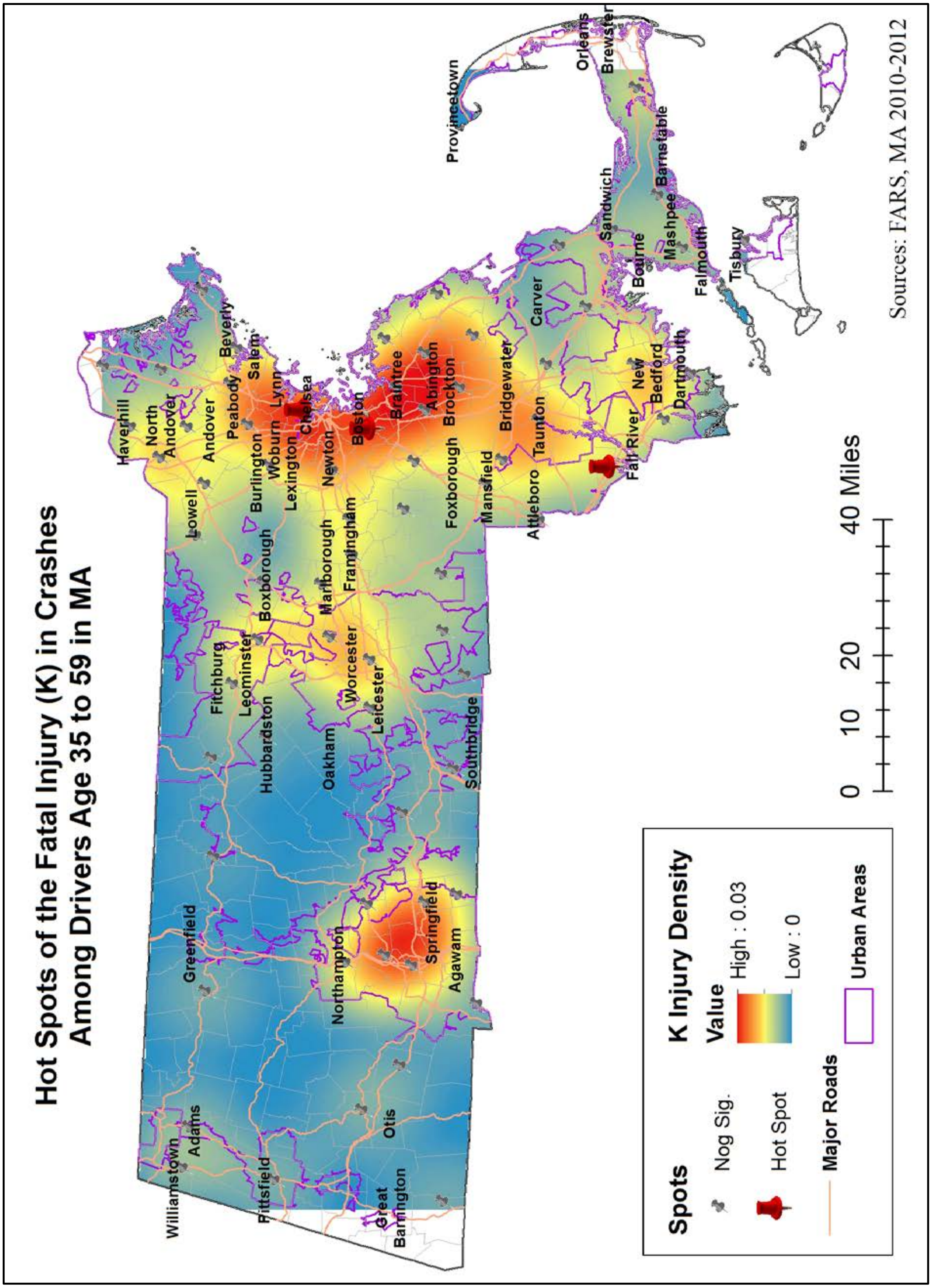


Figure 34. The Hot Spots of Crash Locations by the Fatal Injury among Drivers Age 65 and Older in MA from FARS 2010-2012

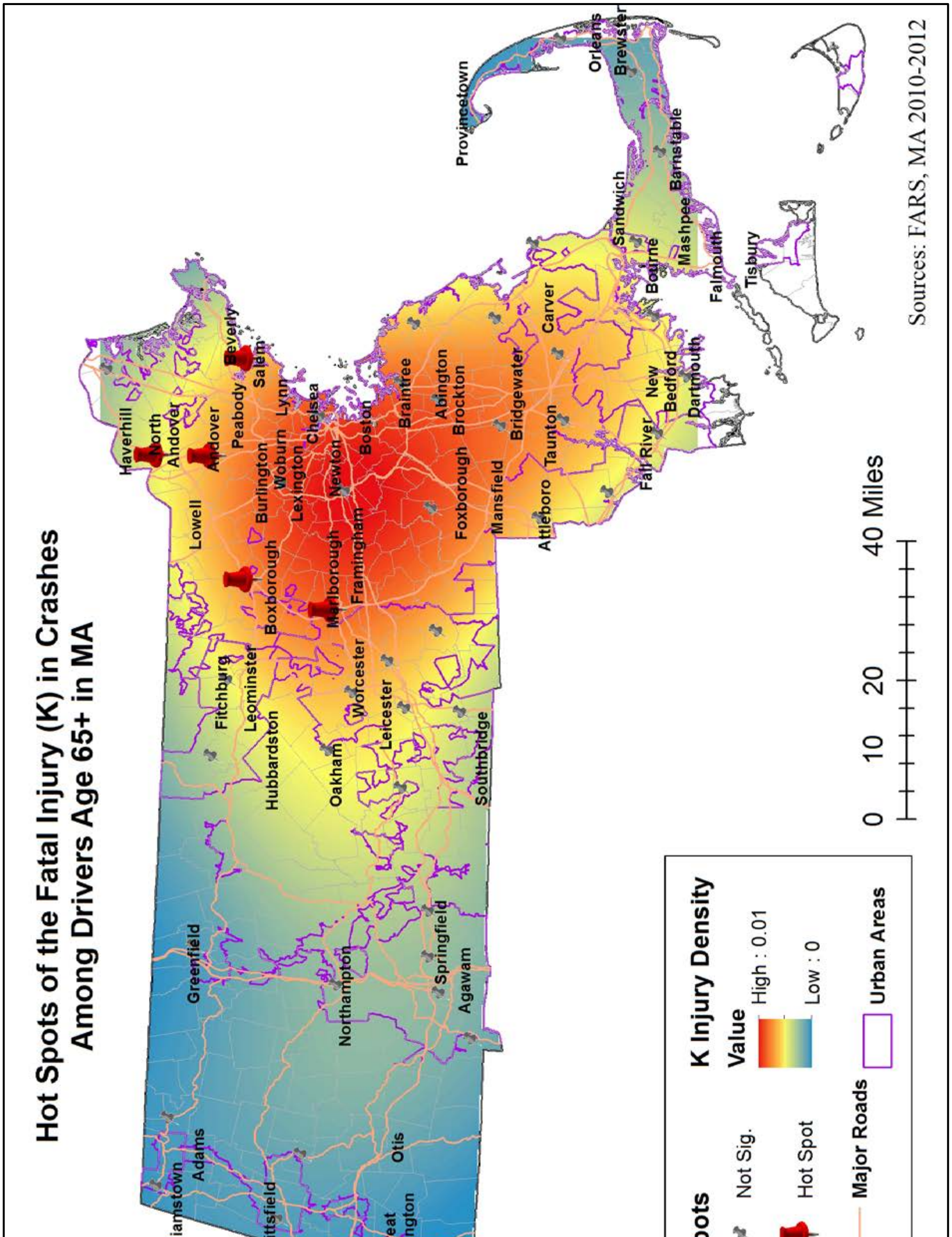


Figure 35. The Hot Spots of Crash Locations by the Incapacitating, Non-incapacitating Evident, and Possible Injury among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

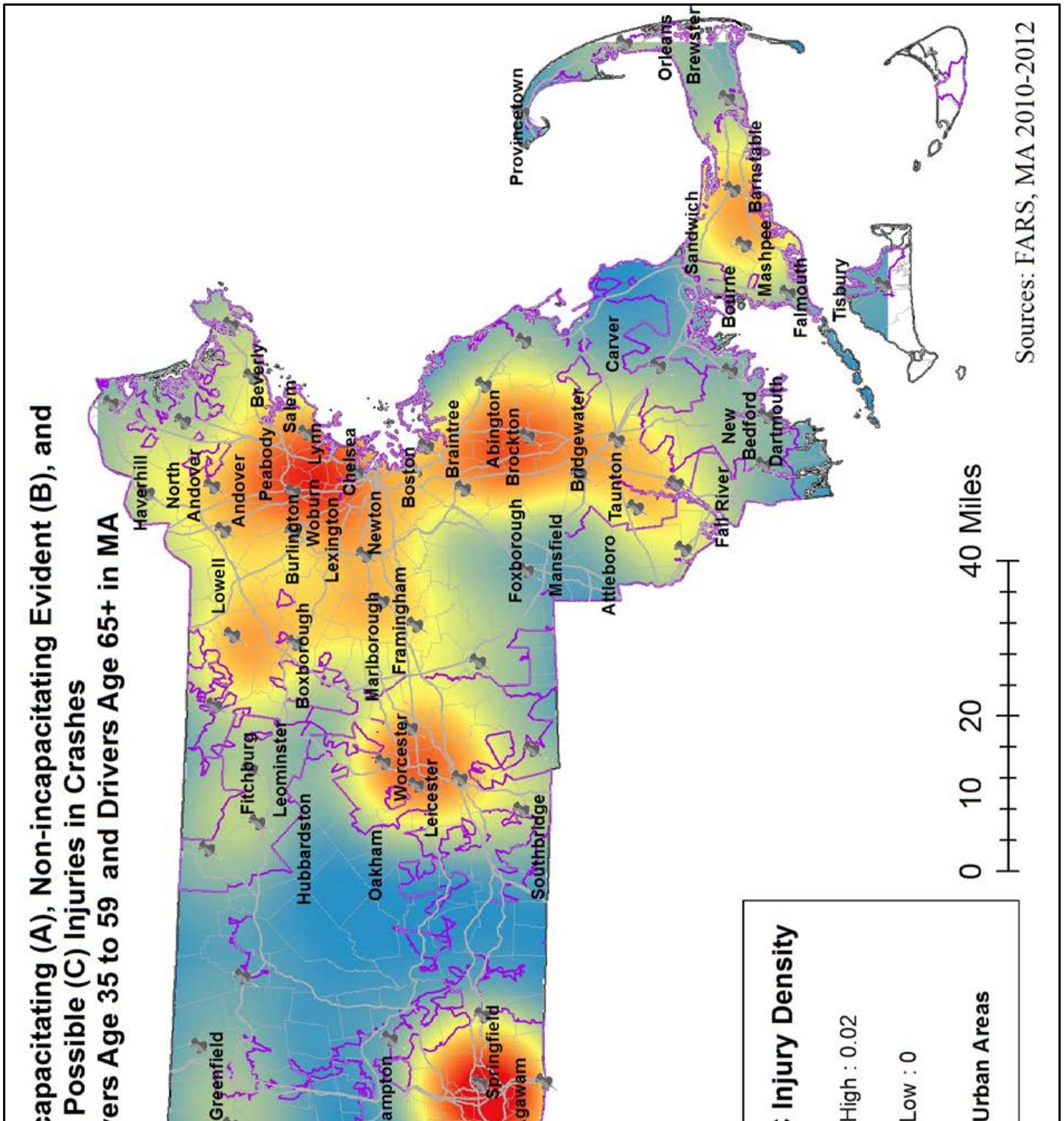


Figure 36. The Hot Spots of Crash Locations by the Incapacitating, Non-incapacitating Evident, and Possible Injury among Drivers Age 35 to 59 in MA from FARS 2010-2012

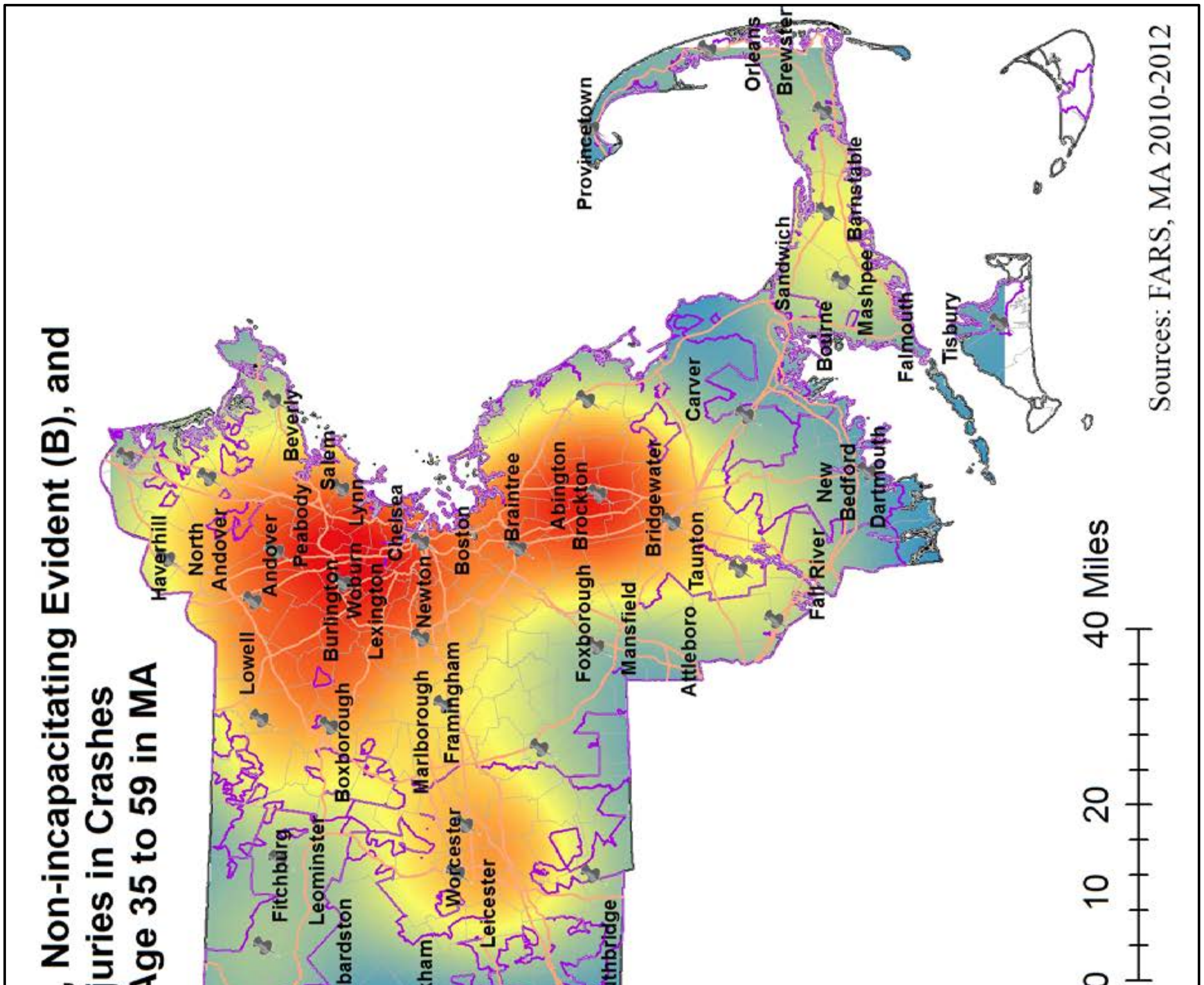


Figure 37. The Hot Spots of Crash Locations by the No Injury
among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

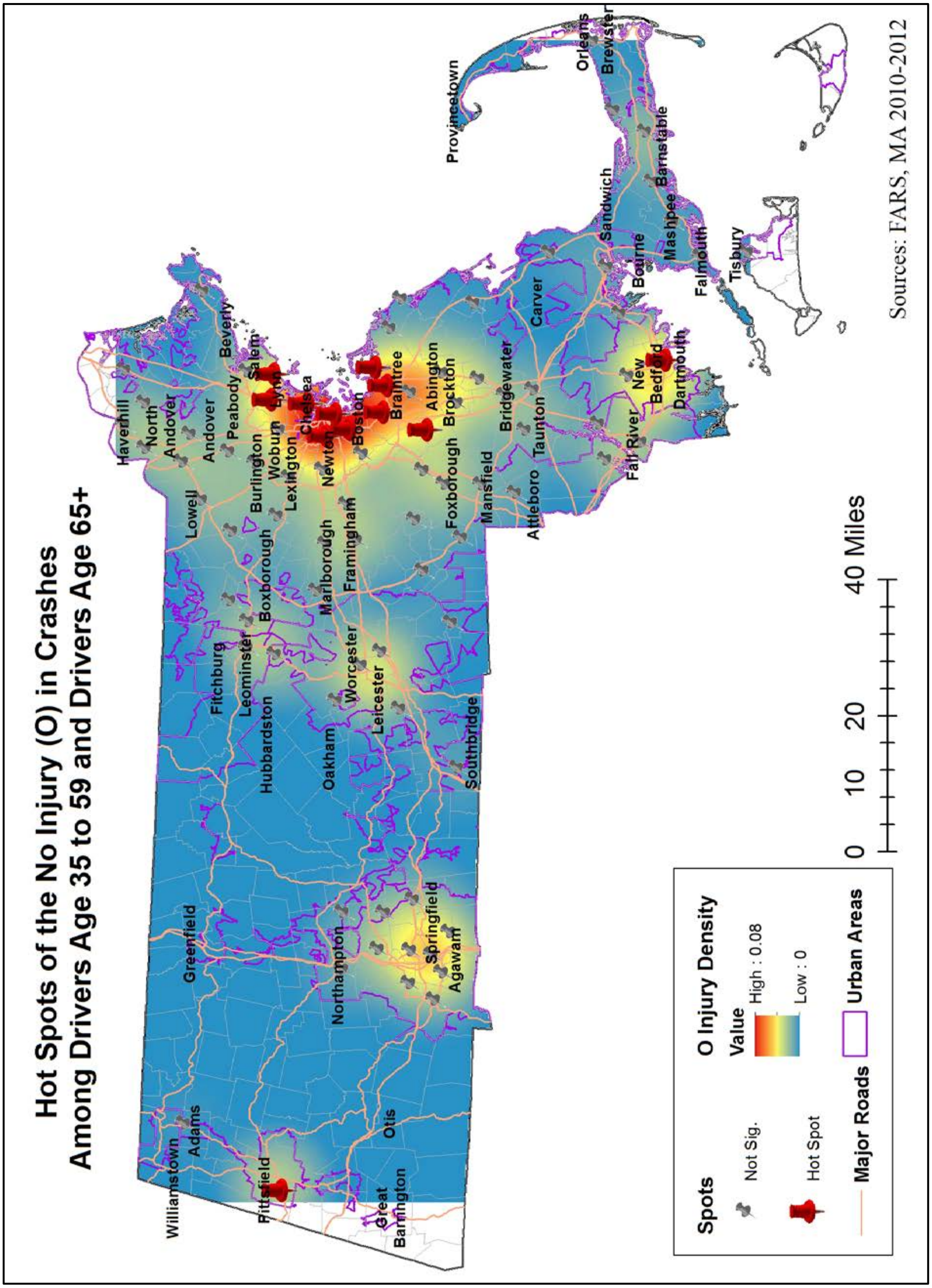
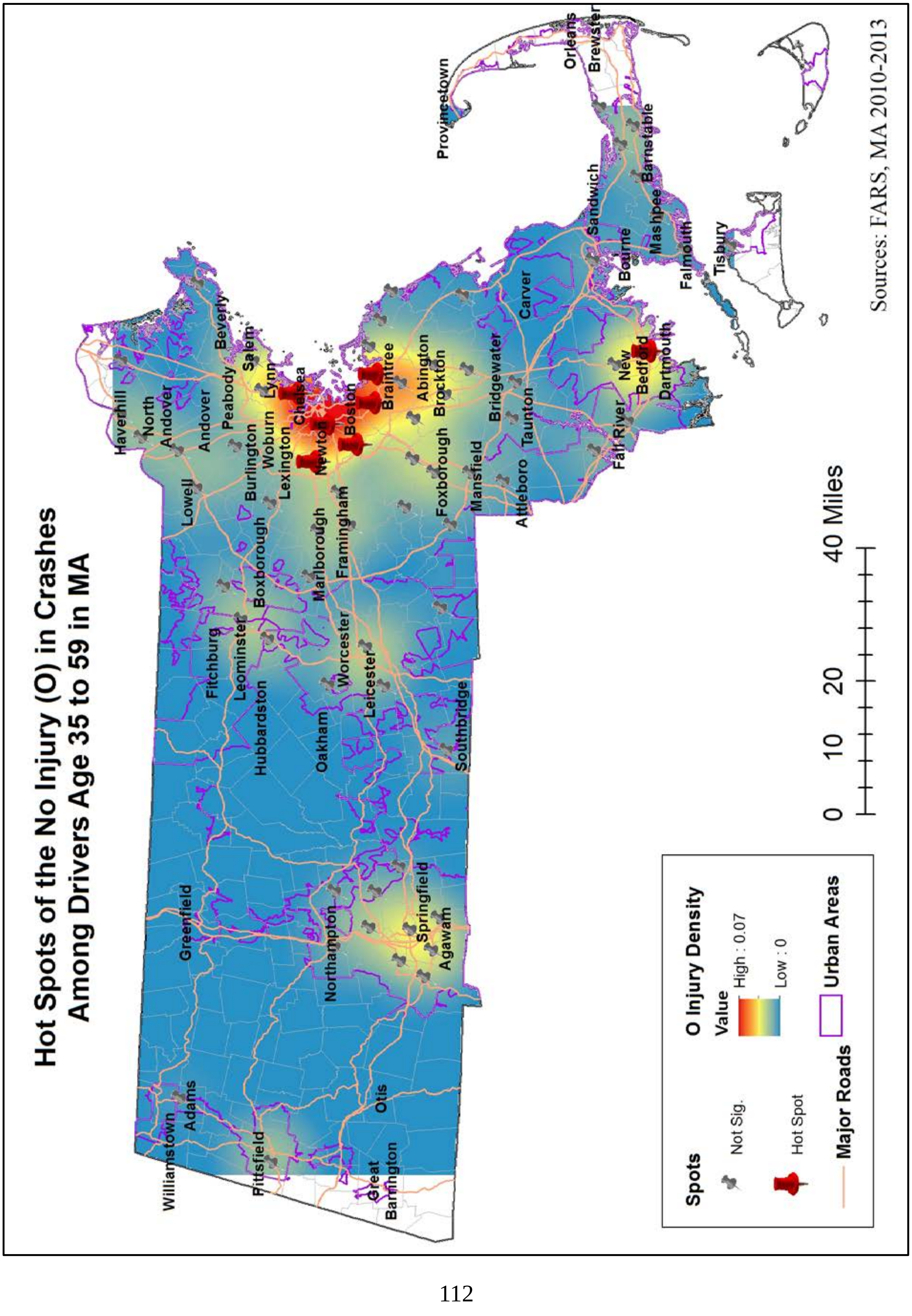


Figure 38. The Hot Spots of Crash Locations by the No Injury among Drivers Age 35 to 59 in MA from FARS 2010-2012



CHAPTER 7

DISCUSSION, LIMITATIONS, AND POLICY IMPLICATIONS

This chapter presents a discussion of the results from the MNL and spatial models, limitations of the study and data, future research recommendations, and policy implications to improve safety on the roads.

Discussion

There has been a growing interest in motor vehicle crash related injuries among drivers in the United States. It is important to identify what factors contribute to severe injury or fatality resulting from car crashes. The main purpose of this dissertation was to examine how individual characteristics, vehicle elements, environmental elements, and driving license policy were associated with level of injury severity ranging from no injury to fatal injury resulting from car crashes. This dissertation used the KABCO scale which classifies a range of injury severity including: fatal injury (K), incapacitating injury (A), non-incapacitating evident injury (B), possible injury (C), and no injury (O).

By investigating the nationally representative annual crash data of GES from 2010 to 2012, this dissertation performed a quantitative analysis of the MNL model to examine the relationships between those multiple factors and injury severity among drivers involved in crashes. Further, because all car crashes occur in a geographical area that can be mapped by GIS, this tool can assist in the spatial analysis that offers both

identification and visualization of crash locations and hot spots of crash by injury severity, driver age, and regional factors.

Before beginning the analysis, it was necessary to explore the literature review of crash related studies to identify potential factors and develop the conceptual frameworks of how multiple factors impact injury severity in crashes. After confirming the dependent and independent variables, this dissertation performed the bivariate analysis to examine the associations between injury severity and the independent variables. The results of bivariate analysis provided distributions of injury severity by each independent variable and indicated significant differences between injury severity and independent variables.

With respect to individual characteristics observed in results from the MNL model, the findings of this dissertation are consistent with previous studies about relationships between crash injury and age, gender, and drivers' conditions. Since there are greater numbers of younger drivers as compared to older drivers in the US., results of this dissertation indicate a reasonable finding that there are greater numbers of younger drivers age 35 to 59 than older drivers age 65 and older in a crash. However, the findings of this dissertation show differences in a rate of injury severity between younger drivers and older drivers. While fewer older drivers are involved in crashes, they are more likely to be injured compared to younger drivers. Overall, it shows that older drivers than younger drivers have greater rates of fatal, incapacitating, and non-incapacitating evident injuries in crashes.

Results also show that the higher risk of injury severity in a crash is associated with the older age groups of drivers. For example, compared to drivers age 35 to 59, drivers age 65 to 74 are more likely to have the incapacitating and non-incapacitating evident injuries, and drivers age 75 to 84 as well as drivers age 85 and older are more likely to have the fatal, incapacitating, and non-incapacitating evident injury when involved in crashes. Notably, the oldest group of drivers (age 85 and older) has a much greater likelihood of the fatal and incapacitating injuries compared to the reference group of drivers (age 35 to 59). Thus, these findings agree with the previous studies that suggest that age is associated with severe injury (Bédard et al., 2002; Cicchino & McCartt, 2014; Cicchino & McCartt, 2015; Finison & Dubrow, 2002). As hypothesized, age is a determinant factor of increase in injury severity resulting from crashes.

Consistent with gender differences in crashes resulting in severe injury (Awadzi et al., 2006; Finison & Dubrow, 2002; Rzeznikiewiz, Tamim, & Macpherson, 2012), the findings of this dissertation demonstrate the gender differences in the study sample that there are more male drivers than female drivers in crashes. However, compared to male drivers, female drivers are more likely to have the incapacitating, non-incapacitating evident, and possible injuries in crashes in spite of lower rates of crash involvement among female drivers. As suggested in the hypothesis, female drivers have a greater likelihood of severe injury when involved in crashes. Regarding findings that older drivers and female drivers have greater risks of severe injury resulting from crashes, it is expected that older female drivers are more likely to have severe injury compared to older male drivers (Baker, et al., 2003; Bédard et al., 2002). This may be due to physical

differences between older men and women (e.g., women have increased risk of osteoporosis, on average are of smaller stature) which would be associated with increased risk for fractures and/or more severe injuries. Also, given the declines in height with age, the vehicle may not “fit” an older female as well as an older male. This mismatch between vehicle and driver is widely recognized as a problem and the focus of the AARP *Carfit* program. This dissertation did not examine the importance of an age by gender interaction in injury severity, but the future research could be warranted to explore this interaction.

In regard to drivers with chronic medical conditions or visual impairment, this dissertation supports previous findings that physically or mentally impaired drivers are more likely to have the fatal, incapacitating, non-incapacitating evident, and possible injuries types in crashes compared to drivers with normal conditions. Several previous studies found that those impaired drivers were at an increased risk of crash involvement and greater likelihood of severe injury (McGwin et al., 2000; Owsley et al., 1998; Owsley & McGwin, 1999). Most prominently, those impaired drivers have a much greater relative risk of having the fatal injury over the no injury (Zhang et al., 2000). Thus, as risks of chronic medical conditions and vision impairments are increasing with aging, the findings of this dissertation provide empirical evidence of potentially high risks of crash involvements and severe injury resulting from crashes among older drivers.

Similarly, compared to drivers with normal conditions, drivers falling asleep while driving are more likely to have incapacitating, non-incapacitating evident, and possible injuries, and drivers operating the vehicle ‘under the influence’ (DUI) are also

more likely to have the fatal, incapacitating, non-incapacitating evident, and possible injuries. These findings are also consistent with previous studies that drivers with DUI are associated with a greater likelihood of severe injury in crashes (Awadzi, et al., 2008; Bédard et al., 2002).

In regards to the number of passengers' impact on injury severity, the finding of this dissertation reveals that drivers with at least one passenger increased the risk of having the fatal, incapacitating, non-incapacitating evident, and possible injuries in a crash compared to drivers without any passengers. It is observed in this dissertation that drivers having passengers are associated with increases in risk of injury severity in crashes. Yet, there remains questions to be answered. While studies of teen drivers have found driving with peers is associated with an increased risk of crash, research on older drivers with passengers has reported a decreased likelihood of having injury in crashes. Researchers have suggested that passengers may act as a co-pilot for older drivers and have played a protective role by watching other vehicles, warning a driver of upcoming danger, or checking traffic signs and these assistive behaviors may be a reason for decreasing risks of injury in crashes. On the other hand, previous studies recommended when older drivers were distracted by passengers while driving, it could yield adverse events resulting potential injury in crashes (Awadzi et al., 2008, Bédard & Meyers, 2004; Classen et al., 2007; Hing et al., 2003). However, this dissertation could not investigate the role of passengers as to they assist or distract drivers while driving. Thus, these tentative conclusions await further refinement and correction in the light of further research.

Next, with respect to the vehicle factors, the findings of this dissertation demonstrate that compared to drivers of pick-up trucks, drivers of sedans experience an increase in likelihood of the non-incapacitating evident and possible injuries, but drivers of mini-van can expect a decrease in likelihood of the incapacitating and non-incapacitating evident injuries in crashes. Drivers of SUV are not significant in the results of this dissertation. As suggested in the hypothesis regarding vehicle types and injury severity, the sedan type of vehicle is a risk factor of injury severity, whereas the mini-van type of vehicles is a protective factor of injury severity (Classen et al., 2007; Farmer et al., 1997; Krull et al., 2000). In fact, it is important to remember that vehicle types are correlated with vehicle weights. The lighter vehicles are associated with the higher risk of injury severity.

Additionally, with respect to the collision side of vehicles (front, right, etc.), the findings of this dissertation show similar patterns to past research that drivers involved in front or right side impact have an increased likelihood of the fatal injury, but decreased likelihood of the non-incapacitating evident and possible injuries compared to drivers involved in rear side of impact. Overall, drivers involved in left side impacts or other types of collision (rollover, under-ride) significantly increase risks of the fatal, incapacitating, and non-incapacitating evident injuries compared to drivers involved in rear side of impact (Classen et al., 2007). These findings suggest that left side impact collisions (driver's side), or rollovers have greater risks of severe injury among drivers in a crash. However, any side of impact on a vehicle is associated with increased likelihood of the fatal injury among drivers. It is highly probable that direct physical force is

influencing the higher damages to drivers with collision of the left side of vehicles.

The function of safety restraints (seat belt or airbag) in the vehicle is well known to protect occupants in the vehicle from adverse events. Consistent with previous studies, the findings of this dissertation reveal that drivers using a seat belt are less likely to have the fatal, incapacitating, non-incapacitating evident, and possible injuries compared to drivers not using a seat belt. Furthermore, the findings of this dissertation highlights that the usage of seat belts provides much greater protections against death or suffering more severe injuries when a crash occurred. Consistent with previous studies, results suggest that the usage of seat belts are efficient in preventing fatality and severe injuries in a crash (Bédard et al., 2002; Classen et al., 2007; Finison & Dubrow, 2002; Liu, Utter, & Chen, 2007; Wang & Kockelman, 2005).

On the other hand, results regarding airbag deployment suggest the opposite, and are in opposition to seat belts use. Compared to drivers involved in a crash in which airbags were not deployed, drivers with airbags deployed are more likely to have the fatal, incapacitating, non-incapacitating evident, and possible injuries in a crash. Results also show that there is a much greater likelihood of severe injury of the fatal and incapacitating injury types. Other studies also found that deployment of the airbag was a risk factor of injury in crashes (Awadzi et al., 2008; Wallis & Greaves, 2002; Yoganandan, Pintar, Zhang, & Gennarelli, 2007). However, interpretation of the impact of airbag deployment in a crash must be done with caution. Unlike seat belts, airbags are programmed to deploy based on a sensor system in the vehicles. When the force or energy of impact reaches a trigger point, the airbag is activated. For example, the airbag

may not deploy when a vehicle has a minor collision such as bumper to bumper in the parking lot. However, the airbag is more likely to deploy when a crash occurs on the interstate freeway while traveling with high speed. As a result, there must be high a correlation between severe crash caused by high speed and the deployment of an airbag. Data regarding the speed of vehicle was not available in the GES crash data. However, results did show that the likelihood of having incapacitating and non-incapacitating evident injuries was increased when drivers involved in a crash on the highway roads. Thus, airbag deployment is associated with more severe crashes and therefore likely results in greater injury severity.

Furthermore, when a severe crash occurs, the deployment of an airbag could be adding more impacts on the upper body of drivers. Wallis and Greaves (2002) noted that the deployment of airbags was related to chest or abdomen injuries in a crash. Compared to younger people, older people with more vulnerable and fragile upper bodies could have severe injuries caused by severe crashes with the deployment of an airbag. By examining the interaction terms between older age and the deployment of airbag, this dissertation provides convincing answers that older drivers with the airbag deployed in a crash had a greater risk of severe injuries of incapacitating and non-incapacitating evident (See Table A2 in Appendix). Therefore, with respect to severe crashes caused by high speed on the highways and fragile or vulnerable older people, the deployment of airbag is associated with an increase in likelihood of severe injury or fatality. Future research is needed to reach a fuller understanding of relationships between airbags and injury severity.

With respect to the environmental factors, it is hypothesized that drivers involved in crashes at intersection roads are more likely to have severe injury compared to those drivers involved in crash at non-intersection roads. The findings of this dissertation demonstrate that crashes at intersection roads are associated with a decrease in the fatal injury, but an increase in the non-incapacitating evident and possible injuries among drivers. Also, results show that other types of intersections such as driveway, ramp, or roundabouts are associated with a decrease in severe injuries of fatal and incapacitating. These findings are contrary to previous studies (Awadzi et al., 2008; Boufous et al., 2008; Classen et al., 2007; Griffin, 2004). It may be that speed or vigilance account for the unexpected findings. For example, vehicle speed near and thru intersections tends to be slower than driving on the open road. Scanning for potential danger and oncoming vehicles may be heightened in intersections than when driving on the open road. As a result, when crashes occur at intersection roads, they may result in less injury severity and fatality as observed in this dissertation.

The initial hypothesis suggested that unfavorable driving conditions (e.g. darkness, raining, or snowing) would have an impact on lower levels of injury severity. In regard to darkness, the results of this dissertation supported the original hypothesis. For example, drivers involved in a crash between 12pm and 5pm are less likely to have the fatal and possible injuries compared to those drivers involved in crash between 6am and 11am. Similarly, crashes occurring between 6pm and 11pm are associated with a decrease in the incapacitating and non-incapacitating evident injuries. Regarding the darkness

conditions, the time period of 6pm to 11pm is related with sunset and darkness but the time period of 12pm to 5pm is typically a full light period. Interestingly, both these time periods were associated with decrease in risk of injury in crashes. Despite these findings, it suggests further research that must be reserved to compare the appropriate time periods of day and of amount or quality of lighting.

An inconsistent finding was observed regarding the hypothesis about unfavorable driving conditions and injury severity. Drivers involved in a crash between 12am and 5am increase the risk of the non-incapacitating evident injury. Similarly, results regarding weather did not support the initial hypothesis. According to this study, rainy weather is associated with an increase in risk of the possible injury for drivers in crashes.

As noted above, the self-regulation of driving behavior play a role in avoiding driving during darkness or adverse weather conditions. This driving behaviors may tend to reduce rates of crash involvement under those conditions. However, this dissertation suggests that unfavorable circumstance such as dark light and bad weather is associated with severe injury in a crash (Awadzi et al., 2008; Baker et al., 2003; Finison & Dubrow, 2002).

Finally, with respect to the policy factors, the findings of this dissertation indicate that three licensing renewal policies (in-person renewal, accelerated renewal cycle, and written/road test for renewal policy) are associated with increase in risk of the incapacitating, non-incapacitating evident, or possible injuries for drivers in a crash. Since the state license renewal policies in this dissertation consider age requirements (varied between 65 to 80 by states) the above three policies have a greater proportion of

older drivers involved in crashes than those of younger drivers. Thus, given findings of greater risk in severe injuries for older drivers than younger drivers, but it should be reiterated that older drivers in states implementing those age-related policies are potentially related with increases in risks of severe injury.

On the other hand, two policies (vision test at license renewal and mandatory physician's medical reporting) were associated with a decrease in risk of the fatal, incapacitating, or non-incapacitating evident injuries for drivers in a crash. The finding regarding the vision test renewal policy is consistent with McGwin et al. (2008), in which drivers age 85 and older were observed to be less likely to have fatal injuries in crashes after vision testing became mandatory renewal procedure in Florida. Mandatory physician reporting has not been well-studied so this finding is a major contribution to the field.

The original hypothesis suggested that certain policy factors would impact injury severity. Specific aspects of the hypothesis were supported by the results, yet contradictory results were observed as well. For instance, Grabowski, Campbell, and Morrisey (2004) and Tefft (2014) found that drivers age 85 and older in states with in-person renewal policy had a reduced risk of fatal crash involvements, yet, the opposite findings were observed in this study. It is important to note that Grabowski et al. had a different outcome variable than this dissertation. They focused on the total rates of fatal crash involvements, whereas this dissertation focused on injury severity of drivers who were involved in crashes. Thus, this dissertation has expanded the understanding of potential state policy measures (vision testing, and mandatory physician medical

reporting) that may be protective factors of severe injury among drivers in crashes.

Furthermore, the spatial analysis of the hot spots in MA showed that road interchanges are especially dangerous. Specifically, the hot spots of crashes were located within the urban boundary where the major roads in MA intersect with each other. This finding is inconsistent with other studies and suggests that drivers were more likely to be involved in a crash resulting in severe injury nearer rural versus urban areas (Brown et al., 2000; Clark, 2001; Finison & Dubrow, 2002; Zwerling, 2005). These cited studies noted that the greater risk of severe injury in rural areas was related to crashes occurring on the highways where most drivers were traveling with high speed. Higher speed is frequently related to worse crash outcomes.

Overall, the spatial analysis by the GIS application in this dissertation was an important approach to visualize the points of crash locations and identify the hot spots of crash by injury severity in MA. While analyzing the points of crash locations, this dissertation shows areas where the crash data points are clustering in greater numbers. In other words, it could be specifying that the urban areas have greater numbers of points which crashes occurred than those of rural areas. Also, GIS distinguishes hot spots between younger drivers and older drivers. However, there are many questions left unanswered – it is difficult to clarify why the hot spots of younger drivers are diametrically opposed to those of older drivers. By considering other crash factors such as traffic volume or aggregating points of crash data in smaller areas (e.g. zip codes, census track, or census blocks) as well as road types (e.g. highways or intersection), it might provide further insight why those hot spots are varied. Therefore, further research

is needed.

In conclusion, this dissertation focused on how multiple factors of individual characteristics, vehicle elements, environments, and licensing renewal policy influence injury severity among drivers involved in crashes by investigating the GES crash data. Also, this dissertation visualized the hot spots of crashes resulting in severe injury among drivers in MA by investigating the FARS crash data. By reviewing the previous studies related with crash and injury severity among drivers, a summary of risk and protective factor for injury outcomes were presented.

According to Table 2 (summary of previous studies) it is highly probable that this dissertation has made a great contribution to crash related research. Undoubtedly, there are many previous studies, but it is difficult to find studies that take individual characteristics, vehicle elements, environments, and policy factors into account. Although one study done by Classen et al (2007) included multiple factors similar to this research, their study did not include the important policy factors included in this analysis. Nor did the study include the hot spot analysis incorporated in the current research.

Furthermore, the findings of this dissertation are overall consistent with results from previous studies. However, this dissertation still provides some strengths in crash related research. First, this dissertation considered 5 different categories of injury outcomes provided with the KABCO scale, whereas many other studies focused on dichotomous outcomes such as injury vs non-injury or fatal injury vs non-fatal injury. There can be little doubt that fatal injury stands in sharp opposition to minor injury. If categorizing just two outcomes of injury, results may give a biased suggestion that

specific factors are associated with severe injury such as fatality when in fact injury occurs on a much larger spectrum. This study's analysis of 5 categories of injury severity, offers a clearer understanding of the relationship between factors that are associated with fatal as well as less severe injury.

Second this dissertation continuously suggests the importance of examining the relationship between multiple factors and injury severity in a crash. Specifically, licensing renewal policy may restrict or cease driving for risky drivers potentially reducing crash involvement and injury outcomes. Despite this importance, many previous studies did not consider policy factors in their investigation of the GES crash data. This study, however, extracted zip code information for drivers involved in a crash. This information offered analysis of license renewal policy by state and observation of its relationship to injury severity.

Third, all crashes have a spatial attribution of environmental elements such as roads, areas, or locations. By using spatial attributions of longitude as well as latitude of crash locations in the FARS crash data, this dissertation performed the spatial analysis to visualize crash locations by drivers' injury severity on the map and presented the hotspot of crash locations by drivers' injury severity in MA. Identification of these crash hotpots will be beneficial for drivers in increasing their awareness of potentially increased risk in crash involvements while driving in or near hotspot areas. Thus, this study offered risk and protective factors as well as a visualization of crash hotspots.

Limitations

This dissertation has several limitations. First, by investigating the GES and FARS crash data, all respondents are involved in a crash. There is no comparison group of samples not involved in a crash. Second, with respect to the outcome variable of injury severity, this dissertation utilized the KABCO scale of injury severity from the crash dataset. This scale is based on a record of police observation made at the site of a crash. Since medical staff is not involved in data collection of injury severity in a crash, it is difficult to know how to specify the exact symptoms of injury and its severity. Therefore, there is a potential inaccuracy of injury severity. Third, the GES crash data does not provide socio-demographic variables of income, education, and race/ethnicity. According to Dugan and Lee (2013), racial and ethnic minorities were more likely to cease driving compared to white drivers. As a result, there could be a difference in crash involvement among race groups.

Future Research

The findings of this dissertation call attention to several issues in need of further investigation. First, as noted above, future research should consider how to improve the quality of measurement for the outcome variable of injury severity. For example, when hospital discharge data related to crashes is combined to actual crash data, future research will yield a better understanding of the association between crash injury and its factors. Similarly, in terms of drivers' physical or mental conditions, this study lacked specific medical conditions about a driver involved in a crash. As increasing aging is associated

with chronic conditions, visual impairments, and cognitive function, future research should investigate how specific conditions influence risk of crash and severe injury.

A second topic for additional research includes the relationship between age and other factors associated with severe injury. For instance, results showed that drivers age 65 and older are more likely to have severe injury in a crash compared to younger drivers age 35 to 59. Factors such as vehicle elements and factors associated with the environment were also observed to be associated with increased risk of severe injury in a crash. Further research is warranted to investigate how those vehicle and environmental factors interact with age in order to gain a clearer understanding the factors that influence injury severity among drivers involved in a crash.

Third, in terms of the spatial analysis, this dissertation finds several hot spots of crashes occurring areas in MA. Depending on drivers' age and injury severity, the hot spots are varied. This study considered the number of crashes occurring by severity. Future research should try to investigate what factors are associated with increased risk of crash resulting in severe injury in those proposed the hot spots areas. For instance, crashes may be occurring due to traffic volume, population density, roadway structures, land use, crash time, etc. Future research should consider these potential factors in order to provide a better understanding and to improve road safety.

Policy Implications

Currently, AARP and American Automobile Association (AAA) are providing educational driving programs (e.g. driver safety course from AARP & online defensive course from senior driving of AAA) related to the safety of older people. Information about these educational programs is available on the internet. These programs should be more available and accessible to older people who lack access and/or knowledge of the internet. Also, family members of older people should be aware of these educational programs of driving safety and encouraged to take the courses.

Further, Insurance Institute for Highway Safety (IIHS) and NHTSA are consistently producing reports regarding crash safety. These reports provide comprehensive information on crash risk factors about drivers, passengers, pedestrians, bike riders, vehicle technology, and environmental structures. The reports from these organizations should be more readily available and incorporated into driving educational programs. For example, in terms of airbag deployment, the benefits of airbags are still being debated. In fact, the results of this study support that airbag deployment is associated with risk of increase in severe injury in a crash. But that is likely due to the speed and force necessary in a crash to trigger and airbag deployment. For minor crashes they are not needed, and minor crashes result in no or minimal injuries. Translating such findings into educational resources takes time and skill.

Finally, with respect to policy, this dissertation reveals that seatbelts are a protective factor of injury severity and that DUI are a risk factor of injury severity in a

crash. A nationwide law mandates that drivers must wear a seatbelt while driving and DUI is an illegal driving behavior. When violating these laws, drivers receive legal consequences. When considering the injury severity associated with both, it is clear that these laws must be maintained continuously and applied consistently to all road users. However, driving license renewal policy for older drivers varies states. Although it is impossible to make universal driving renewal policy to all states, the findings of this mandatory physician reporting for at risk drivers are protective factors of injury severity in a crash. Considering physically or mentally impaired drivers are at increased risk of injury severity in crashes, such policy will be very beneficial for reducing risk of crash and injury severity. Currently, only 6 states in the United State implement the mandatory physician report for at risk drivers. This study suggests that those states not currently implementing this policy, as well as those states that have voluntary reporting, would benefit from mandated reporting in regards to decreasing risk of severe injury during crashes.

APPENDIX A
TABLES

Table A1. Comparisons Mean between Study Sample (n=106,631) and Missing Cases

Variables	Missing N	Missing Mean	Study Sample Mean	Chi-square	p
Individual					
Age groups					
Age 35 to 59	6,237	82.07%	80.86%	9.45	0.024*
Age 65 to 74		11.26%	11.45%		
Age 75 to 84		5.19%	5.95%		
Age 85 and older		1.48%	1.76%		
Gender: Female	7,712	42.80%	44.82%	11.78	0.001***
Driver's conditions					
Normal	6,169	89.72%	93.07%	120.93	0.000***
Impaired		5.28%	3.08%		
Asleep		1.23%	0.76%		
DUI		3.76%	3.09%		
Number of passengers					
Having passengers	7,809	24.32%	24.96%	1.62	0.203
Vehicle					
Safety restraints					
No seat belt	7,809	3.28%	2.25%	730.51	0.000***
Usage of seat belt		84.81%	92.79%		
Missing seat belt		11.91%	4.96%		
None-deployed airbag	7,809	52.95%	70.34%	2134.92	0.000***
Deployed airbag		16.05%	17.16%		
Missing airbag		31.00%	12.50%		
Body Types					
Sedan	5,501	59.08%	55.08%	51.70	0.000***
Mini-van		8.29%	8.57%		
SUV		19.94%	20.38%		
Pick-up truck		12.69%	15.97%		
Point of collision					
Front	6,653	50.22%	49.26%	17.46	0.002**
Rear		26.53%	26.25%		
Right-side		11.27%	11.09%		
Left-side		10.93%	11.81%		
Other collisions		1.05%	1.59%		
Number of vehicles					
One vehicle	7,809	23.10%	14.85%	380.28	0.000***
Two vehicles		60.49%	67.00%		
Three+ vehicles		16.40%	18.15%		

Note. *$p < .05$. **$p < .01$. *** $p < .001$.

(Table A1 Continued)

Table A1. Comparisons Mean between Study Sample (n=106,631) and Missing Cases (Continued)

Variables	Missing N	Missing Mean	Study Sample Mean	Chi-square	p
Environment					
Intersection roads					
No, intersection		43.00%	38.03%		
Yes, intersection	7,438	46.06%	49.86%	72.64	0.000***
Other intersections		10.94%	12.11%		
Highway roads	7,788	9.57%	11.21%	19.96	0.000***
Crash area of population					
Small city		25.21%	17.57%		
Mid-city	7,809	8.37%	8.90%	308.15	0.000***
Large city		39.30%	41.03%		
Other city		27.11%	32.50%		
Time of the day					
Morning (06:00-11:59)		28.55%	29.34%		
Afternoon (12:00-17:59)	7,422	44.58%	46.46%	36.39	0.000***
Evening (18:00-23:59)		20.60%	19.22%		
Night (00:00-05:59)		6.27%	4.98%		
Month of crash					
Spring		21.76%	24.26%		
Summer	7,809	24.04%	24.25%	36.06	0.000***
Fall		28.51%	26.04%		
Winter		25.70%	25.45%		
Weather conditions					
Clear weather		70.14%	73.20%		
Rain	6,956	11.03%	8.92%	54.75	0.000***
Snow		3.11%	2.38%		
Other weather		15.73%	15.50%		
Policy					
In-person renewal	7,809	30.20%	19.44%	522.18	0.000***
Accelerated renewal cycle	7,809	21.77%	3.80%	4927.28	0.000***
Vision test for renewal	7,809	61.37%	25.16%	4769.54	0.000***
Written/road test for	7,809	4.41%	0.88%	817.51	0.000***
Medical reporting for at risk-drivers	7,809	15.46%	11.54%	107.37	0.000***

Note. **p* < .05.***p* < .01.****p* .001.

Table A2. Multinomial Logistic Model for Injury Severity with Interaction Terms between Deployed Airbag and Age 65+

Variables	Fatality[1]		Incapacitating[1]	
	RR	95% CI	RR	95% CI
Individual				
Age groups				
Age 35 to 59 (Ref.)				
Age 65 to 74	1.236	(0.733-2.085)	1.108	(0.936-1.310)
Age 75 to 84	2.460**	(1.386-4.367)	1.107	(0.881-1.392)
Age 85 and older	2.899**	(1.333-6.309)	1.634**	(1.155-2.313)
Gender: Female	0.94	(0.699-1.263)	1.564***	(1.425-1.718)
Driver's conditions				
Normal (Ref.)				
Impaired	19.016***	(13.452-26.881)	4.868***	(4.067-5.827)
Asleep	2.009	(0.757-5.333)	2.856***	(2.026-4.028)
DUI	2.355**	(1.331-4.168)	3.141***	(2.553-3.864)
Number of passengers				
Having passengers	1.400*	(1.012-1.938)	1.169**	(1.049-1.301)
Vehicle				
Safety restraints				
No seat belt (Ref.)				
Usage of seat belt	0.022***	(0.016-0.032)	0.094***	(0.077-0.114)
Missing seat belt	0.061***	(0.036-0.102)	0.127***	(0.099-0.163)
Non-deployed airbag (Ref.)				
Deployed airbag	13.658***	(9.583-19.466)	12.892***	(11.474-14.484)
Missing airbag	0.776	(0.422-1.429)	1.178	(0.973-1.425)
Body Types				
Sedan	0.923	(0.627-1.358)	0.911	(0.797-1.040)
Mini-van	0.802	(0.450-1.431)	0.755**	(0.613-0.930)
SUV	1.009	(0.656-1.554)	0.937	(0.803-1.093)
Pick-up truck (Ref.)				
Point of collision				
Front	3.499***	(1.953-6.269)	1.04	(0.910-1.189)
Rear (Ref.)				
Right-side	4.884***	(2.335-10.215)	0.966	(0.807-1.155)
Left-side	7.236***	(3.933-13.315)	1.677***	(1.426-1.972)
Other collisions	33.457***	(16.337-68.517)	3.958***	(3.040-5.153)
Number of vehicles				
One vehicle (Ref.)				
Two vehicles	0.98	(0.692-1.386)	0.809**	(0.700-0.935)
Three+ vehicles	1.177	(0.638-2.171)	1.103	(0.934-1.303)

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

(Table A2 Continued)

Table A2. Multinomial Logistic Model for Injury Severity with Interaction Terms between Deployed Airbag and Age 65+ (Continued)

Variables	Fatality[1]		Incapacitating[1]	
	RR	95% CI	RR	95% CI
Environment				
Intersection roads				
No, intersection (Ref.)				
Yes, intersection	0.503***	(0.353-0.716)	1.007	(0.904-1.121)
Other intersections	0.538*	(0.297-0.976)	0.805**	(0.683-0.949)
Highway roads	1.34	(0.948-1.895)	1.347***	(1.175-1.544)
Crash area of population				
Small city	1.32	(0.688-2.531)	1.049	(0.871-1.263)
Mid-city (Ref.)				
Large city	1.551	(0.880-2.733)	1.145	(0.971-1.351)
Other city	2.917***	(1.676-5.076)	1.639***	(1.390-1.933)
Time of the day				
Morning (06:00-11:59) (Ref.)				
Afternoon (12:00-17:59)	0.620**	(0.446-0.862)	0.925	(0.831-1.030)
Evening (18:00-23:59)	0.884	(0.602-1.297)	0.795***	(0.698-0.905)
Night (00:00-05:59)	1.3	(0.831-2.035)	1.194	(0.976-1.461)
Month of crash				
Spring (Ref.)				
Summer	1.084	(0.755-1.557)	1.087	(0.957-1.235)
Fall	0.799	(0.532-1.201)	0.977	(0.863-1.106)
Winter	0.883	(0.614-1.270)	0.844*	(0.740-0.962)
Weather conditions				
Clear weather (Ref.)				
Rain	1.399	(0.839-2.334)	0.911	(0.777-1.067)
Snow	0.376	(0.125-1.130)	0.732	(0.531-1.010)
Other weather	1.414	(0.971-2.060)	1.032	(0.913-1.165)
Policy				
In-person renewal	1.524	(0.910-2.552)	1.337**	(1.110-1.611)
Accelerated renewal cycle	1.72	(0.950-3.115)	0.978	(0.753-1.269)
Vision test for renewal	0.590*	(0.372-0.937)	0.841	(0.700-1.011)
Written/road test for	0.471	(0.138-1.612)	1.246	(0.766-2.027)
Medical reporting for at risk drivers	0.542**	(0.351-0.838)	0.502***	(0.425-0.592)
Interaction terms				
Deploy airbag*Age 65+	1.783	(0.975-3.260)	1.882***	(1.500-2.362)
Constant	0.003***	(0.001-0.009)	0.045***	(0.032-0.064)
Pseudo R Square		**0.11**		

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

(Table A2 Continued)

Table A2. Multinomial Logistic Model for Injury Severity with Interaction Terms between Deployed Airbag and Age 65+ (Continued)

Variables	**Non-Incapacitating[1]**		**Possible[1]**	
	RR	**95% CI**	**RR**	**95% CI**
Individual				
Age groups				
Age 35 to 59 (Ref.)				
Age 65 to 74	1.048	(0.947-1.159)	0.889*	(0.807-0.978)
Age 75 to 84	1.168*	(1.021-1.337)	0.789***	(0.697-0.893)
Age 85 and older	1.181	(0.964-1.446)	0.856	(0.697-1.050)
Gender: Female	1.466***	(1.384-1.552)	1.609***	(1.527-1.694)
Driver's conditions				
Normal (Ref.)				
Impaired	2.430***	(2.112-2.795)	2.123***	(1.829-2.463)
Asleep	2.655***	(2.028-3.478)	1.843***	(1.398-2.430)
DUI	2.515***	(2.171-2.913)	1.389***	(1.178-1.637)
Number of passengers				
Having passengers	1.104**	(1.036-1.177)	1.169***	(1.104-1.237)
Vehicle				
Safety restraints				
No seat belt (Ref.)				
Usage of seat belt	0.241***	(0.204-0.285)	0.439***	(0.363-0.532)
Missing seat belt	0.267***	(0.217-0.329)	0.420***	(0.334-0.526)
Non-deployed airbag (Ref.)				
Deployed airbag	10.811***	(10.024-11.661)	5.365***	(5.001-5.756)
Missing airbag	1.210***	(1.090-1.342)	1.009	(0.925-1.101)
Body Types				
Sedan	1.122**	(1.031-1.222)	1.297***	(1.200-1.401)
Mini-van	0.882	(0.779-1.000)	1.043	(0.933-1.166)
SUV	1.052	(0.954-1.160)	1.07	(0.978-1.170)
Pick-up truck (Ref.)				
Point of collision				
Front	0.921*	(0.856-0.992)	0.493***	(0.463-0.525)
Rear (Ref.)				
Right-side	0.878*	(0.789-0.976)	0.517***	(0.472-0.567)
Left-side	1.258***	(1.140-1.388)	0.644***	(0.592-0.702)
Other collisions	3.166***	(2.636-3.802)	1.222	(0.994-1.501)
Number of vehicles				
One vehicle (Ref.)				
Two vehicles	0.677***	(0.619-0.742)	1.078	(0.986-1.179)
Three+ vehicles	1.105	(0.990-1.233)	1.490***	(1.342-1.653)

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

(Table A2 Continued)

Table A2. Multinomial Logistic Model for Injury Severity with Interaction Terms between Deployed Airbag and Age 65+ (Continued)

Variables	Non-Incapacitating[1]		Possible[1]	
	RR	95% CI	RR	95% CI
Environment				
Intersection roads				
No, intersection (Ref.)				
Yes, intersection	1.288***	(1.206-1.376)	1.270***	(1.195-1.349)
Other intersections	1.036	(0.941-1.139)	0.952	(0.872-1.039)
Highway roads	1.175**	(1.063-1.297)	0.897*	(0.813-0.990)
Crash area of population				
Small city	1.083	(0.968-1.212)	1.084	(0.980-1.199)
Mid-city (Ref.)				
Large city	1.078	(0.974-1.194)	1.283***	(1.171-1.405)
Other city	1.676***	(1.513-1.856)	1.405***	(1.277-1.545)
Time of the day				
Morning (06:00-11:59) (Ref.)				
Afternoon (12:00-17:59)	0.958	(0.898-1.022)	0.916**	(0.864-0.971)
Evening (18:00-23:59)	0.96	(0.885-1.042)	0.853***	(0.792-0.919)
Night (00:00-05:59)	1.187*	(1.035-1.360)	1.002	(0.879-1.142)
Month of crash				
Spring (Ref.)				
Summer	1.08	(0.999-1.168)	1.04	(0.967-1.120)
Fall	0.904*	(0.836-0.978)	1.042	(0.971-1.117)
Winter	0.863***	(0.796-0.934)	0.978	(0.911-1.050)
Weather conditions				
Clear weather (Ref.)				
Rain	1.015	(0.918-1.123)	1.134**	(1.032-1.245)
Snow	0.848	(0.698-1.029)	0.932	(0.783-1.109)
Other weather	1.078	(0.998-1.163)	1.066	(0.993-1.144)
Policy				
In-person renewal	1.460***	(1.314-1.622)	0.949	(0.850-1.058)
Accelerated renewal cycle	1.244**	(1.076-1.438)	1.187*	(1.023-1.377)
Vision test for renewal	0.778***	(0.701-0.865)	1.031	(0.933-1.140)
Written/road test for	1.321	(0.999-1.747)	1.051	(0.801-1.379)
Medical reporting for at risk drivers	0.884*	(0.800-0.976)	1.490***	(1.385-1.603)
Interaction terms				
Deploy airbag*Age 65+	1.561***	(1.342-1.816)	1.615***	(1.386-1.881)
Constant	0.082***	(0.065-0.104)	0.140***	(0.110-0.179)
Pseudo R Square		**0.11**		

Note: [1] No injury was used for the reference outcome variable in the MNL model. * < .05.***p*< .01.*** *p*< .001.

APPENDIX B
FIGURES

Figure B1. Distribution of Crash Locations by Injury Severity
among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

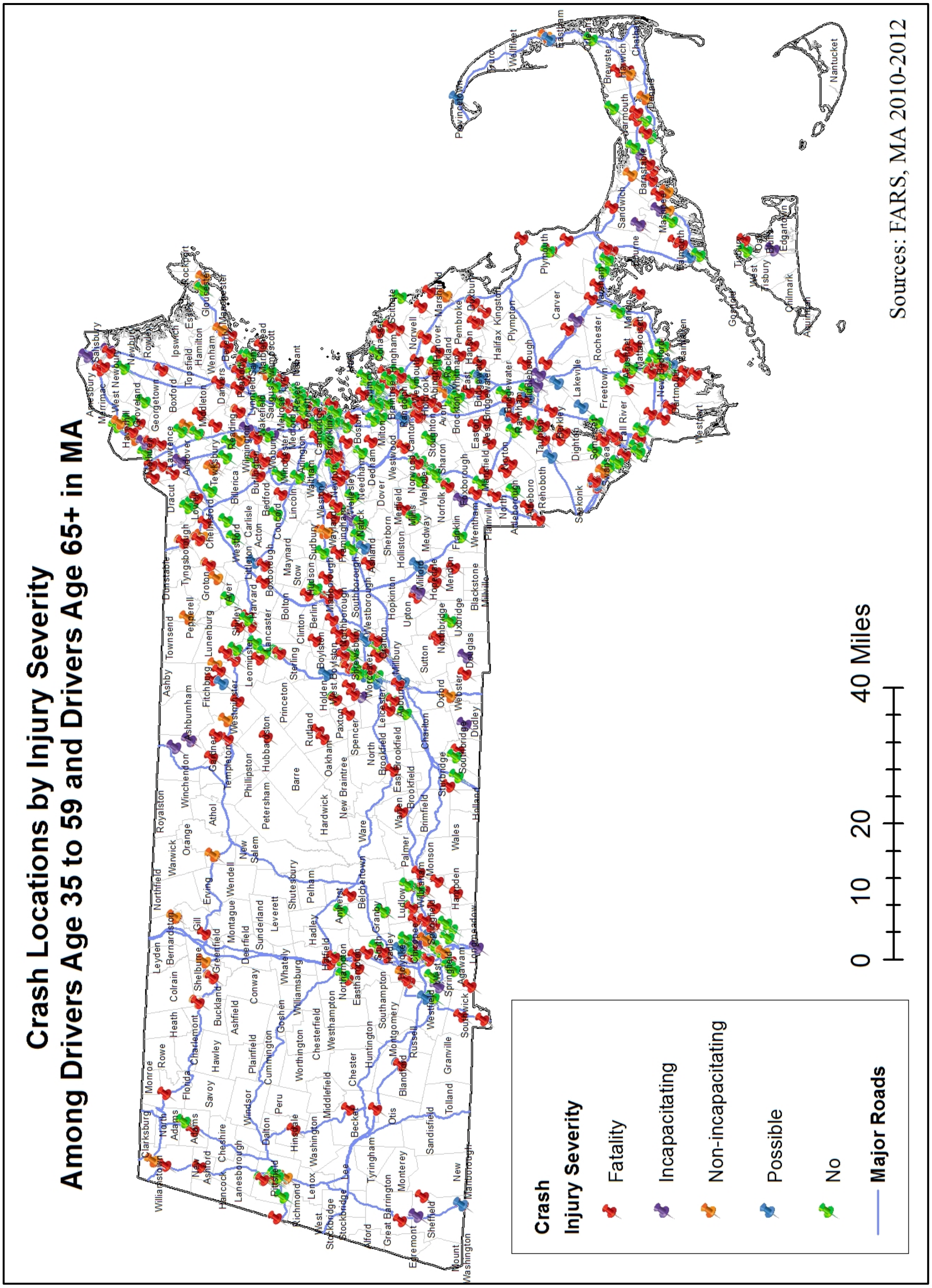


Figure B2. Injury Severity with Density of Population Age 35 to 59 in MA from FARS 2010-2012

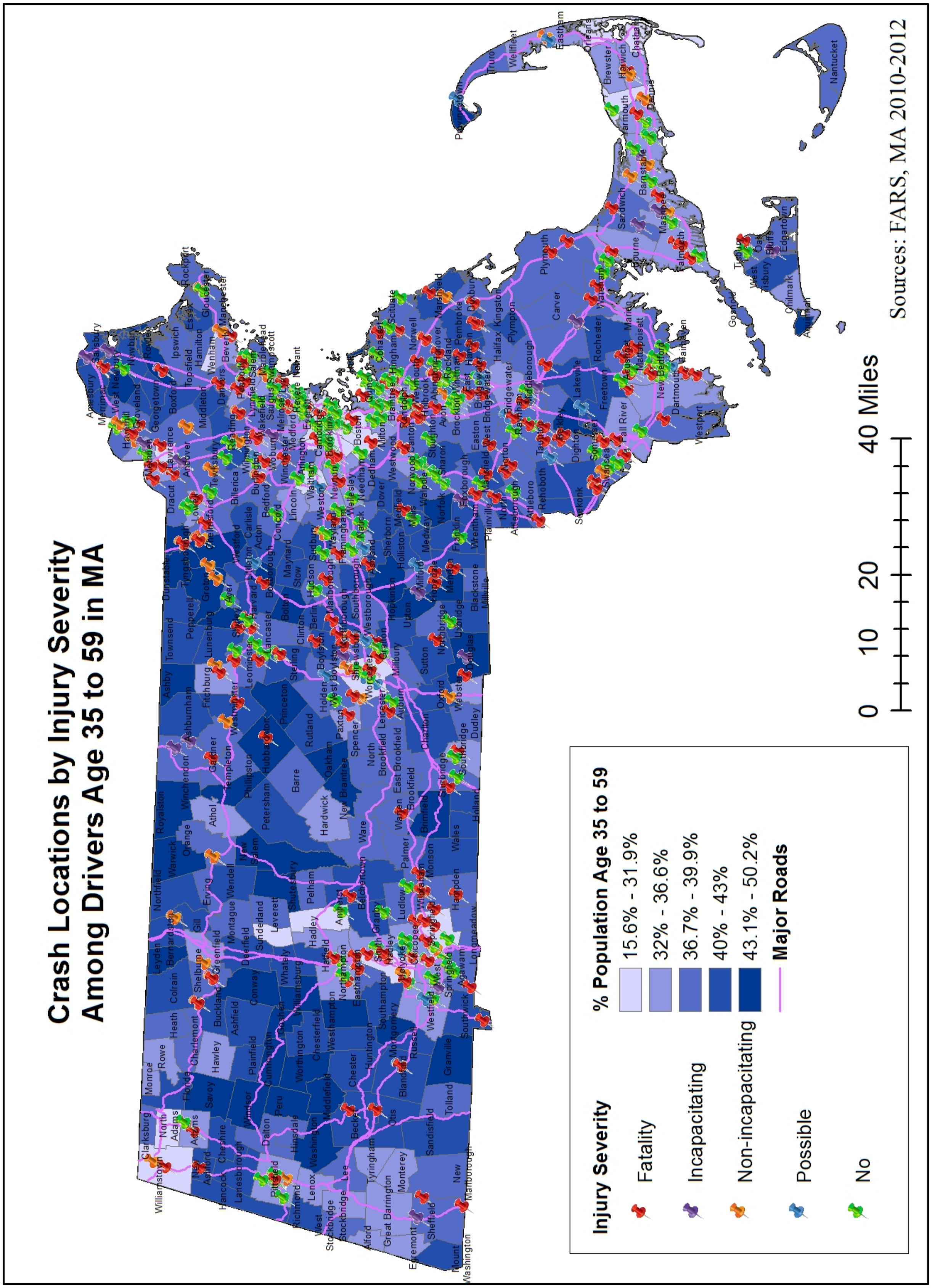


Figure B3. Injury Severity with Density of Population Age 65 and Older in MA from FARS 2010-2012

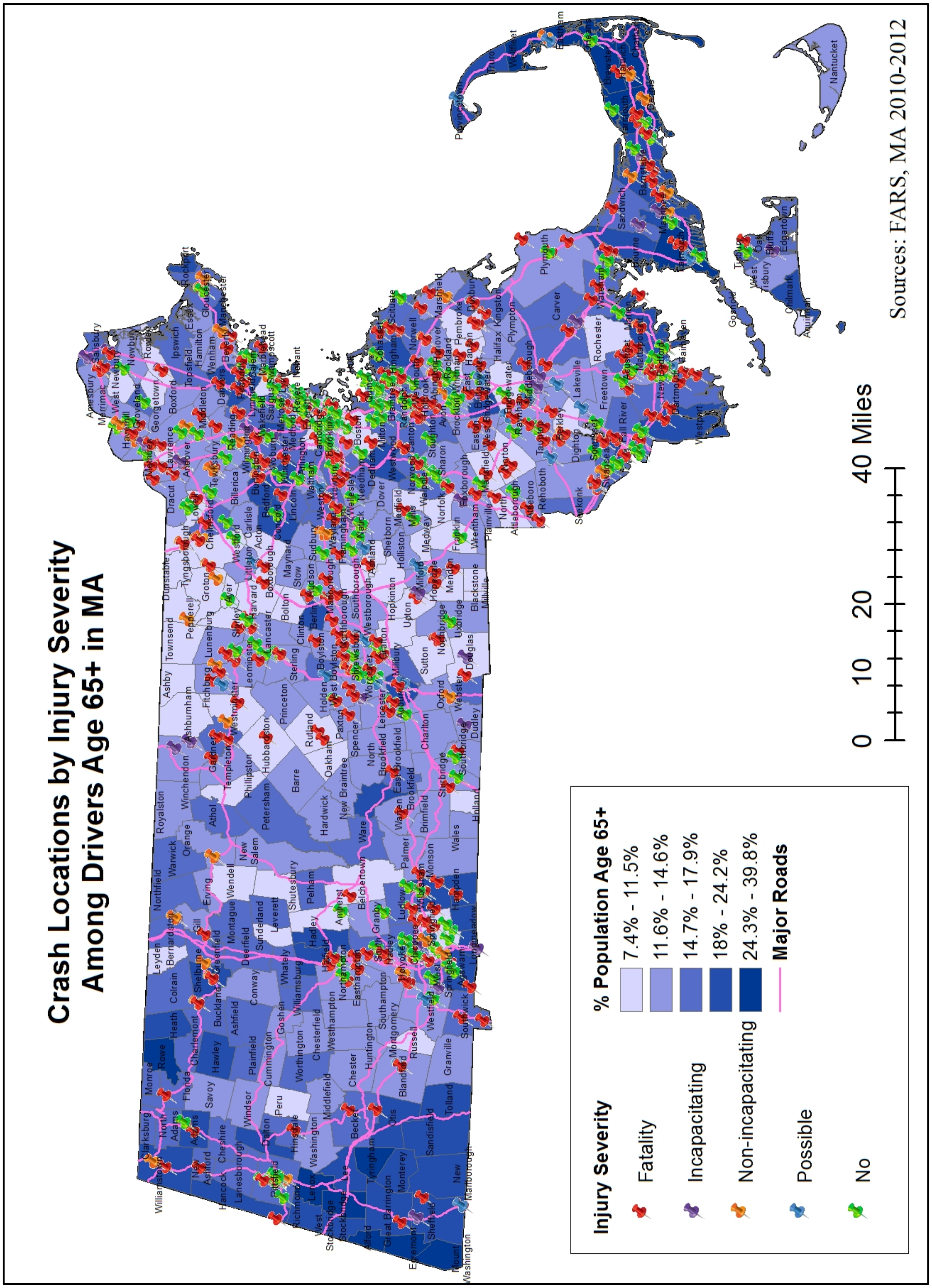


Figure B4. The Hot Spots of Crash Locations by the Fatal Injury
among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

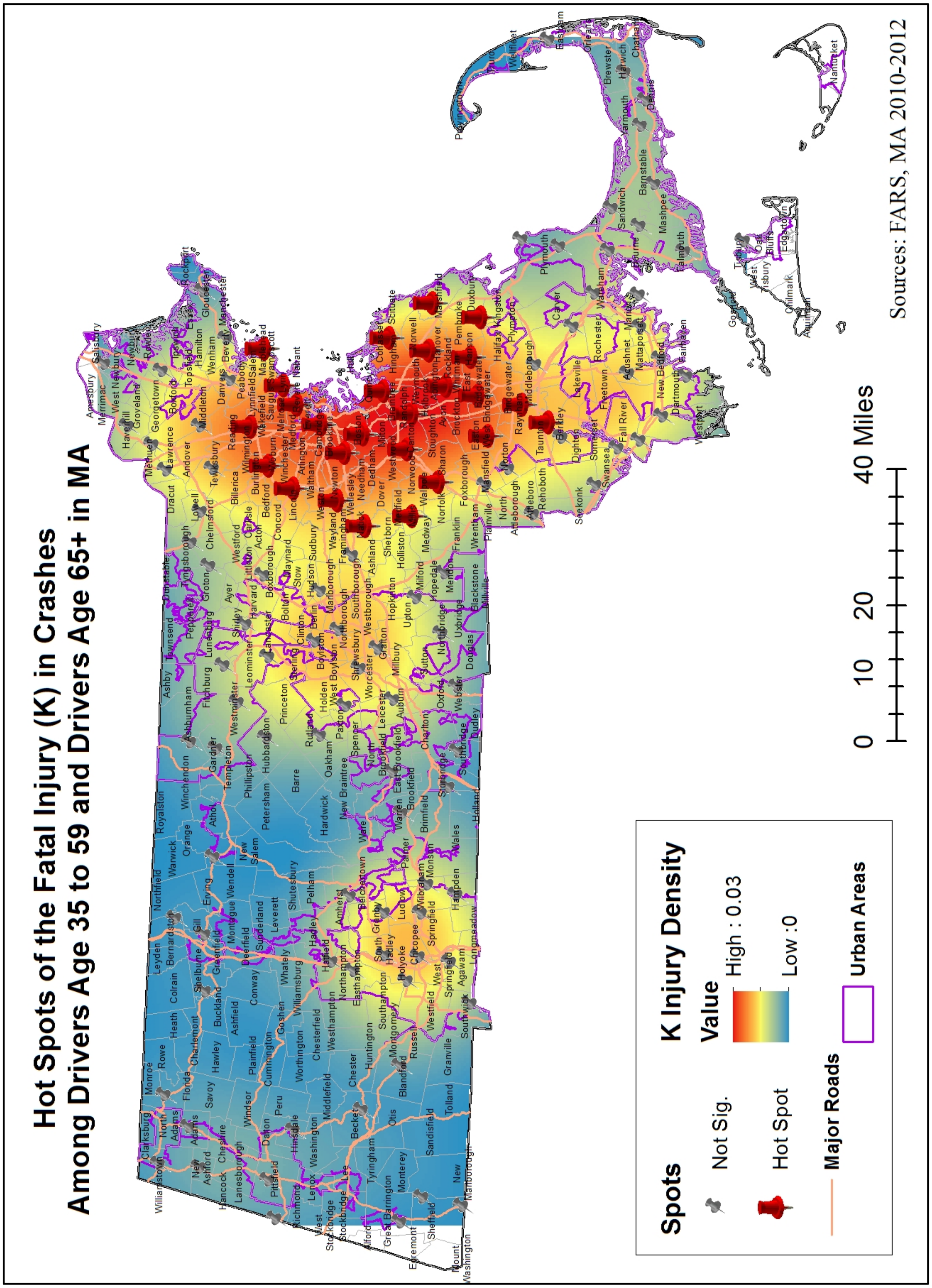


Figure B5. The Hot Spots of Crash Locations by the Fatal Injury
among Drivers Age 35 to59 in MA from FARS 2010-2012

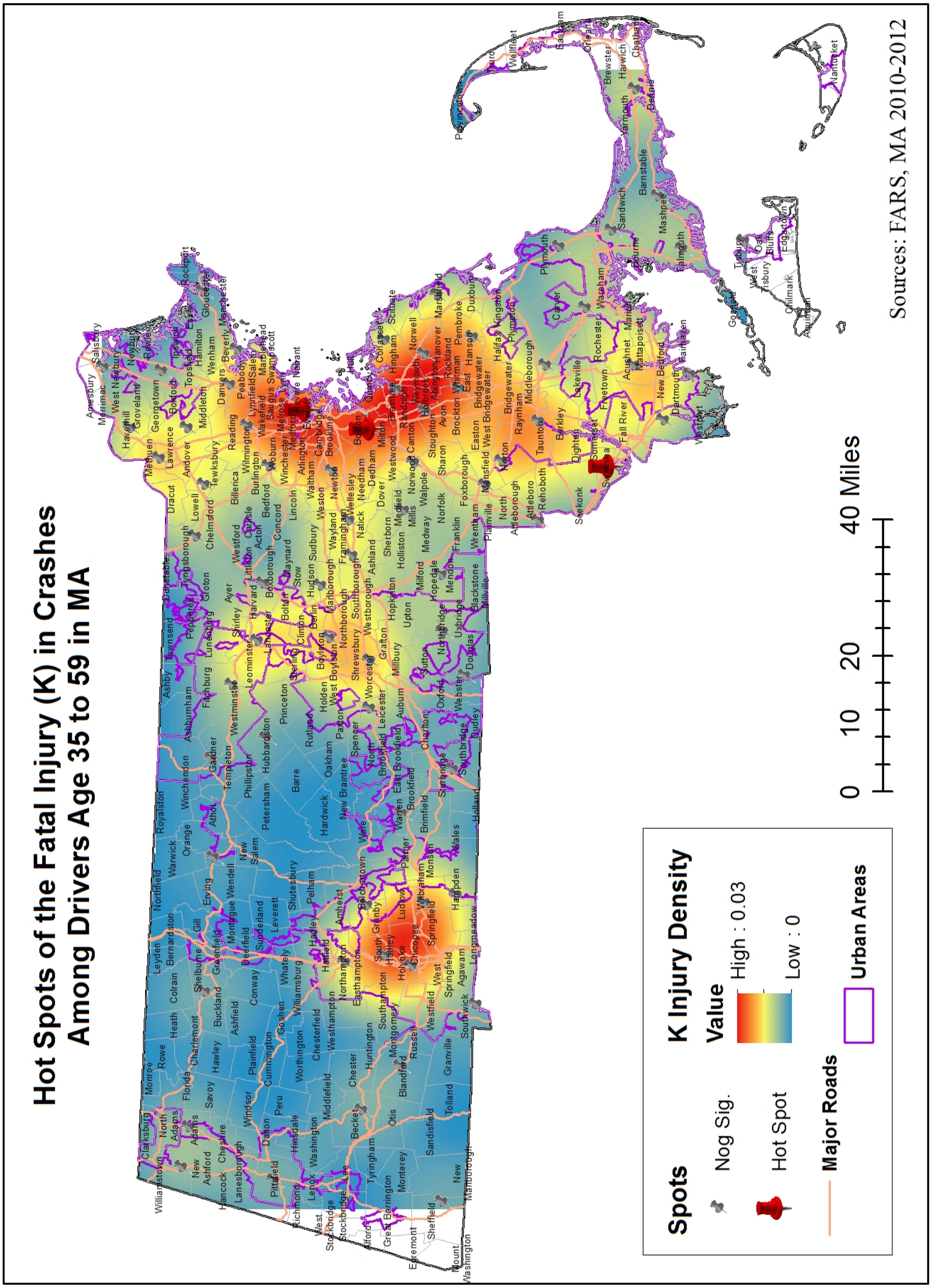


Figure B6. The Hot Spots of Crash Locations by the Fatal Injury
among Drivers Age 65 and Older in MA from FARS 2010-2012

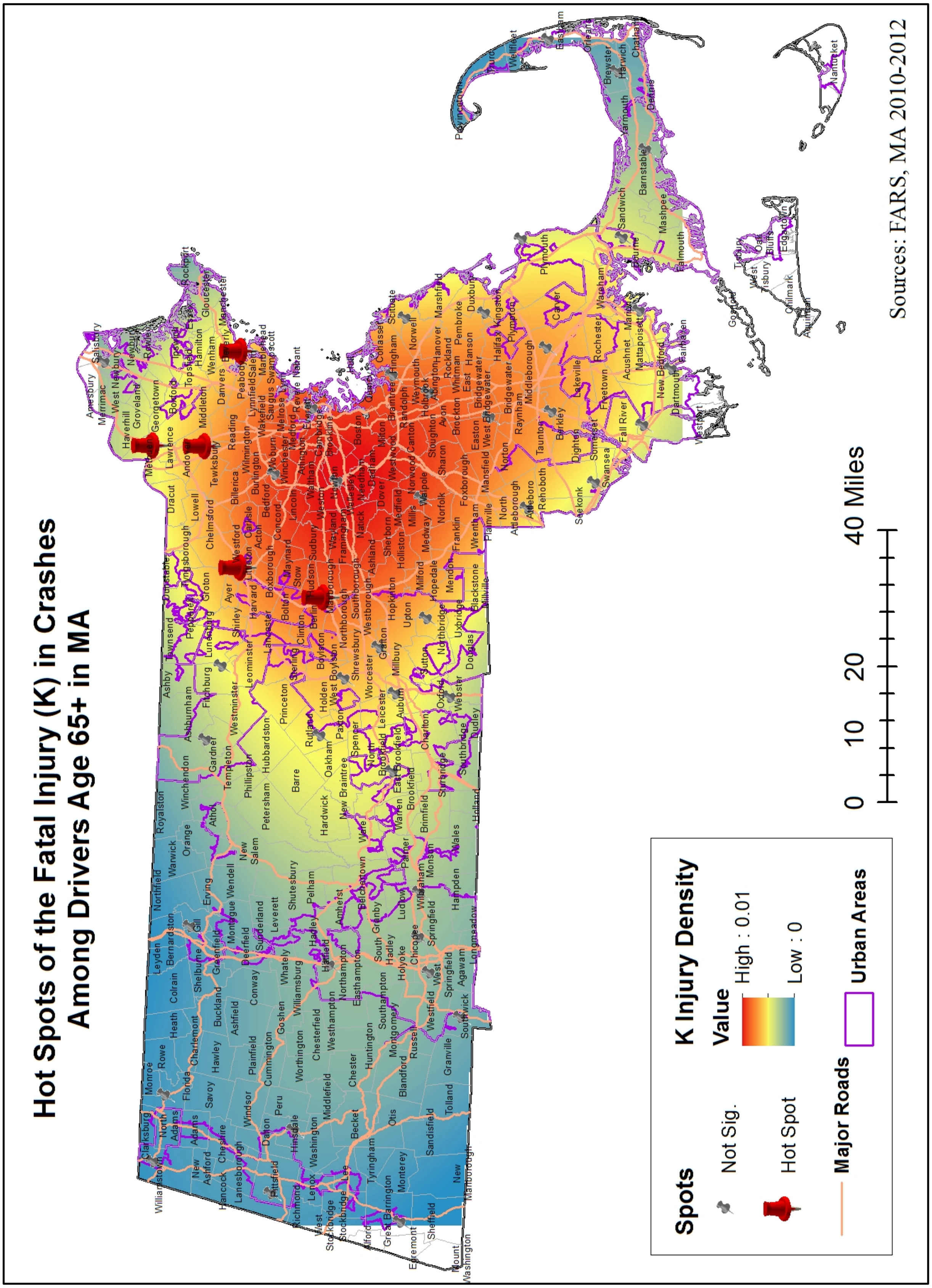


Figure B7. The Hot Spots of Crash Locations by the Incapacitating, Non-incapacitating Evident, and Possible Injury
among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

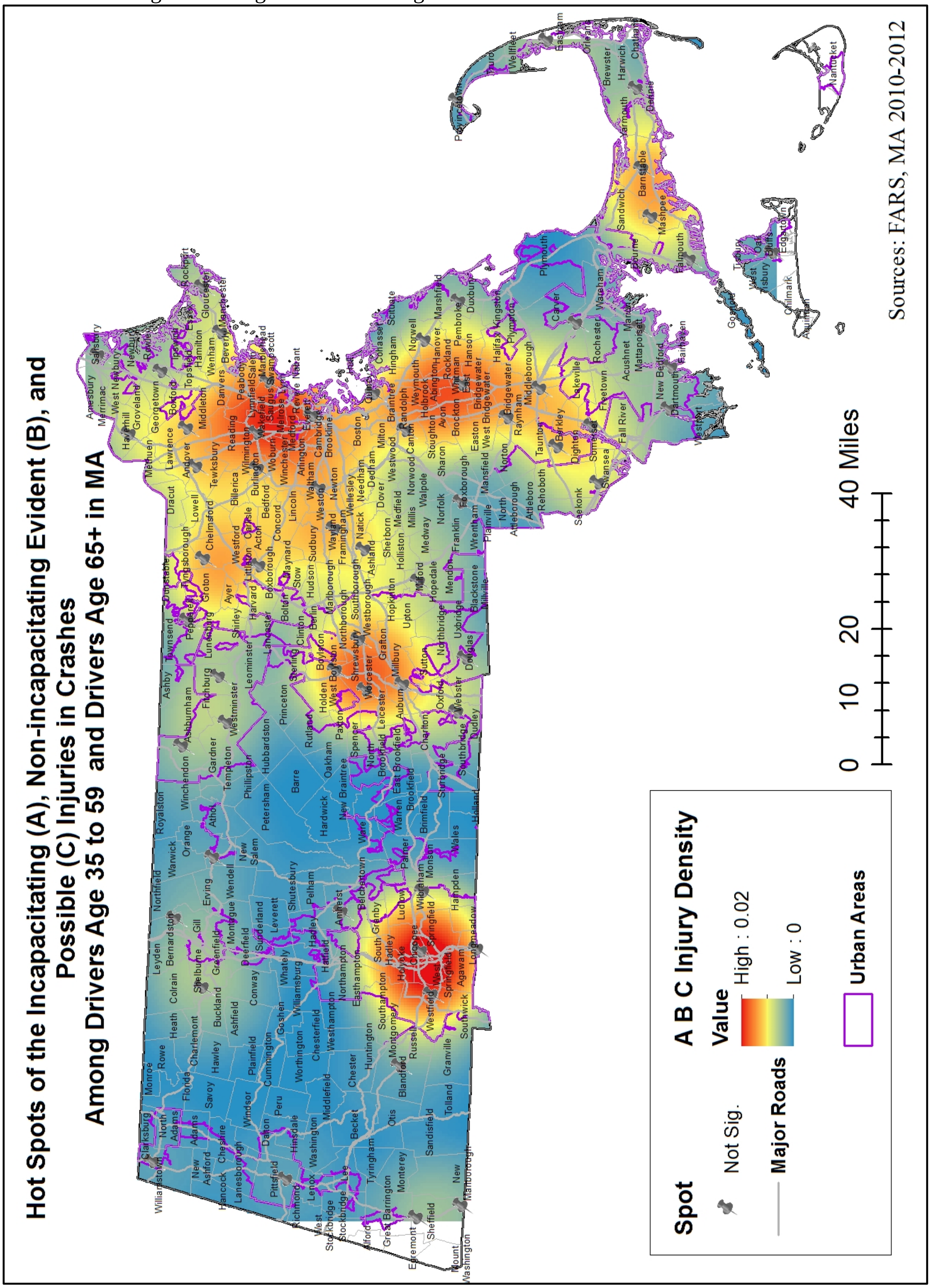


Figure B8. The Hot Spots of Crash Locations by the Incapacitating, Non-incapacitating Evident, and Possible Injury
among Drivers Age 35 to 59 in MA from FARS 2010-2012

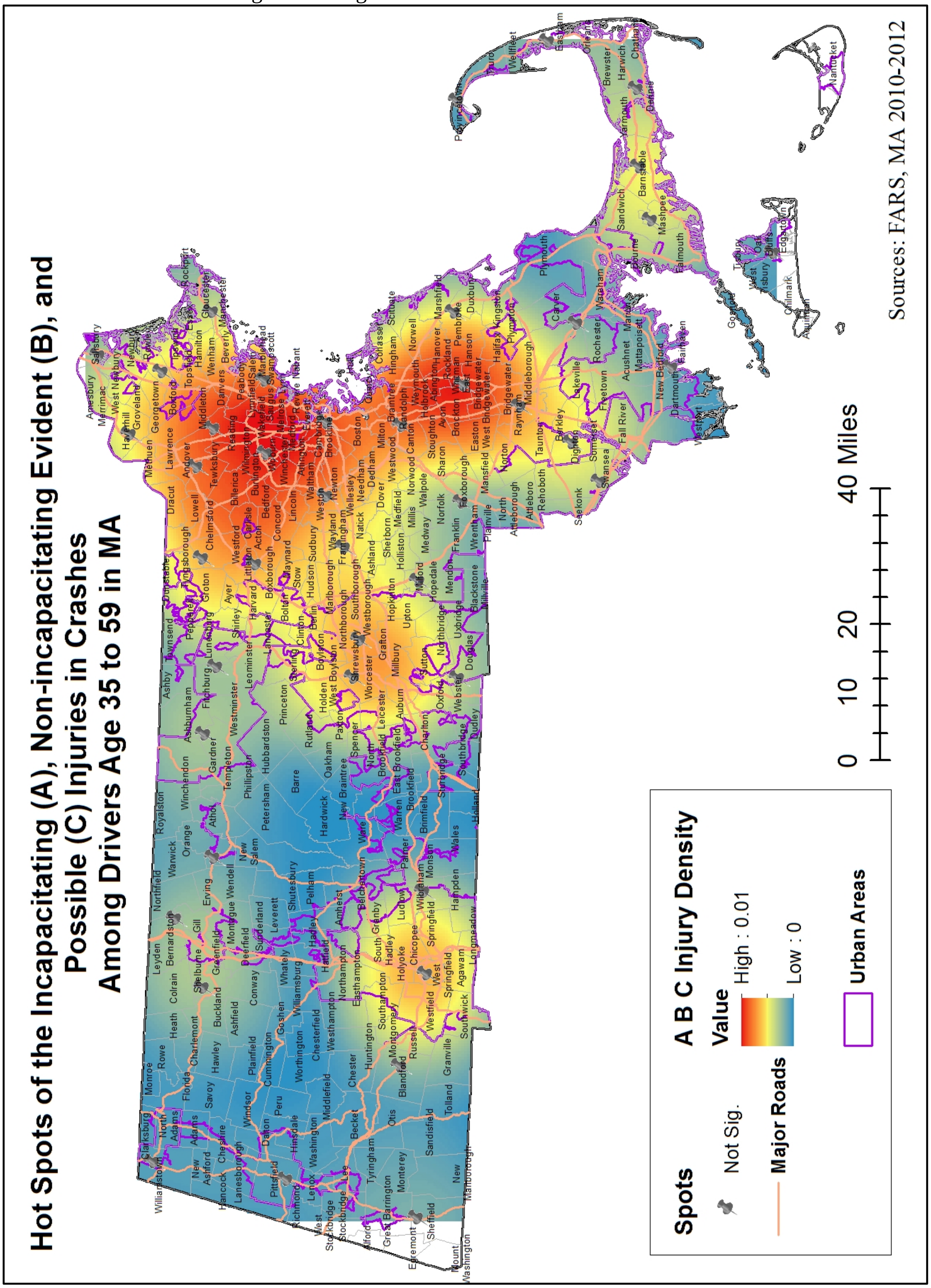


Figure B9. The Hot Spots of Crash Locations by the No Injury
among Drivers Age 35 to 59 and Age 65 and Older in MA from FARS 2010-2012

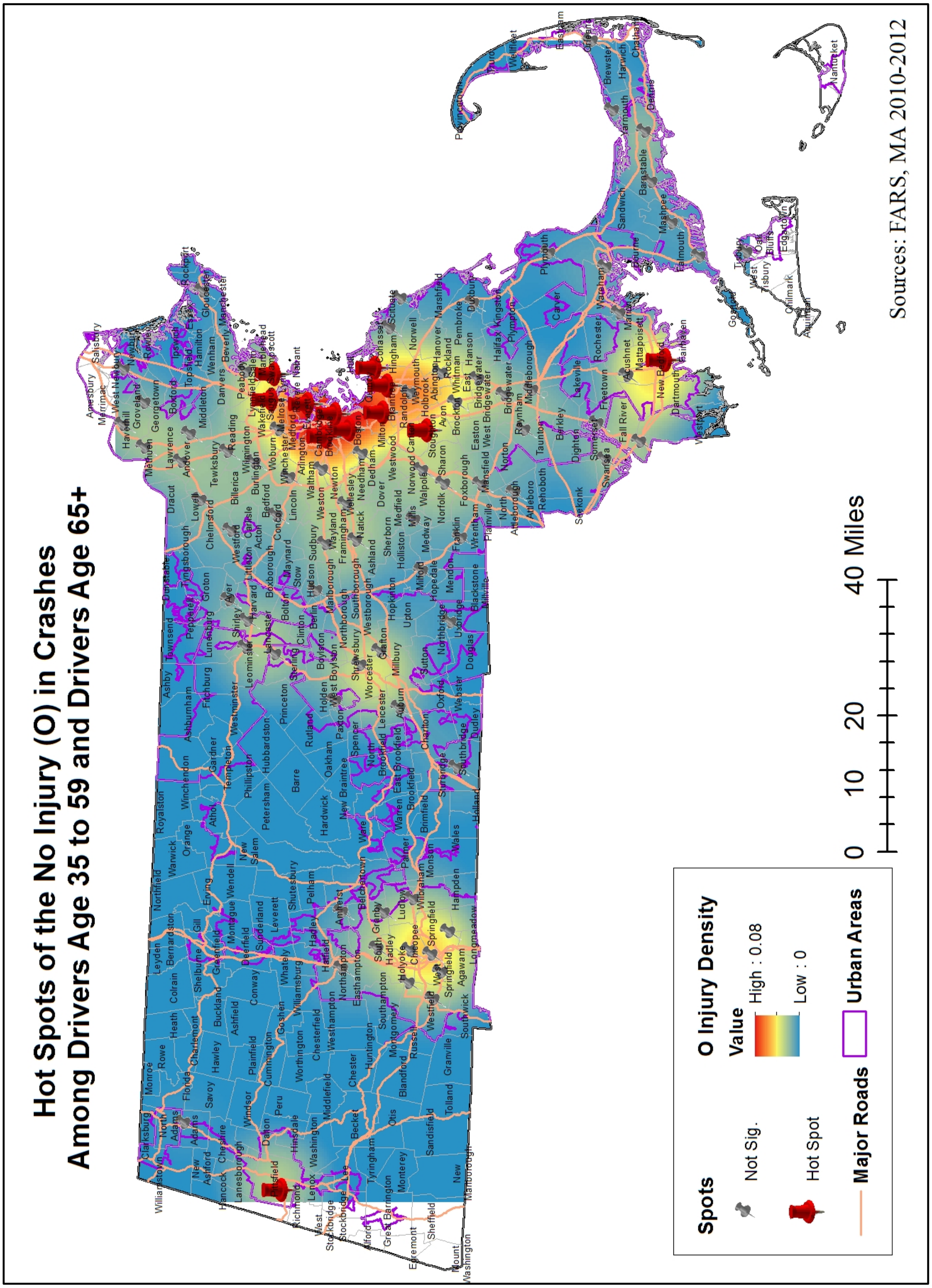
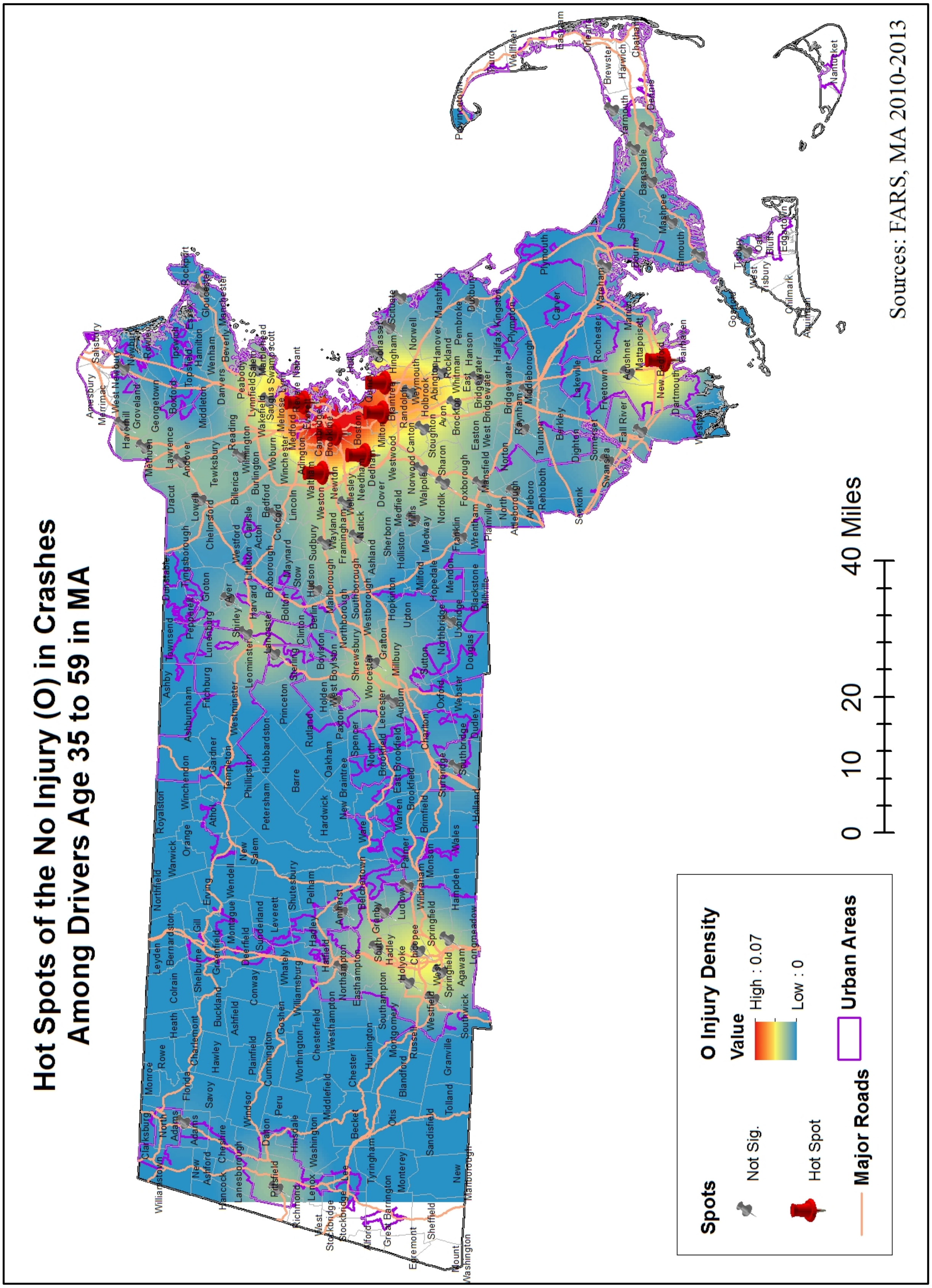


Figure B10. The Hot Spots of Crash Locations by the No Injury among Drivers Age 35 to 59 in MA from FARS 2010-2012



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