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Using LiDAR Data to Analyze Access Management Criteria in Utah

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ABSTRACT

Using LiDAR Data to Analyze Access Management Criteria in Utah

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The Utah Department of Transportation (UDOT) has completed a Light Detection and Ranging (LiDAR) data inventory that includes access locations across the UDOT network. The new data are anticipated to be extremely useful in better defining safety and in completing a systemwide analysis of locations where safety could be improved, or where safety has been improved across the state. The Department of Civil and Environmental Engineering at Brigham Young University (BYU) has worked with the new data to perform a safety analysis of the state related to access management, particularly related to driveway spacing and raised medians.

The primary objective of this research was to increase understanding of the safety impacts across the state related to access management. These objectives were accomplished by using the LiDAR database to evaluate driveway spacing and locations to aid in hot spot identification and to develop relationships between access design and location as a function of safety and access category (AC). Utah Administrative Rule R930-6 contains access management guidelines to balance the access found on a roadway with traffic and safety operations. These guidelines were used to find the maximum number of driveways recommended for a roadway. ArcMap 10.3 and Microsoft Excel were used to visualize the data and identify hot spot locations. An analysis conducted in this study compared current roadway characteristics to the R930-6 guidelines to find locations where differences occurred. This analysis does not indicate the current AC is incorrect; it simply means that the assigned AC does not meet current roadway characteristic based on the LiDAR data analysis. UDOT can decide what this roadway will become in the future and help shape each segment using the AC outlined in the R930-6.

A hierarchal Bayesian statistical before-after model, created in previous BYU safety research, was used to analyze locations where raised medians have been installed. Twenty locations where raised medians were installed in Utah between 2002 to 2014 were used in this model. The model analyzed the raised medians by AC. Only three AC were represented in the data. Regression plots depicting a decrease in crashes before and after installation, posterior distribution plots showing the probability of a decrease in crashes after installation, and crash modification factor (CMF) plots presenting the CMF values estimated for different vehicle miles traveled (VMT) values were all created as output from the before-after model. Overall, installing a raised median gives an approximate reduction of 53 percent for all crashes. Individual AC analysis yielded results ranging from 32 to 44 percent for all severity groups except severity 4 and 5. When the model was only run for crash severity 4 and 5, a larger reduction of 57 to 58 percent was found.

Keywords: access management, LiDAR, driveway, raised median, access category, access density, safety, hierarchal Bayesian statistics

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1 INTRODUCTION

Access management encourages the efficient and safe movement of people and goods by reducing conflicts on the roadway system. The Access Management Manual, Second Edition, defines access management as "the coordinated planning, regulation, and design of access between roadways and land development" (Williams et al. 2014). It involves a variety of methods that include improvements to benefit transit, pedestrians, and bicyclists, as well as different treatments for urban, suburban, and rural settings (Williams et al. 2014).

Access management research is not new in the state of Utah. Brigham Young University (BYU) researchers have worked with the Utah Department of Transportation (UDOT) planners and engineers to complete a variety of research projects over the years. These projects have included research on assessing the safety benefits of access management techniques (Schultz and Lewis, 2006), a prioritization process for access management implementation (Schultz and Braley, 2007), analysis of crashes in the vicinity of major crossroads (Schultz et al. 2008), and research on the safety of raised medians (Schultz et al. 2010). This research has been well received in the state of Utah and nationally with several research papers published based on the Utah research (Schultz et al. 2009, Schultz et al. 2007, Schultz et al. 2011).

One of the challenges with the early research completed on access management was the collection of data, particularly data related to midblock driveway openings on the system. Driveway data have been estimated in several previous projects to determine relationships between access management and safety. More recently, UDOT has completed a Light Detection and Ranging (LiDAR) data inventory that includes access locations across the UDOT roadway network. The new data were anticipated to be useful in better defining safety and in completing a systemwide analysis of locations where safety could be improved, or where safety has been improved across the state.

This chapter explains the purpose and objectives of this research, and how this report is organized.

1.1 Purpose

The purpose of this research was to use the LiDAR dataset to perform a safety analysis of the state related to access management, particularly related to driveway spacing and raised medians. Ongoing safety research being completed by BYU for UDOT hinted at a strong correlation between driveway spacing and safety, one that has been previously explored, but that can be expanded upon with new data and with the variety of new projects that have been conducted since any previous access management research was completed in the state (Schultz et al. 2016). Previous research has been conducted on the safety implications of raised medians, however, more data are available since the UDOT LiDAR data collection (Schultz et al.2010). Therefore, the new data were used to identify the safety impacts of raised medians. Finally, the results of the research were used to determine if there is a relationship between safety and UDOT access categories, thus hinting at possible changes to these categories.

1.2 Objectives

The first objective of this research was to increase understanding of the safety impacts across the state highway network by using the LiDAR database to analyze the implementation of access management techniques, particularly with respect to driveway spacing and raised medians. Evaluation of driveway spacing aided in the identification of hot spots, performing a systemic analysis of safety on the state's highway network, and developing relationships between access design and location as a function of safety and access category (AC). A geographical information system (GIS) and spreadsheet tools was used to visualize the data and identify hot spot locations. A Bayesian statistical before-after model, created in previous BYU safety research, was used to analyze locations found with raised medians to find how installing a raised median affects safety (Schultz et al. 2013, Schultz et al. 2016).

The second objective was to provide UDOT with a tool to gain a better and more updated understanding of the safety benefits of access management in the state. Although this type of research has been conducted in the past, it had been approximately seven years since the last research project in the state relating to access spacing was conducted. The new data that are available were used to improve this research and allow for an analysis of the state highway network. In addition, the use of the LiDAR database allowed researchers to find recommendations and improvements for future LiDAR data collection before it is gathered and uploaded to the UDOT Online Data Portal. This research helped UDOT toward their goal of zero fatalities as improvements to the system that can improve safety were identified.

1.3 Organization

This report is organized into the following chapters: 1) Introduction; 2) Literature Review; 3) Data Collection; 4) Analysis; and 5) Conclusions. A Reference section and Appendices follow the identified chapters.

Chapter 2 is a literature review that defines access management and outlines access management techniques. LiDAR data and Utah's access management rules are also discussed.

Chapter 3 outlines the steps taken to visually analyze the roadway datasets using ArcMap 10.3 and segment these datasets using an automated Microsoft Excel workbook.

Chapter 4 describes the process of analyzing roadway segments across the state of Utah, largely focusing on AC and raised median installation. The results of these analyses are also explained in this chapter.

Chapter 5 expounds on the results of the analyses and presents the conclusions that were drawn from these results. In addition, recommendations for improvements and future research are provided.

2 LITERATURE REVIEW

A comprehensive literature review has been performed on general aspects of access management and the techniques involved as well as specific topics for this research. This process consisted of gathering all information that could contribute to this study. Several topics are addressed in this literature review. First, access management will be defined and explained. Second, access management techniques will be summarized and the safety benefits of these techniques will be discussed. Next, the guidelines that the state of Utah uses to implement access management techniques will be outlined, followed by a discussion about LiDAR data and its uses. Lastly, background information regarding crash severity and hierarchal Bayesian modeling will be presented.

2.1 Access Management

Access management is defined as "the coordinated planning, regulation, and design of access between roadways and land development" (Williams et al. 2014). It involves reducing conflicts on the roadway through a variety of methods that help improve safety. Many areas may require access management but were not originally designed with access management techniques. It is possible that many areas simply do not have room for the growth that would come with the implementation of these techniques. However, letting the roadway "deteriorate with the assumption that the network can be replaced, widened, or reconstructed in the future is not practical" largely due to the cost of reconstruction (Williams et al. 2014). As the flow of traffic increases, the quality of traffic flow declines (ITE 2004). Careful planning can anticipate the growth of traffic volumes on the roadway and therefore access management techniques can be included to minimize congestion and reduce costs. The American Association of State Highway and Transportation Officials (AASHTO) document, A Policy on Geometric Design of Highways and Streets, states "…some degree of access management should be included in the development of any street or highway, particularly on a new facility where the likelihood of commercial development exists" (AASHTO 2011).

2.2 Access Management Techniques

Unlimited access onto an arterial street causes a decrease in speed, capacity, and safety due to an increase in potential conflicts for vehicles (Eisele and Frawley 2005). Therefore, certain elements need to be added to limit access as appropriate. Limiting access can be accomplished through access management techniques which are "designed to increase roadway capacity, manage congestion, and reduce crashes" (ITE 2004). Driveway consolidation, median treatments, and left-turn lanes are a few of the access management techniques. Overall, access management increases safety for all vehicles on the roadway by reducing the number of conflict points on an arterial. This section will go in depth about driveway consolidation, median treatments, and left-turn lanes and discuss how they are used to increase traffic operations and safety.

2.2.1 Driveway Consolidation

Many studies have shown that an increase in spacing between access points on an arterial street improves operations and safety by decreasing the number of conflict points. Gluck et al.

(1999) conducted a safety analysis on different roadways across the country and found that doubling access frequency from 10 to 20 driveways per mile consistently increased crash rates by 40 percent. An increase of driveway frequency from 10 to 60 driveways per mile increased crash rates by nearly 200 percent. Overall, every additional access point increased the crash rate by approximately 4 percent (Gluck et al. 1999).

A 2015 study conducted at Clemson University analyzed driveway characteristics in South Carolina. The characteristics analyzed included driveway spacing, driveway width, the number of entry lanes, the annual average daily traffic (AADT) of the corridor, and the corridor speed limit. Individual crash modification factors (CMFs) were calculated with the assumption that every variable was independent of all other variables. One of the results of the study was the determination that the width of the driveway significantly affects the crashes associated with that driveway. The study reported that "reducing a 40-foot continuous driveway to a 24-foot typical 2 lane driveway will result in a crash reduction of 35%" (Stokes et al. 2015). Figure 2-1 shows how the CMF was transformed for different driveway widths. The difference in driveway widths is noted as DW_a-DW_b. DW_a represents the width of the driveway after the width was reduced and DW_b represents the width of the driveway before the width was reduced. For example, if a 40-foot continuous driveway was reduced to a 24-foot two-lane driveway, DW_a-DW_b is equal to -16 feet. This results in a CMF of approximately 0.65 which results in a crash reduction of 35 percent (Stokes et al. 2015).

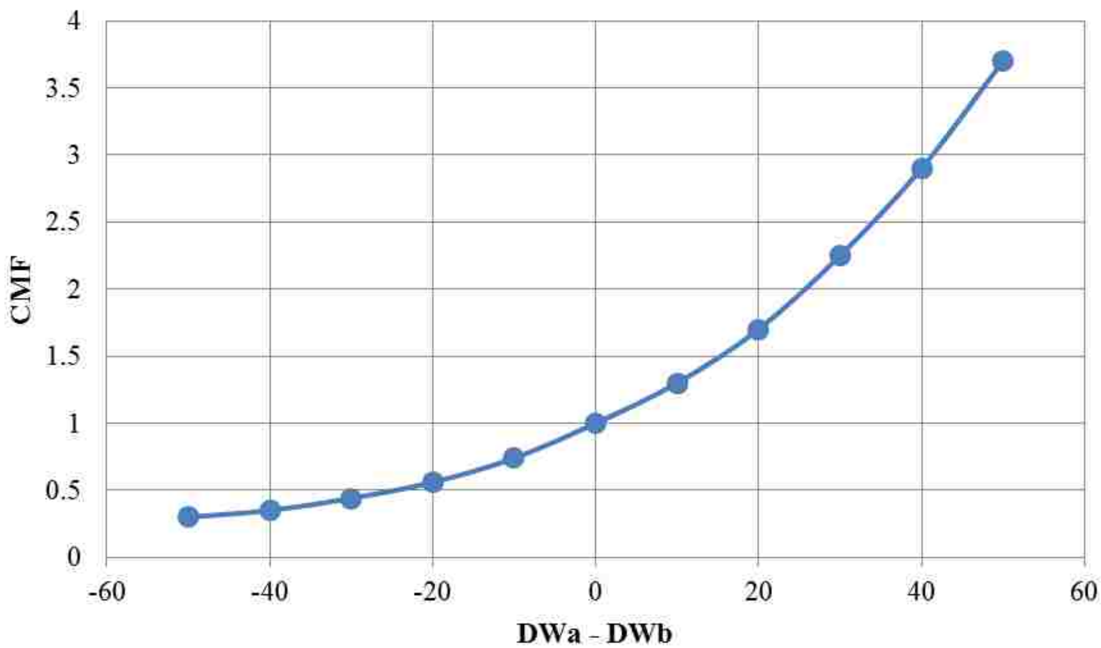

Figure 2-1: CMFs for change in driveway width (Stokes et al. 2015).

Stokes et al. (2015) also determined that the spacing of adjacent driveways significantly affects the crashes associated with that area. Figure 2-2 shows how the CMF changes with a corresponding change in driveway spacing on the roadway. DS_a-DS_b is the difference in driveway spacing after a modification occurs. DS_a represents the driveway spacing in feet after a modification while DS_b represents driveway spacing in feet before a modification. An example of using this graph is given by the authors as follows. Increasing driveway spacing from 150 feet to 200 feet results in a CMF of 0.98, which means there is a crash reduction of 2 percent. Decreasing driveway spacing from 100 feet to 50 feet results in a CMF of 1.02, this corresponds to a 2 percent increase in crashes.

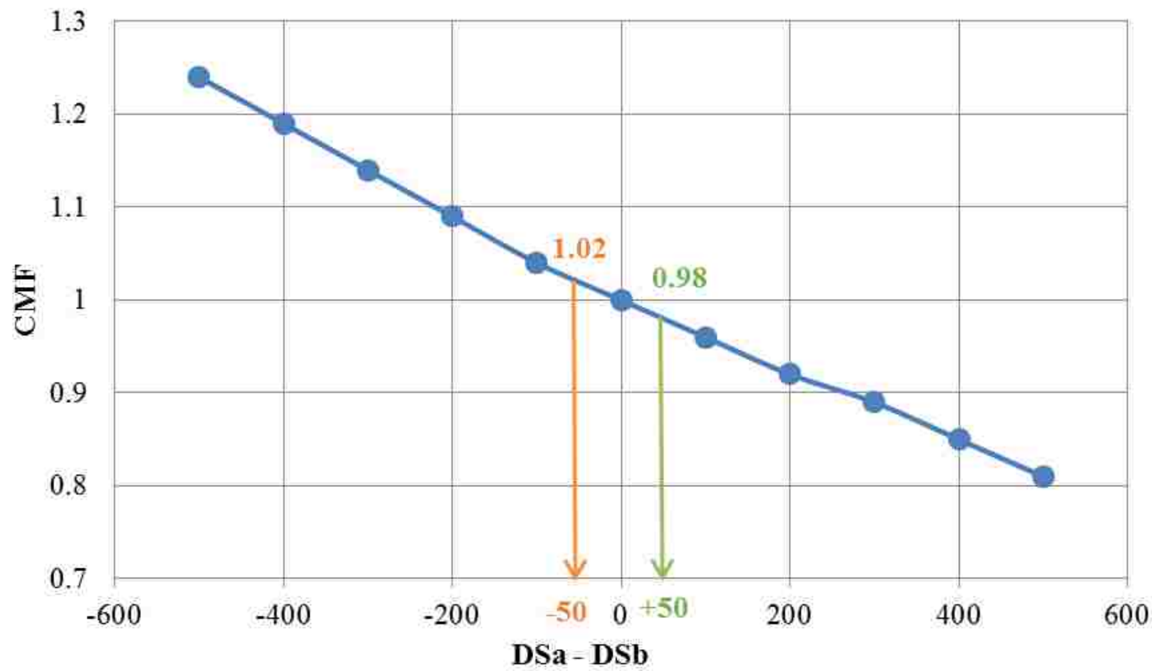

Figure 2-2: CMF for a change in driveway spacing (Stokes et al. 2015).

2.2.2 Median Treatment

According to the Access Management Manual, Second Edition, more than “two-thirds of all access-related collisions involve left-turning vehicles” (Williams et al. 2014). Medians can be an effective way to reduce the percentage of left-turn collisions. The presence of a median has an important impact on safety and operations. There are three general types of medians; undivided traversable medians, two-way left-turn lanes (TWLTL), and nontraversable medians. Each type of median is pictured in Figure 2-3 and will be expounded upon in this section.

a b c

Figure 2-3: Example of Median Types: a) undivided transversable median, b) TWLTL, c) nontraversable median (Google Images 2016).

2.2.2.1 Undivided Traversable Medians

Undivided traversable medians, pictured in Figure 2-3a, do not physically prevent vehicles from crossing over into the opposing direction of traffic (Williams et al. 2014). Painted medians are one example of an undivided traversable median. This median type separates opposing traffic flow and communicates to the driver not to cross; however, no physical restraint prevents vehicles from crossing (ODOT 2011). Due to the lack of control over vehicles, undivided traversable medians do not assist in access management efforts.

2.2.2.2 TWLTL

As defined in the Access Management Manual, Second Edition, a TWLTL is “a continuous lane located between opposing traffic flows that provides a refuge area from which vehicles may complete a left-turn from a roadway” (Williams et al. 2014). Roadways with a TWLTL, such as the street pictured in Figure 2-3b, are considered safer than roadways with an undivided traversable median. Generally, Williams et al. (2014) found that the crash rate is reduced by 35 percent with a TWLTL as opposed to undivided highways. Previous researchers assembled various studies on medians and found that 9 out of 10 cases reported a reduction in total crashes. A reduction in crash rates was reported at 10 out of 12 sites after implementing a

TWLTL (Gluck et al. 1999). Capacity tends to increase and delay decrease as left-turn vehicles move out of the through traffic lanes.

2.2.2.3 Nontraversable Medians

Nontraversable medians are physical barriers in the road that separate the two opposing traffic flows (Williams et al. 2014). Examples of nontraversable medians are raised medians, concrete barriers, or landscaped islands. A raised median is pictured in Figure 2-3c. Nontraversable medians limit access but create space for left-turn lanes when needed.

Nontraversable medians additionally reduce the frequency of crashes and their severity. Schultz et al. (2010) completed a study for UDOT on the impacts of raised medians and cable barriers after they are installed. A hierarchical Bayesian model was created to analyze overall crash data and severity crash data where raised median and cable barriers were installed. St. George Boulevard (SR 34) was one location that was studied. A raised median was installed in 2006 that extended over the entire length of SR 34, between I-15 and Bluff Street. Using the hierarchal Bayesian model, it was found that the overall crash frequency decreased after the installation of the raised median by nearly 26 percent. This study found that the entire distribution, shown in Figure 2-4, was less than zero which indicates a 100 percent probability that a decrease in crash frequency occurred. This distribution shows the difference between the before and after periods of crash frequency for the installation of the raised median in 2006. Severe crash frequency decreased by approximately 61 percent after the installation of the raised median (Schultz et al. 2010). The probability distribution in Figure 2-5 shows the distribution of the difference between the before and after periods for severe crashes. Almost the entire distribution in Figure 2-5 is less than zero. This indicates nearly a 99 percent probability that SR 34 experienced a decrease in frequency of the severe crashes.

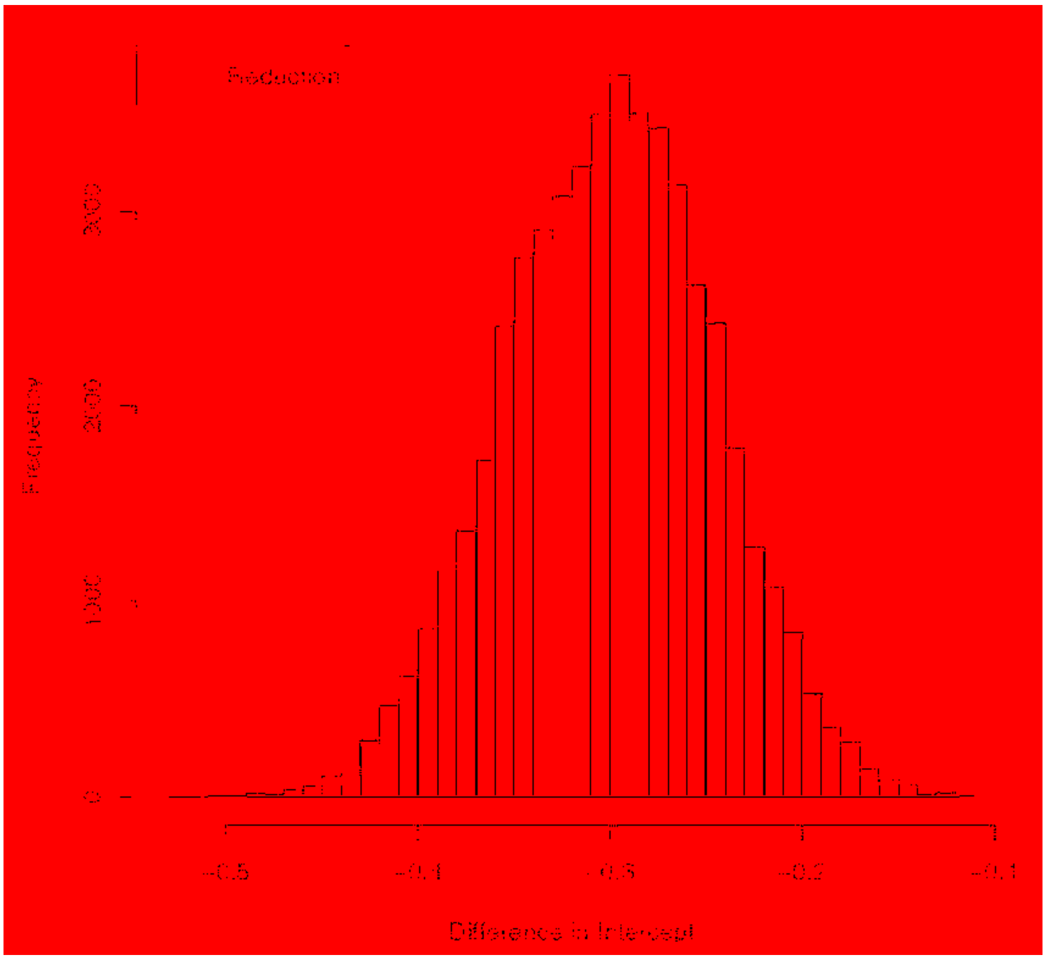

Figure 2-4: Distribution of differences in crash frequency on SR 34 (Schultz et al. 2010).

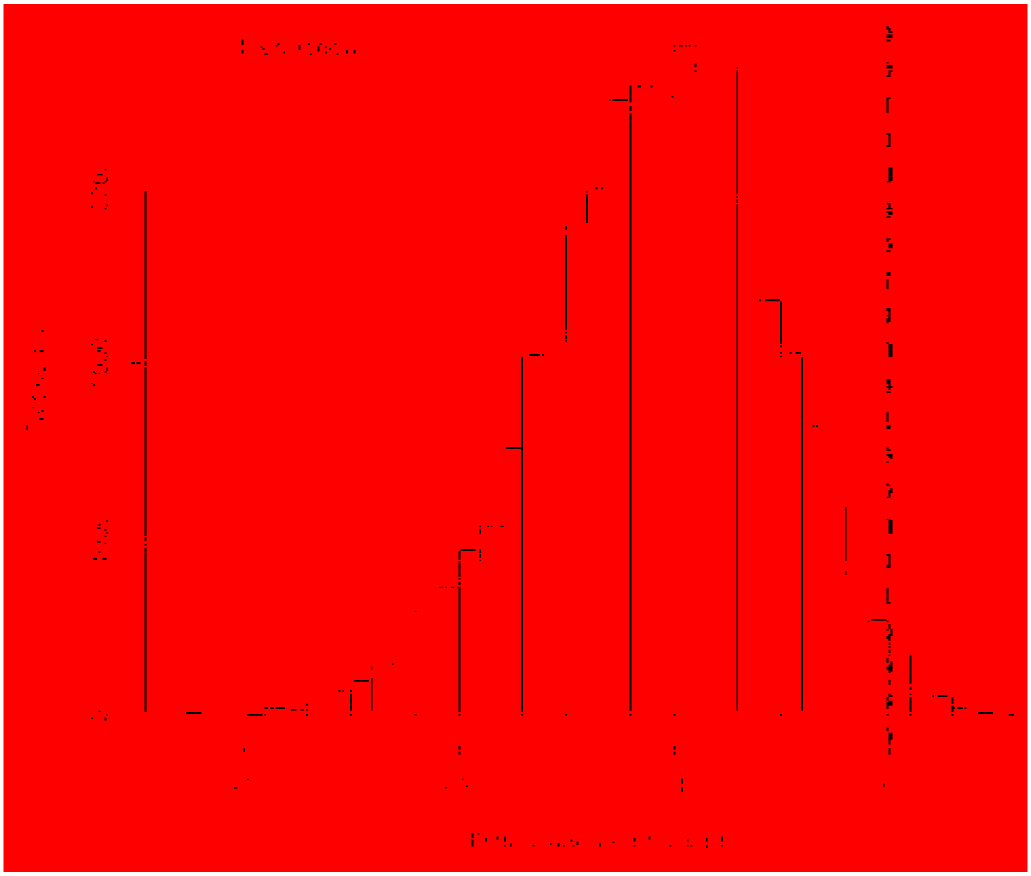

Figure 2-5: Distribution of differences in severe crashes on SR 34 (Schultz et al. 2010).

Schultz and Lewis (2006), to assist in assessing the safety benefits of access management, conducted a crash analysis to quantify the effects of access management techniques on collision types. Through an analysis of six locations in Utah, the general trend observed was that rear-end and single-vehicle crashes increased with the installation of a raised median, while right-angle crashes, considerably one of the most serious types of crashes, decreased. Segments with a raised median were shown to save money for the economy due to a decrease in total cost of crashes per year. In addition, this research showed that crash rates were not always reduced on the corridors analyzed; however, other safety benefits such as fatality rates and severity of crashes consistently decreased (Schultz and Lewis 2006).

It has been observed over the years that roadways with nontraversable medians are generally safer than roadways with TWLTLs. Gluck et al. (1999) explains that the crash rates for a raised median averaged about 5.2 crashes per million vehicle miles traveled (VMT), while crash rates for a TWLTL averaged 7.3 crashes per million VMT. Eisele and Frawley (2005) examined 11 different corridors located in Texas and Oklahoma. Two of the corridors installed a raised median in the place of a TWLTL. One corridor experienced a 17 percent reduction in crash rate while the second location experienced a 58 percent reduction. Although the raised median decreased crash rates, there was a speed reduction of approximately 3 mph when a raised median replaced a TWLTL (Eisele and Frawley 2005). It has been suggested that TWLTLs encourage an increase in access opportunities rather than control access largely because of the uninhibited left-turning access, therefore, a raised median can be implemented to manage highway access (Gluck et al. 1999).

Schultz and Braley (2007), through a statistical analysis, created a decision tree to recommend access management techniques for state routes in Utah. The decision tree suggested adding a raised median when the AADT for that roadway is greater than 25,000 vehicles per day and when the signal spacing on the road is greater than 2 signals per mile. The results from this research showed that raised medians corresponded to lower crash severities than TWLTLs do. This is largely due to the number of conflict points that exist with a TWLTL and that the number of conflict points increase as more signals are added to the road. Installing a raised median was recommended for 37 or the 175 roadway segments that were analyzed using the decision tree (Schultz and Braley 2007).

2.2.3 Left-Turn Lanes

Exclusive left-turn lanes remove slowing vehicles from the traffic stream. Otherwise, in a shared lane for through and left-turn vehicles, through vehicles experience delay as the left-turn vehicles slow down to safely complete the turn (Williams et al. 2014). With the use of a left-turn bay, an example of which is shown in Figure 2-6, a decrease in rear-end and right-angle collisions was experienced (Gluck et al. 1999). In addition, a left-turn lane increases the capacity on a roadway while decreasing delay, fuel consumption, and vehicle emissions (Williams et al. 2014). Gluck et al. (1999) found that left-turn lanes reduce crashes and crash rates by 20 to 65 percent as well as decrease the severity of the crashes.

When there are frequent left-turns completed at an intersection, a left-turn lane may be warranted. The year 2000 edition of the Highway Capacity Manual (HCM) explains that an exclusive left-turn lane may be warranted where left-turn volumes exceed 100 or more vehicles per hour. A double left-turn lane may be warranted where left-turn volumes exceed 300 or more left-turn vehicles per hour (TRB 2000). Left-turns, when merged with through traffic, can increase conflicts, delays, and crashes. This concept is shown in Figure 2-7, where northbound and southbound traffic are depicted. Red vehicles wish to complete a left-turn, while the purple vehicles want to proceed through the intersection. It is depicted that the left-turn vehicle in the northbound direction has to wait for the through vehicles going southbound to clear before the turn can be completed. Northbound through vehicles must wait for the left-turning vehicle to begin turning before they can advance through the intersection, which causes through vehicles to be delayed. The number of through vehicles that experience delay grows with each additional left-turning vehicle. Table 2-1 shows the proportion of through vehicles that are blocked by left-turning vehicles per cycle. Where there is one left-turn per cycle, it is estimated that 40 percent of through vehicles are blocked (Gluck et al. 1999).

Figure 2-6: Example of a left-turn bay in Orem, Utah (Google Earth 2016).

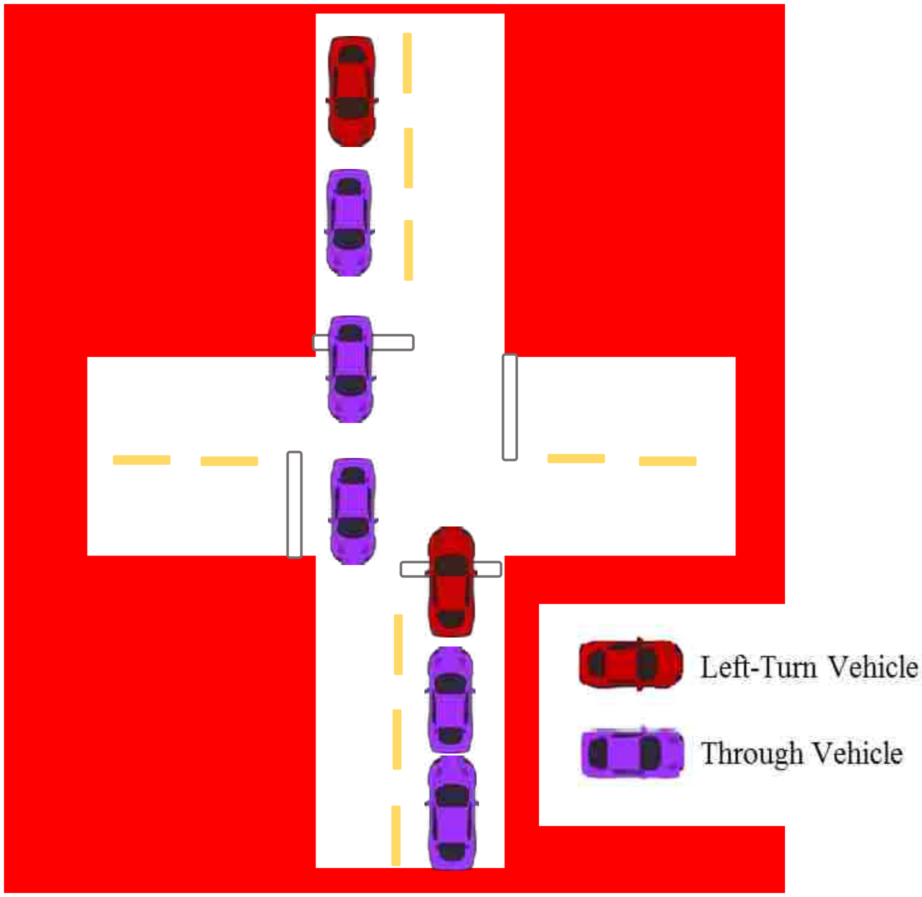

Figure 2-7: Diagram depicting through vehicle delay in a shared lane.

Table 2-1: Proportion of Through Vehicles Blocked by Left-Turns (Gluck et al. 1999)

Left-Turns/Cycle	Percentage of Through Vehicles Blocked
0.5	0.25
1	0.40
2	0.60
3	0.70
4	0.75
5	0.80
6	0.84
7	0.86
8	0.88
9	0.89
10	0.90

2.3 Utah Access Management Guidelines

The Utah Department of Administrative Services published Rule R930-6 in August of 2013 for the implementation of access management in Utah. This rule is meant to maximize public safety and establish highway access management procedures to protect Utah's highway system. Failure to manage access can increase traffic congestion and delays and decrease speeds and capacity of the facility (UDOT 2013).

Access management standards "have been developed for segments or classifications of highways that have similar context and functions" (UDOT 2013). Rule R930-6 outlines 10 categories that are based on the posted speed limit; signal, street, and driveway spacing; whether the highway has an urban or rural design; and the functional classification based on the Federal Highway Administration (FHWA) standards. These access categories, shown in Table 2-2, are useful in implementing statewide access management requirements and ensure a consistent and systematic application of these standards.

Table 2-2: Access Categories Outlined in R930-6 (UDOT 2013)

Category		Description
1	I	Freeway/Interstate
2	S-R	System Priority-Rural
3	S-U	System Priority-Urban
4	R-R	Regional-Rural
5	R-PU	Regional Priority-Urban
6	R-U	Region-Urban
7	C-R	Community-Rural
8	C-U	Community-Urban
9	O	Other Importance
10	F-FR	Freeway One-Way Frontage Road

Designs for access connections must comply with current UDOT Standards and the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA 2009). Each classification has different criteria for access. Category 1 access is only through interchanges that are "properly spaced, located, and designed in accordance with Department and FHWA standards and regulations" (UDOT 2013). For highways classified as a category 4 through category 9, direct access can be granted as long as it does not cause an operational or safety problem for the state highway, as determined by the Department. Table 2-3, computed from Table 2-4, explains the maximum number of driveways per mile that each category warrants, taking into account one side of the roadway and both sides of the roadway. Table 2-4 shows the minimum signal, street, driveway, and interchange spacing for each state highway category. For this research, driveway spacing will be a main focus.

Table 2-3: Maximum Access Allowed per Category

AC	Minimum Driveway Spacing (ft)	Maximum Access per Mile		Speed Limit	Urban Code
		On One Side of Roadway	On Both Sides of Roadway		
1	N/A	-	-	≥ 45	-
2	1000	5.3	10.6	≥ 45	Rural
3	N/A	-	-	≥ 40	Urban
4	500	10.6	21.2	≥ 45	Rural
5	350	16.5	33.0	≥ 45	Urban
6	200	26.4	52.8	≤ 40	Urban
7	150	35.2	70.4	≤ 40	Rural
8	150	35.2	70.4	≤ 40	Urban
9	150	35.2	70.4	-	-
10	N/A	-	-	-	-

Table 2-4: State Highway Spacing Standards (UDOT 2013)

Category		Minimum Spacing (ft)					
					Interchange to Crossroad Access Spacing		
		Signal Spacing	Street Spacing	Driveway Spacing	to 1st Right-in Right-out Driveway	to 1st Intersection	from Last Right-in Right-out Driveway
1	I	N/A	N/A	N/A	n-a	n-a	n-a
2	S-R	5280	1000	1000	1320	1320	1320
3	S-U	2640	N/A	N/A	1320	1320	1320
4	R-R	2640	660	500	660	1320	500
5	R-PU	2640	660	350	660	1320	500
6	R-U	1320	350	200	500	1320	500
7	C-R	1320	300	150	n-a	n-a	n-a
8	C-U	1320	300	150	n-a	n-a	n-a
9	O	1320	300	150	n-a	n-a	n-a
10	F-FR	1320	660	N/A	n-a	n-a	n-a

"N/A" = Not Allowed

"n-a" = Not Applicable

2.4 LiDAR Data

LiDAR data collection methods are changing the way data are collected. As a safer, faster, and more accurate way to collect data, LiDAR data, although expensive to collect, can be widely used. This section will discuss what LiDAR data are, how to decide when to use LiDAR data, and three case studies outlining LiDAR data collection methods used in three states.

2.4.1 What is LiDAR Data?

LiDAR is a laser based system that emits light pulses which hit objects and reflect back to the data collection equipment (Bolstad 2012). The laser pulse travels to an object and returns; this is an element LiDAR uses to calculate distances (Beasy 2008). The data collected can be organized as a point cloud where different objects, elevations, vegetation, and buildings can be identified.

There are two general types of LiDAR; airborne and terrestrial (Esri 2015b). Airborne LiDAR data are regularly collected with an aerial vehicle. The aircraft would have the LiDAR equipment installed on board in addition to global positioning systems (GPS) and inertial measurement units (IMU) (Esri 2015a). Terrestrial LiDAR is an additional mode to collect data that has become more prominent in the past several years. Mobile LiDAR, a subset of terrestrial LiDAR, uses laser scanning equipment mounted on top of a vehicle, with GPS and IMU, to quickly gather large datasets needed to create accurate digital representations of the roadway and its surroundings (Olsen et al. 2013). A mobile LiDAR vehicle is pictured in Figure 2-8. Mobile LiDAR has "major implications for the way in which geospatial data is collected, exploited, managed, and maintained by transportation agencies" (Olsen et al. 2013).

Figure 2-8: Mobile LiDAR vehicle (FHWA 2014).

LiDAR offers "the promise of transforming the way in which transportation agencies plan, design, construct, and maintain their highway networks" (Olsen et al. 2013). The measurements obtained are highly accurate and data can be collected safely at highway speeds. Mobile LiDAR data collection reduces worker exposure to traffic hazards and improves mobility of the public by eliminating lane closures for survey workers (Yen et al. 2011). Additionally, one dataset can be used for many applications and information. The phrase "collect once, use many" is correctly noted (Olsen et al. 2013). LiDAR data collection costs will continue to fall as the system is more commonly used.

2.4.2 When to Use Mobile LiDAR

It is important to weigh the cost verses the benefit to determine if LiDAR is the best approach for a project. Olsen et al. (2013) suggests the following two criteria for using LiDAR data: first, it is important to account for all potential uses of the data that will be collected during its lifespan. When important data can be collected all at once with LiDAR and then used for multiple projects, it may be worth the initial cost. The second point to consider when deciding whether the use of Mobile LiDAR is right for the project at hand is whether the data will integrate into existing data processes. What programs and software would need to be improved or updated? Would the use of LiDAR mean a whole system update? Is this something that can be financially achievable? As LiDAR becomes more available, most agencies will need to modify their standard procedures to integrate mobile LiDAR into the existing system. This can be a costly and extensive process; however, it will generate savings in the future (Yen et al. 2011). As LiDAR data collection systems become more widely used, the costs of data collection will fall. Although costs vary depending on the project, data collection could be coordinated with other interested agencies to split the costs of data collection (Olsen et al. 2013).

2.4.3 Case Studies

Massachusetts, Minnesota, and Utah have all began collecting terrestrial transportation LiDAR data using a vehicle as the device to collect data. Each of these will be discussed in the following sections.

2.4.3.1 Massachusetts

In 2014, the Massachusetts Department of Transportation (MassDOT) began collecting signage data for the entire state to create a sign management system due to a new minimum retro-reflectivity requirement effective in 2008 (Boudreau and Greenman-Pedersen 2015). This requirement has since been incorporated into the MUTCD. The overview of the project included an inventory of all signage on state-owned roadways, night-time retro-reflectivity conditions, and an asset management system that MassDOT could implement (Day 2014). Using the mobile LiDAR system, sign inventory on state roadways for the east side of the state were collected in 2014 and data for the rest of the state was to be collected during the year 2015. Figure 2-9 shows the progression of the MassDOT mobile LiDAR data collection through thick, colored lines. The data collected in 2014 are shown with green bold lines while the data collected in 2015 are shown with red bold lines. LiDAR data were post-processed and integrated into a web-based asset management system called VUEWorks that merged easily with the GIS MassDOT was using. With the data in VUEWorks, MassDOT can see an image of any specific sign and its condition so regular improvements can be made to signs throughout the state (Boudreau and Greenman-Pedersen 2015).

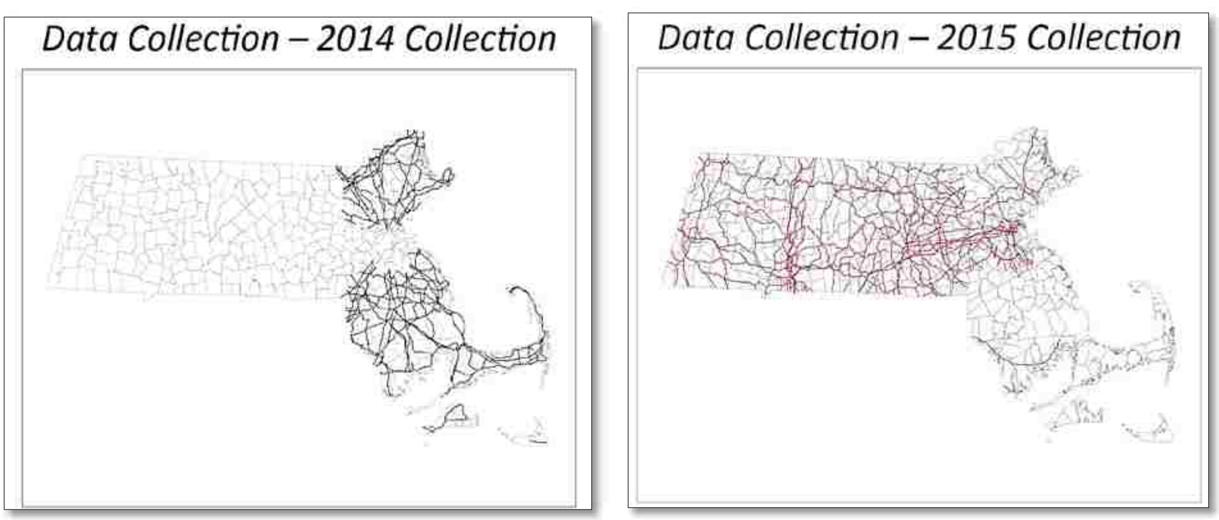

Figure 2-9: Data collection plan for MassDOT (Boudreau and Greenman-Pedersen 2015).

2.4.3.2 Minnesota

A Department of Transportation is responsible for maintaining the transportation infrastructure of the state. To achieve this, accurate field data are needed to prioritize and plan for maintenance. The Minnesota Department of Transportation (MnDOT) found that guardrail and barrier inventory was not accurate or up to date. Therefore, MnDOT needed to collect accurate field data to prioritize and plan for maintenance. Mobile LiDAR was used for this project and imagery on all MnDOT mainline, overpasses, interchanges, weigh stations, rest areas, and historical sites were collected. Very precise LiDAR data were needed for this project including an "absolute survey-grade accuracy of +/- 0.1 foot" or better for the LiDAR data and "+/- 1 foot (or better) for the images" (Stefanski 2014). Following the data collection, the barrier data were evaluated to identify any barriers that needed to be replaced. After data analysis, the inventory was complete and can be used for on-going maintenance activities and future design projects (Stefanski 2014). The LiDAR dataset collected for barrier data has additionally been used to extract other assets, such as traffic sign GPS locations and noise wall locations.

2.4.3.3 Utah

UDOT maintains 15 percent of the total roadway centerline miles open to the public in Utah (FWHA 2014). Traditionally, collecting data at all of these sites required an excessive amount of time; therefore, UDOT wanted to find new state-of-the-art data collection methods to improve and develop rigorous safety, maintenance, and preservation programs; obtain data to assist in making safety, pavement, and asset management decisions; and gather the most data while maintaining a high level of accuracy and quality (FHWA 2014). To find a new data collection method, 11 companies were invited to present different data collection methods to UDOT. Mandli Communications Inc. was awarded the contract and began collecting data in

2012 using 3D LiDAR. Data were to be updated every two years within a six-year contract. The first update on the data was collected in 2014 with the second update in 2016. About 20 different asset datasets were collected, including median and barrier presence, guardrails, striping, bike lanes, and a pavement photolog. UDOT has benefitted greatly from this data. Knowledge on the quantity and quality of roadway improves budgeting, divisions in UDOT work closer together by sharing access to the data, and an enhanced ability to perform safety analyses based on roadway attributes and crash data was improved by the 3D LiDAR data collection (FHWA 2014).

2.5 Crash Severity

The Highway Safety Manual (HSM) defines crash severity as the "level of injury or property damage due to a crash" (AASHTO 2010). The KABCO scale is used to divide crashes into five categories based on the most severe injury sustained during a crash. These crash severity levels are (AASHTO 2010):

K—Fatal injury: an injury that results in death;

A—Incapacitating injury: any injury, other than a fatal injury, that prevents the injured person from walking, driving, or normally continuing the activities the person was capable of performing before the injury occurred;

B—Non-incapacitating evident injury: any injury, other than a fatal injury or incapacitating injury, that is evident to observers at the scene of the crash in which the injury occurred;

C—Possible injury: any injury reported or claimed that is not evident or outlined in the previous categories;

O—No injury, property damage only.

UDOT uses similar crash severity categories in their crash database, however, UDOT uses number values instead of the KABCO scale. Table 2-5 shows how HSM and UDOT severity levels correspond. Crash severity categories are used to find locations where high severity crashes occur. Once locations are found, safety improvements can be made to the roadway to reduce and eliminate fatal and incapacitating injury crashes.

Table 2-5: HSM and UDOT Severity Categories

Crash Type	HSM Severity Level	UDOT Severity Level
Fatal	K	5
Incapacitating Injury	A	4
Non-incapacitating Injury	B	3
Possible Injury	C	2
Property Damage Only	O	1

2.6 Hierarchical Bayesian Modeling

To better understand how the model used in this study operates, a few foundational statistical principles must be discussed. Gelman (2004) provides a foundational background on Bayesian statistics, including the base notation, where $p(\cdot)$ is denoted as a marginal distribution and $p(\cdot|\cdot)$ as a conditional distribution. As part of the transportation research conducted in this, and previous studies, an adaptation of Bayes' rule is used as outlined in Equation 2-1 (Schultz et al. 2010, Schultz et al. 2013):

$$p(\theta, y) = p(y)p(\theta|y) \tag{2-1}$$

Where, y = crashes per mile, and

θ = mean number of crashes per mile

This equation can be rearranged and written as outlined in Equation 2-2.

$$p(\theta|y) = \frac{p(\theta, y)}{p(y)} = \frac{p(y|\theta)p(\theta)}{p(y)} \quad (2\text{-}2)$$

The distribution $p(\theta)$ denotes the prior distribution for θ. The prior, also referred to as a prior probability distribution, of an uncertain quantity p is the probability distribution that would express the uncertainty about p before the data are taken into account. It is meant to attribute uncertainty associated with that data rather than randomness to the uncertain quantity. The prior is useful in that it allows the incorporation of information available into the model before the collection of data and reflects the belief of what will happen. The distribution $p(y|\theta)$ *is* the likelihood of the data given the parameter θ. The conditional distribution $p(\theta|y)$ is the posterior distribution of θ given the data. The posterior distribution is used to draw conclusions in this study. Bayesian statistics uses multiple linear regression to find the most important variables to use in an analysis, as outlined in more detail in Chapter 4.

2.7 Chapter Summary

The use of access management reduces conflicts on the roadway and improves safety. Access management techniques such as driveway consolidation, medians, and left-turn lanes all have an impact on safety and crash frequency. Controlling access frequency ensures that the number of conflict points and crashes occurring stays low while the installation of a raised median often brings a reduction in crash severity and a decrease in right-angle crashes. Utah's Administrative Rule R930-6 is meant to give consistent guidelines for access management procedures in the state. Standards outlined in this rule will be used for this study. Mobile LiDAR is a technology that is reshaping the way roadway data are collected. Several states have used LiDAR and Utah's LiDAR data will be regularly used throughout this study. Though it can be an expensive system to apply, it can be a great tool to use if a cost verses benefit analysis is performed and acceptable for use. Crash severity is used to define the worst extent of a crash that occurs. With the use of crash severities, locations with high severity crashes can be found so safety improvements can be made to those locations. A hierarchal Bayesian model was created in previous BYU research and will be used in this report to determine the safety effects of installing a raised median.

3 DATA COLLECTION

In 2012, Utah began collecting LiDAR data to build an extensive roadway system database in the state. The LiDAR data collection process is a precise method to collect data. After the LiDAR data are collected, the raw data are processed and loaded into UDOTs Open Data site, where the data can be downloaded by the public. This chapter briefly discusses the datasets that are used in this research, how the data were reviewed using ArcMap 10.3, and how the data were prepared for analysis and corridor selection using Microsoft Excel.

3.1 Datasets

Several different datasets were used in this research that have been received through UDOT's Open Data portal (UDOT 2016) and other UDOT contacts. The datasets used are as follows; Historic AADT, 2014 Driveways, 2014 and 2016 Medians, 2014 Lanes, 2013 UDOT AC Identification, 2015 Speed Limit, Functional Class, and Urban Code. Crash Data, Crash Location, Crash Rollup, and Crash Vehicle data, spanning from 2002-2014 were provided by the UDOT Traffic & Safety Division for the project. Route and mile point data were essential for this study and are prevalent in each dataset. This section will expound on the uniform characteristics in each dataset, critical data columns for datasets retrieved from UDOT's Open Data portal, and critical data columns for each crash dataset.

3.1.1 Data Uniformity

Datasets downloaded from the UDOT Open Data site have separate attribute data that corresponds with that dataset; however, uniform data fields exist that allow the datasets to be related linearly or spatially. Four roadway identification fields were used to relate the datasets for analysis. These fields include “ROUTE_ID,” “DIRECTION,” “BEG_MILEPOINT,” and “END_MILEPOINT” for every dataset.

The “ROUTE_ID” field matches the federal and state highway numbering system. The direction of traffic flow is described by the “DIRECTION” field. “BEG_MILEPOINT” and “END_MILEPOINT” identifies the beginning and ending point on the route that the roadway segment characteristics exist.

3.1.2 UDOT Open Data Datasets

Each dataset has individual characteristic and attribute data that correspond with the dataset. According to the UDOT Data Portal, the AADT dataset has AADT data that dates from the most recent year back to 1981 on some segments. However, in addition to AADT data, the traffic counter station number and single truck counts are also included in this dataset. All of this information is not needed for the analysis conducted for this study; therefore, critical data columns were chosen for each dataset that allowed BYU researchers to have only the information needed for the analysis. Table 3-1 shows the critical data columns for the AADT dataset, which include the route number, beginning mile point, end mile point, and seven years of AADT data. Similar tables for all of the Utah Data Portal data used in this project are shown in Appendix A.

Table 3-1: Critical Data Columns for the AADT Dataset

Heading	Description
ROUTE	Route ID: numeric route number for a given road segment
BEGMP	Beginning Mile point: beginning milepost of the road segment
ENDMP	End Mile point: end milepost of the road segment
AADT[YEAR]	AADT [YEAR]: historical dataset of Annual Average Daily Traffic data from each year; at least 7 years of data are needed (i.e., AADT2012)

3.1.3 Crash Data

The crash data collected for this project includes Crash Data, Crash Location, Crash Rollup, and Crash Vehicle data. Each dataset includes a column called CRASH_ID and a CRASH_DATETIME column where every ID corresponds to a crash that occurred. This labeling is uniformly used throughout each crash data file. This allows the information about a specific crash to be found quickly in each dataset.

Aside from a uniform crash ID column, each crash dataset contains different information about the crash. The Crash Data dataset includes the crash severity as well as weather conditions, pavement conditions, the type of collision, and other roadway conditions. The Crash Location dataset has information on the route and location of the crash. The Crash Rollup dataset includes the number of injuries, whether pedestrians or bicyclists were involved, and related circumstances for the crash that occurred. Information on posted speed limit and estimated speeds at the time of the crash, the number occupants in the vehicle, and the vehicle make and model is found in the Crash Vehicle dataset. Tables depicting the critical columns for each crash dataset collected for this project are found in Appendix A.

3.2 Data Review

ArcMap 10.3 was used to allow researchers to review and familiarize themselves with the data and visually find hotspot areas. Crash, driveway, and median data were used to review and visualize datasets in an effort to find correlations within the data and hotspots in the state. Crash, driveway, and median datasets including the visual analysis completed in ArcMap for each dataset will be expounded upon, and initial hotspots found in ArcMap will be presented in this section.

3.2.1 Crash Data

ArcMap 10.3 was used to review and visualize the crash data to find hotspot locations where large numbers of crashes occurred. Initially, a point density analysis was performed to find crash hotspots around the state. Point density is a tool that calculates the density of point features around each output cell (Esri 2011a). To classify these hotspots, the UDOT safety categorical ranking percentiles were used. These percentiles are shown in Table 3-2. Five categories were created where, when visually analyzed, the lower 5 percent of crashes were given a dark green color, the middle 60 percent of crashes were colored yellow, and the top 5 percent were given a bright red color. This green to red color scheme coincides with least problematic to most problematic classifications respectively, and can be seen in Figure 3-1.

Table 3-2: UDOT Safety Categorical Ranking Percentiles (Schultz et al. 2015)

UDOT Classification	UDOT Percentile
Most Problematic	0%-5%
More Problematic	5%-20%
Some Problematic	20%-80%
Less Problematic	80%-95%
Least Problematic	95%-100%

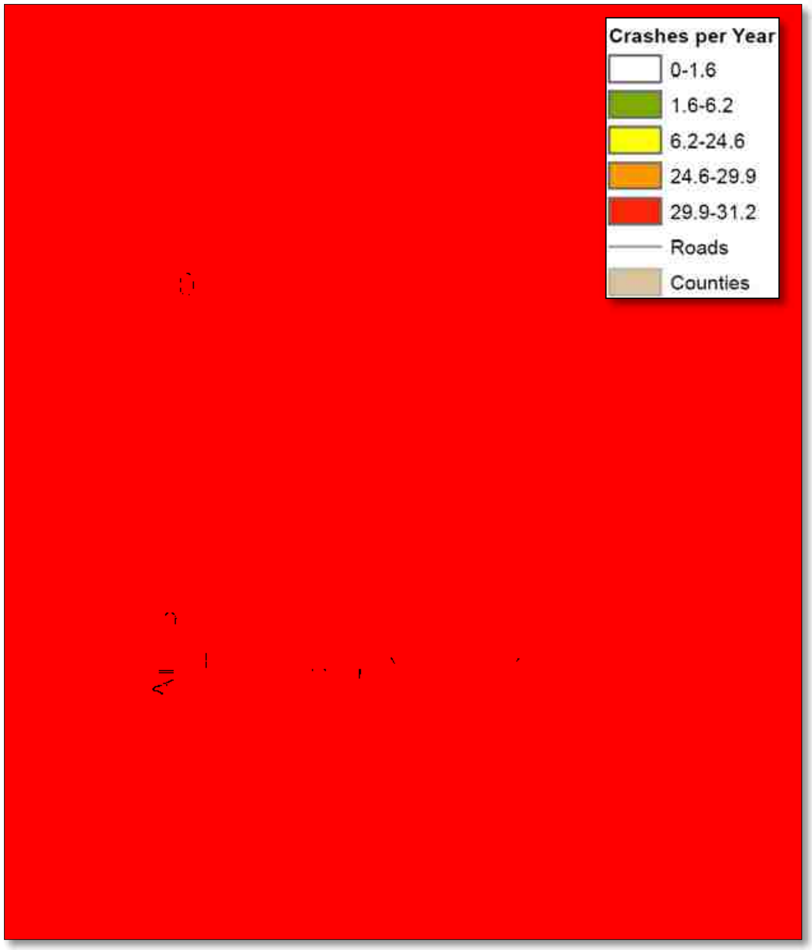

Figure 3-1: Crash density on State Street and University Parkway in Orem, Utah.

With a radius of 30 meters (98.4 feet) and a cell size of 5 square meters (16.4 square feet), the point density was created and is depicted in Figure 3-1. The units of point density are crashes per square mile. To make these units easier to comprehend, a conversion factor was found to convert the units into number of crashes per five years. This conversion calculation is shown in Equation 3-1.

$$\frac{\#\,Crashes}{1\;Mile^2} * \pi r^2\;meter^2 * \frac{3.861e^{-7} Mile^2}{1\;meter^2} = \frac{\text{Crashes}}{5\text{ yrs}} \tag{3-1}$$

Five counties were the primary focus of this research; Salt Lake, Davis, Utah, Cache, and Washington. Over these five counties, the number of crashes occurring per square mile varied considerably. Maximum values from the point densities before and after using the conversion factor are shown for each county in Table 3-3. The crash data used spans over five years from 2010 to 2014. Note that the number of crashes per five years is the number of crashes occurring within the 30 meter (98.4 feet) radius specified and is not the number of crashes for the entire county over all five years.

Table 3-3: Point Density Values for Five Counties

County	Crashes per Sq. Mile per 5 Years	Crashes per 5 Years in a 30m Radius	Crashes per Year in a 30m Radius
Salt Lake County	283,968	310	62.0
Davis County	169,465	185	37.0
Utah County	142,900	156	31.2
Cache County	102,595	112	22.4
Washington County	90,686	99	19.8

As depicted, Salt Lake County has over 200 more crashes in a 30 meter (98.4 feet) radius between 2010 and 2014 than Washington County, which has the lowest maximum density. Since Salt Lake County has a higher population density compared to Washington County, there are more crashes per square mile. St. George, in Washington County, has only a few main roadways thus, it is likely to have less crashes per square mile. To keep crash percentiles consistent within each county, the same density scale was used for each county. Utah County was the median county in terms of maximum number of crashes per square mile, thus, the Utah County density scale, shown in Table 3-4, was used for the other counties as well. This gave consistency as each county was analyzed to identify possible hotspots.

Table 3-4: Point Denisty Scale Used for Each County

UDOT Percentile	Utah County: Crashes per Year
0%-5%	0-1.6
5%-20%	1.6-6.2
20%-80%	6.2-24.6
80%-95%	24.6-29.9
95%-100%	29.9-31.2

Creating a crash density using ArcMap 10.3 tools allowed researchers to visualize where multiple crashes were occurring in an area. The color scheme used to display the crash density allowed hotspot locations to be found quickly. BYU researchers found that the biggest hotspot locations were intersections because crashes from each approach were added into the 30 meter (98.4 foot) radius that was used to calculate the crash density. Intersections were outside the scope of this project so locations between intersections were largely analyzed. It was interesting to see where crashes occurred and where problem areas were located.

3.2.2 Driveway Data

Two different methods were used to visualize the driveway data and each will be explained in this section. One method uses the line density tool while the other uses the spatial join tool in ArcMap 10.3. The classification for these densities use the UDOT safety categorical ranking percentiles presented previously in Table 3-2.

3.2.2.1 Line Density

Using ArcMap 10.3, the line density tool was executed on the driveway dataset, which covered the entire state of Utah. The line density tool calculates the length of each line, or driveway in this case, that falls within a circular area. The total length of the driveway inside the circle is summed and divided by the circle's area (Esri 2011b). Similar to the point density run on the crash dataset, a 30 meter (98.4 feet) radius and a 5 meter (16.4 square feet) cell size was used. The output units for this access density are given in miles of access per square mile. Unlike the crash units, there was not an agreeable way of simplifying these units; therefore, they were left as is. Visually, shown in Figure 3-2, this density looks similar to the crash density except that an orange to blue color scheme is used. Table 3-5 shows the classification used to view this access density method.

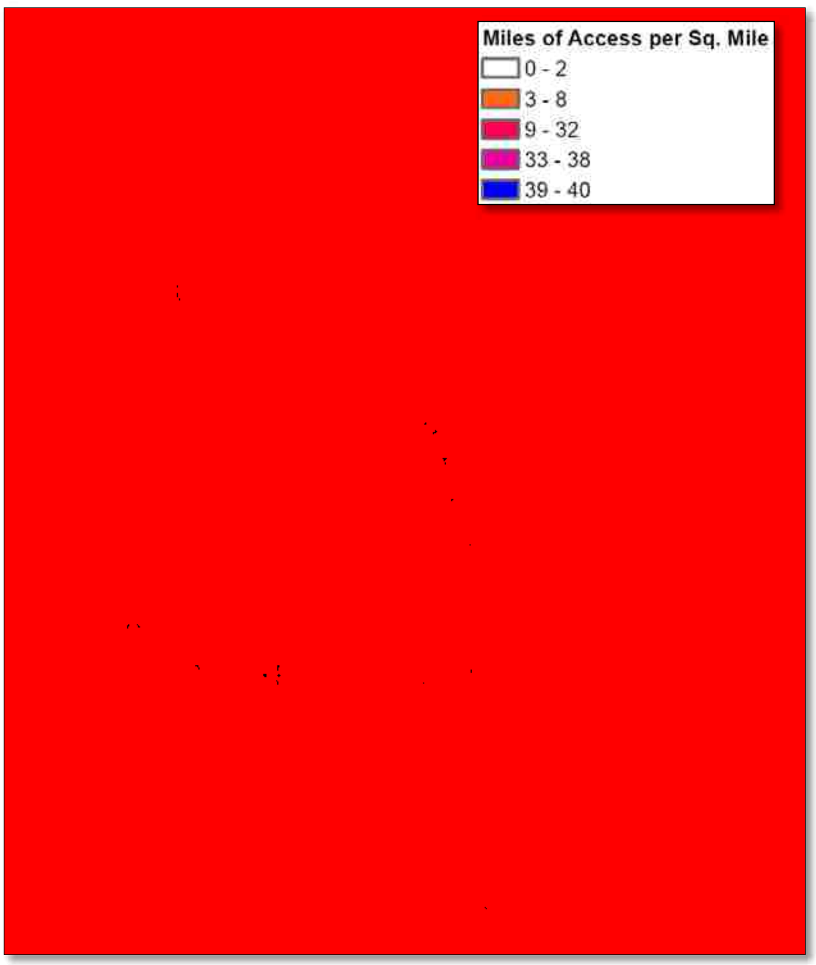

Figure 3-2: Driveway density depicting line density on State Street and University Parkway in Orem, Utah.

Table 3-5: Classification for Line Density

UDOT Percentile	Miles of Access per Square Mile
0%-5%	0-2
5%-20%	3-8
20%-80%	9-32
80%-95%	33-38
95%-100%	39-40

3.2.2.2 Spatial Join

Another way to visualize the driveway data used AADT data and a tool in ArcMap 10.3 called spatial join. The AADT data are broken up into segments of roadway that are based on similar characteristics. These segment lengths are not uniform, thus there are a wide variety of different segment lengths. Spatial join is a tool that joins attributes from one feature to another based on their spatial relationship (Esri 2016). The target feature for the spatial join tool was the AADT data and the join features was the driveway data. A join count column was added to the output attribute table after the spatial join tool was executed. The join count gave a number for each AADT segment that corresponded to the number of driveways on the segment within a distance of 15 meters (49.2 feet). Since most driveways are not spatially on the roadway but are offset slightly from the roadway line in ArcMap, this buffer was used to make sure all of the driveways were included.

To obtain units of driveways per mile, the join count was normalized by the length of the AADT segment as shown in Equation 3-2. Table 3-6 depicts the classification used to display both access densities found. This classification is based off of the access per mile recommended for each AC for both sides of the roadway as shown previously in Table 2-3. Visually, this method gives a linear density along the roadway which can be seen as the colored linear lines in Figure 3-3.

$$Linear\ Driveway\ Density = \frac{Driveway\ Count\ (driveways)}{Length\ of\ AADT\ Segment\ (miles) * 10^8} \qquad (3\text{-}2)$$

Table 3-6: Classification for Spatial Join

UDOT Percentile	Accesses per Mile
0%-5%	0-5
5%-20%	6-20
20%-80%	21-83
80%-95%	84-99
95%-100%	100-104

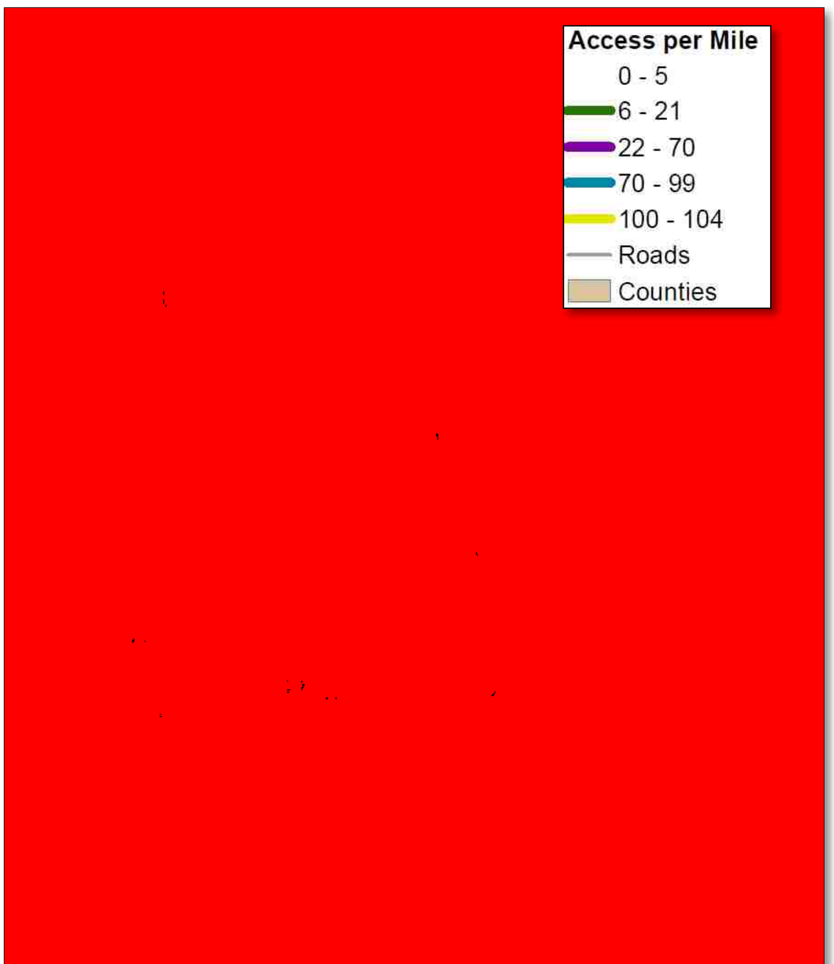

Figure 3-3: Driveway density depicting spatial join on State Street and University Parkway in Orem, Utah.

3.2.3 Median Data

The original median data are comprised of 10 different median types. These include:

1. Depressed
2. No Median
3. Other Divided
4. Painted
5. Railroad
6. Raised Island
7. Raised Median
8. Rapid Transit
9. Separate Grades
10. Undivided

Working with so many different types of medians proved difficult in ArcMap 10.3 because of the frequency in which the median type changed on the majority of roadways. A proposal was presented to the Technical Advisory Committee (TAC) to consolidate the medians for this project. The consolidated medians were determined as follows:

1. Raised Median
    a. Raised Island
    b. Raised Median
2. Rail and Transit
    a. Railroad
    b. Rapid Transit

3. Painted Median
    a. Painted Median
4. Other
    a. Depressed Median
    b. Other Divided
    c. Separate Grades
5. No Median
6. Undivided
7. TWLTL

Initially there were questions as to what the difference was between an undivided median and a road with no median, and why TWLTLs were not in the median dataset. By definition a TWLTL can be specified as a type of lane, therefore, TWLTL information was found in the lane dataset rather than in the median data. Through the join tool in ArcMap, the TWLTL data were added to the median data since a TWLTL acts as a separate type of median dividing opposing directions of traffic. Doing this proved to be inaccurate because other median types overlapped with the TWLTL; therefore, the TWLTL was analyzed separately as part of the lane data.

In addition, it was found that majority of the time where roadways had a TWLTL, the median type was categorized as no median type. The process of adding TWLTLs into the median dataset assisted researchers in learning the difference between an undivided median and a roadway with no median. The undivided median was a double painted line separating opposing traffic flows while the no median type seemed to dominantly be where TWLTLs were positioned. Consolidating medians was a useful way to simplify the data visually to assist in making preliminary correlations.

3.2.4 Initial Correlations and Hotspots

Crash density was used to find locations with high crash frequencies. These locations were compared to the line density and spatial join access density methods and the median type on the roadway to evaluate whether the higher crash locations visually correlate with higher driveway densities and/or the median type. Several locations were found when comparing crash density, access density, and median type. These locations are listed in Table 3-7 while maps depicting comparisons at these locations are found in Appendix B.

Table 3-7: Locations Found Through Visually Inspecting Data in ArcMap 10.3

Locations	Cross Streets
Main St., Cache County	300 S. to 1800 N.
500 W., Davis County	1500 S. to 400 N.
400 S., Salt Lake City	400 E. to 900 E.
5400 S., Salt Lake City	5600 W. to Redwood Rd.
Foothill Dr., Salt Lake County	Parleys Way to Sunnyside Ave.
Redwood Rd., Salt Lake County	4700 S. to Rosa Parks Dr.
State St., Orem, Utah County	1600 S. to 400 N.
N. Main St., Spanish Fork, Utah County	300 S. to 1000 N.
St. George Blvd., Washington County	Bluff St. to I-15

Access density was also compared with AC to visually observe if the number of driveways found on a roadway coincide with the number of driveways recommended for each as outlined in the Administrative Rule R930-6. Comparisons were made with the two access density methods and the current AC. Figure 3-4 depicts a map of downtown Salt Lake City. The spatial join access density method and the current AC are color coordinated with each other; meaning, AC 2 is colored green, as shown in the bottom inset map, while the corresponding access per mile, shown in the top inset map, is colored green as well. If the colors are different between the two, then the access density is not what the R930-6 suggests for that category. Having a lower access density than the AC guidelines advise is acceptable; however, a problem arises when the access density is greater than what is recommended for the AC. With an increase in driveways on a roadway, the number of conflict points increase which decreases safety on the roadway.

Observing 400 South in Figure 3-4 can illustrate the color coordination between the two inset maps. The bottom inset map shows 400 South colored yellow which, according to the legend, corresponds to an AC 6. In the top inset map, however, 400 South is colored light orange which has between 52.9 and 109.9 driveways per mile. This driveway count, according to the bottom inset map legend, corresponds to an AC 7, 8, or 9. Since 400 South is acting as a higher AC than it is currently classified, it has a higher number of accesses per mile than the Administrative Rule R930-6 recommends. Subsequently this segment falls outside of the R930-6 guidelines; therefore, UDOT can take a closer look at this roadway to see if there is a safety issue on this roadway that needs to be addressed.

Figure 3-5 shows a map of State Street in Orem, located in Utah County, Utah. This map compares the AC to both access density methods. The spatial join access density method, shown in the right inset map, and the AC data, shown in the left inset map, are color coordinated similar to Figure 3-4. As shown in the left inset map, State Street north of University Parkway is currently classified as an AC 8. However, as shown in the right inset map, State Street north of University Parkway is partially acting as an AC 6. This is acceptable since the driveway density of an AC 6 is less than the driveway density recommended for an AC 8.

The ArcMap 10.3 analysis explained in this section was beneficial in visualizing the crash, median, driveway, and AC data. However, more detailed results could not be concluded from this analysis; therefore, an automated Excel spreadsheet was used to find detailed results.

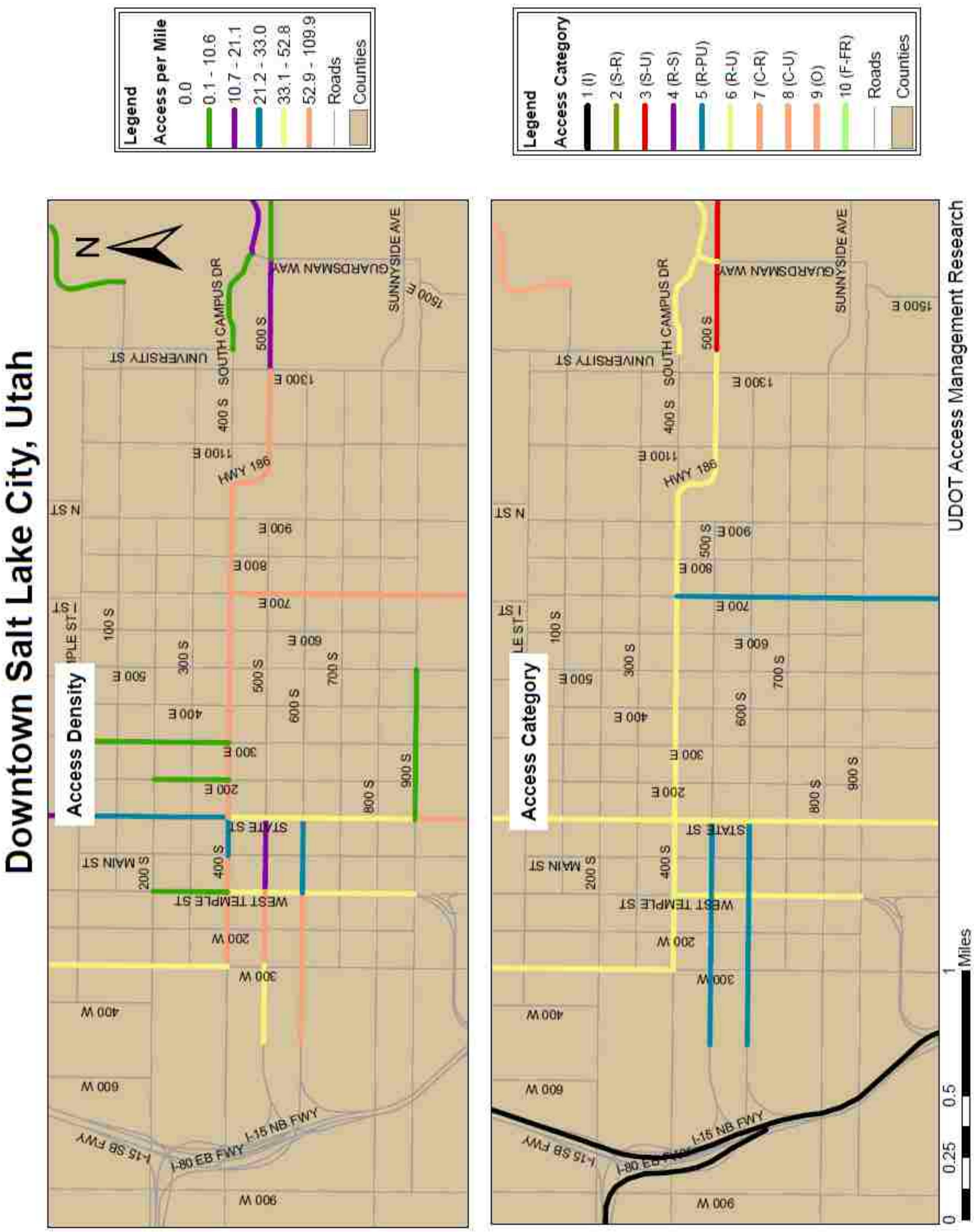

Figure 3-4: Comparison between access density spatial join and the current AC for downtown Salt Lake City, UT.

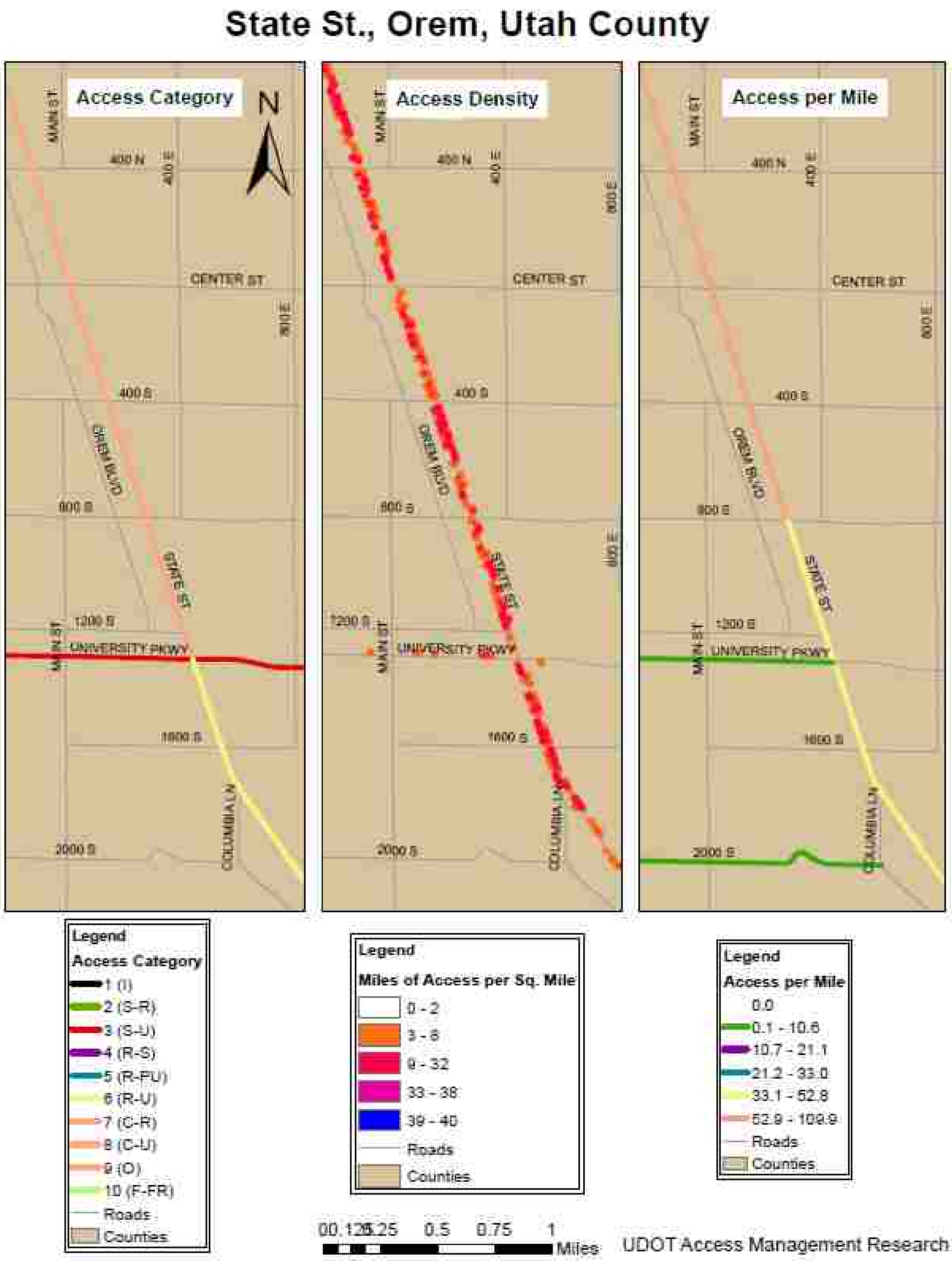

Figure 3-5: Map comparing existing AC and line density and spatial join for State Street in Orem, UT.

3.3 Data Preparation

Microsoft Excel was used to prepare the data for more detailed analysis and corridor selection. An Excel workbook, prepared in 2015 for a UDOT safety study by BYU was modified and used to automate the process of combining multiple datasets and segmenting them based on a change in characteristics or on a specified length (Schultz et al. 2016). Modifications were made to this segmentation workbook to add more datasets and change the programming code to segment the datasets in a different way than the original. This section will briefly address the original workbook that was created, the modifications made to the original workbook for this project, and the output generated from the modifications. In addition, short segment discrepancies and the effect utility driveways had on the output will be discussed.

3.3.1 Original Workbook

The original Roadway and Crash Data Preparation workbook was created in 2015 and is made up of two parts (Schultz et al. 2016). The first is roadway segmentation and the other is combining crash data. The roadway segmentation part uses five datasets to create roadway segments. These datasets include historic AADT, functional class, speed limit or sign faces, lanes, and urban code. Figure 3-6 shows the interface for this worksheet. Once each of these datasets are imported, the user can choose whether to segment the data by characteristic or by a specific length. An Excel spreadsheet is created with the segmented data.

Combining crash data uses four crash datasets; Crash Location, Crash Data, Crash Rollup, and Crash Vehicle. Once these datasets are imported into the workbook, the Combine Crash Data command button appears that, when executed, creates two spreadsheets. One contains all of the crash data and the other contains vehicle data related to each crash.

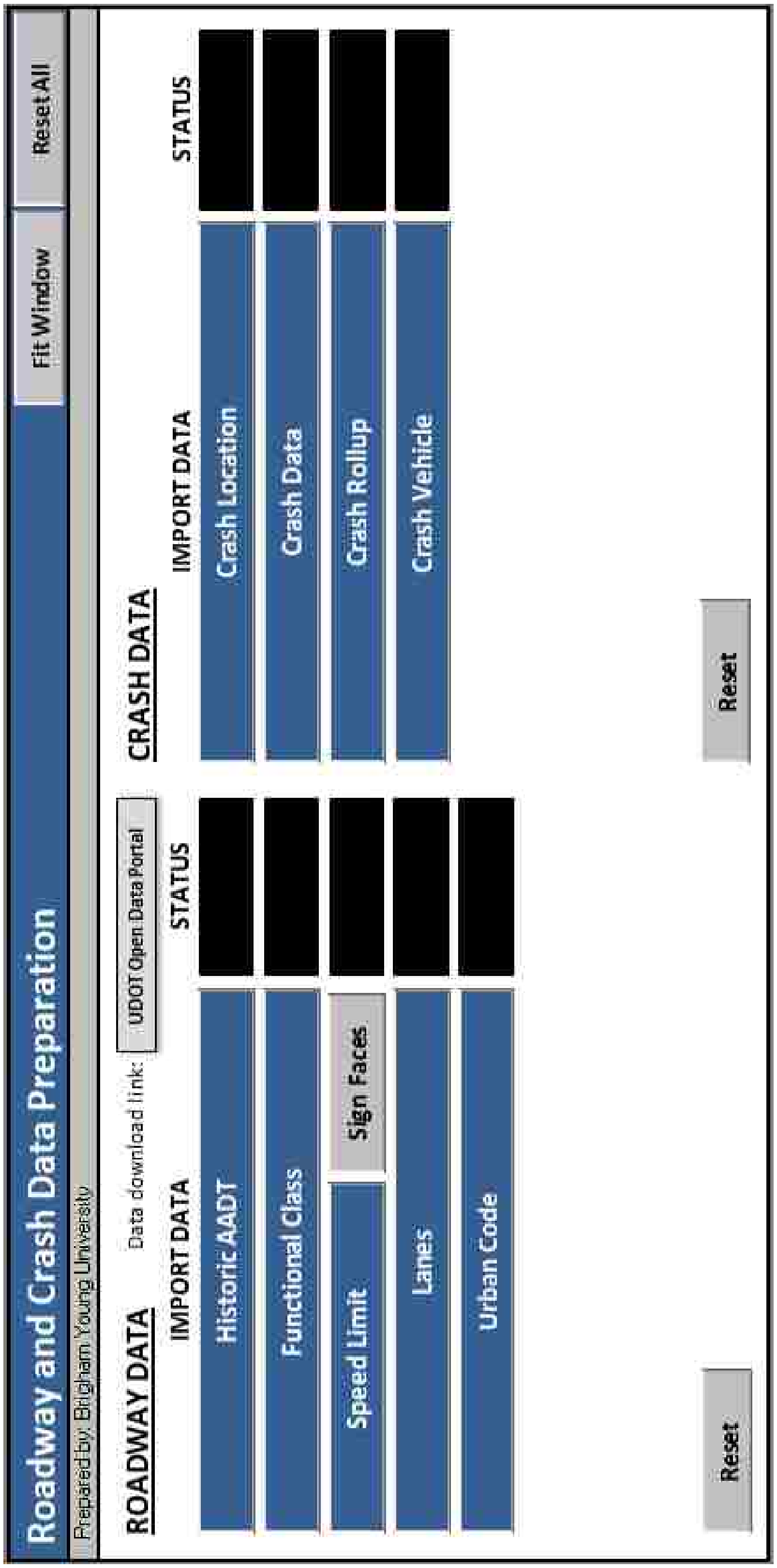

Figure 3-6: Orgininal roadway and crash data preparation workbook (Schultz et al. 2016).

This workbook was coded using Visual Basic Application (VBA) software that allows the user to input data and create new spreadsheets by executing commands. Figure 3-6 shows the interface of the workbook. When an import button is executed, it allows the user to select a data input file. Once the user selects the input file, the VBA macros will copy the data that are critical to the segmentation process; such as beginning and ending mile point, route, and data specific to that dataset (e.g., AADT for every year). These critical datasets are placed in an individual sheet in the workbook. After each dataset is imported, the "Status" bar next to the button turns green.

When all the datasets are imported into the workbook, a new button appears that allows the user to choose whether the data will be segmented by a change in the data or by a specified maximum length that the user determines. Figure 3-7 shows this new button. Once the Roadway Segmentation button is executed, segmentation on the roadway begins. First, the VBA code checks to ensure that all data files have been copied into the workbook. Next, Excel goes through each data sheet and deletes routes that are not present in all five roadway datasets and verifies that each dataset has the same ending mile points for each route. Dataset mile point columns are found and the sheet with the lowest mile point is the beginning mile point for the segmented data. Every time the code comes across a change in a dataset or specified length, a new segment begins. After the data have been segmented, headers are added to the spreadsheet and the user selects a folder location to save the segmented data.

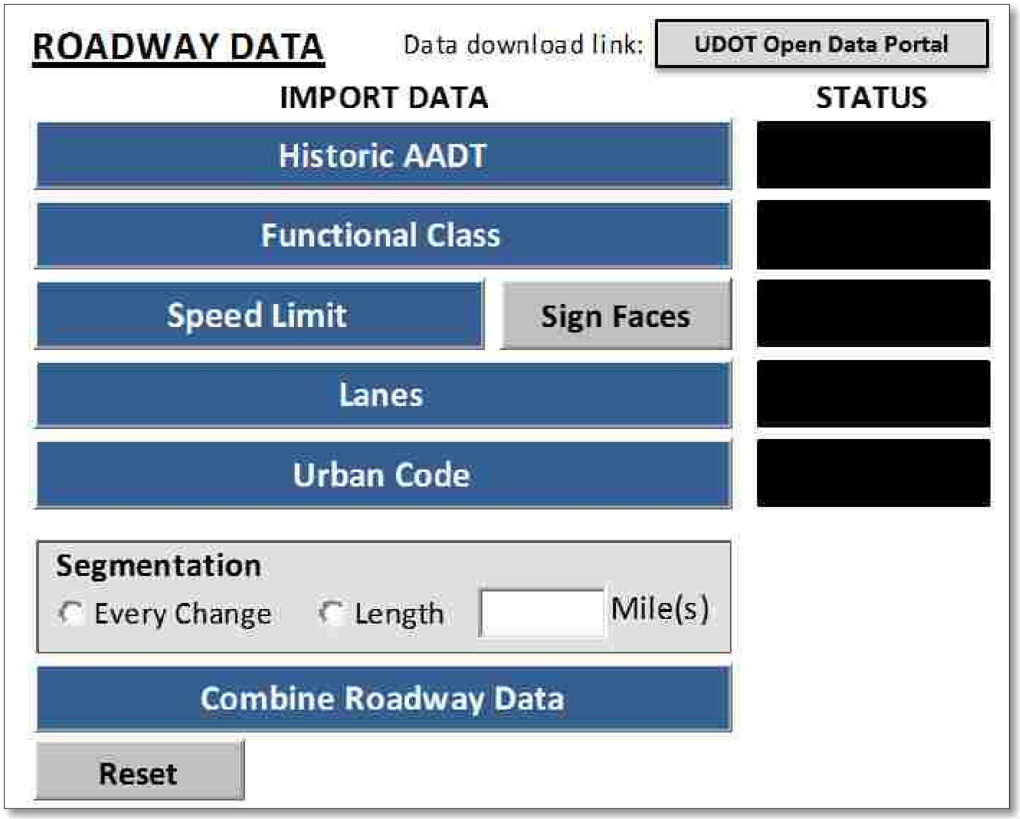

Figure 3-7: Segmentation options and combine road segmentation button (Schultz et al. 2016).

3.3.2 Roadway and Crash Data Preparation Modification

Several modifications were made to the Roadway Data portion of the data preparation workbook to help achieve the purpose of selecting corridor locations to analyze for this research. These modifications made it possible to add more datasets and combine the roadway data in a different manner than the original workbook. The revised user interface is pictured in Figure 3-8. Driveway data, median data, AC, and crash location were four datasets added to the Roadway Data section of the workbook. In addition, changes were made to the VBA code for the lane data and new codes were created throughout the workbook to adjust for the specific needs of this research. No changes were made to the Crash Data portion of the workbook. This section will summarize modifications made to the Roadway Data portion of the workbook, including changes made to the lane data, the addition of median data, and the inclusion of driveway and crash data.

3.3.2.1 Lane Data Modifications

Originally, through lane data was the only lane type included in the segmentation process. For this study however; TWLTL, left lane, and right lane data needed to be included. This proved to add some difficulty to the segmentation process when the data were segmented on every change. Since four different lane types were to be segmented, every lane change that occurred created a new segment. The number of segments increased dramatically from approximately 6,000 with just the through lane, to over 40,000 with all four lane types. Having so many segments was not feasible for this research as most segments were very small, giving inaccurate information and limited analysis potential. To avoid having so many segments, the roadway data were not segmented by the lane data. Instead, the segmentation was based off of AADT, AC, speed limit, functional class, and urban code. Following the segmentation, the maximum number of through lanes, right lanes, left lanes, and TWLTLs were given for each segment. Using the maximum number of lanes for each lane type provides information to the user regarding the breakdown of lane types.

It should be noted that although segments include data on the maximum number of lanes, the results may include lanes from the opposite side of an intersection. For example, the segmented data may show that there are two left-turn lanes; however, upon looking at a map, there is only one left-turn lane. The segmented data says two left-turn lanes because it may be counting the left-turn lane in the opposite direction as well. Although this workbook splits the data in a useful format, it is important to look at what is actually happening along the segment to understand the data correctly.

3.3.2.2 Median Data Additions

Similar to the lane data, the roadway data were not segmented based on the median data. For this workbook, all 10 median types, listed previously in Section 3.2.3, were used. After segmentation was completed using AADT, AC, speed limit, functional class, and urban code; the first four median types, ordered by length, for each segment were placed in the output segmentation sheet. The top four predominate median types were found by calculating the length of each median type for every segment. Median lengths were calculated using the beginning and ending mile points for the segmented roadway data and the median data. The four longest median types were added to the output sheet for every roadway segment.

When conducting the research, it was noted that the 2014 median dataset had inconsistencies throughout the data. Mile points were acting in the negative direction and the beginning and ending mile points occasionally equaled each other. These discrepancies were fixed by removing all of the rows of data in the dataset that fit these discrepancies to create a smoother dataset. In addition, the 2016 median data was received by UDOT before it was uploaded to the Open Data Portal. These data had fewer inconsistencies and were used in connection with the 2014 data.

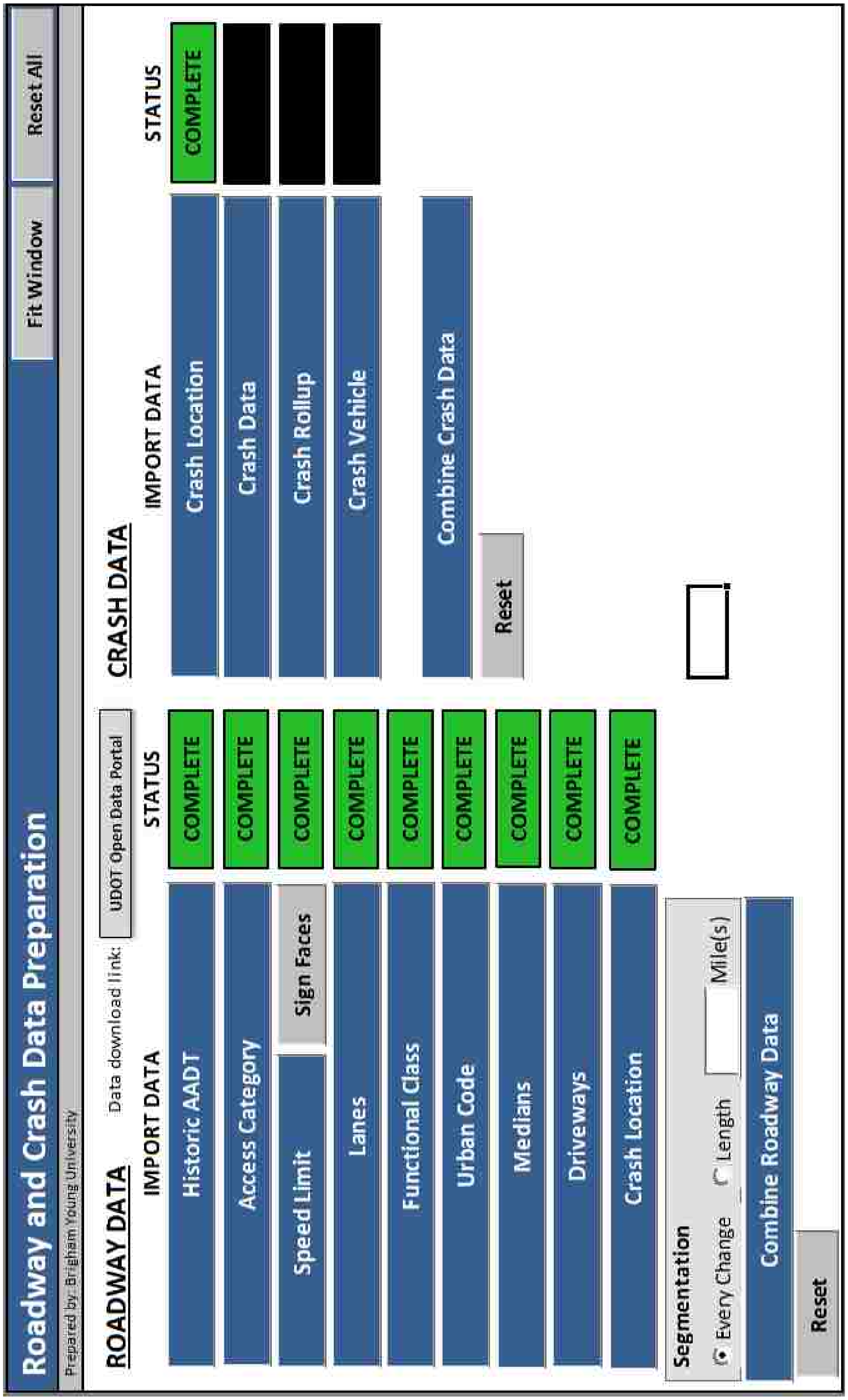

Figure 3-8: Modified roadway and crash data preparation workbook .

3.3.2.3 Driveway and Crash Data

Another modification that was made to the segmentation workbook was the inclusion of driveway data and crash data. These two datasets were used to calculate driveway densities and crash densities for each segment. The number of driveways on each segment were counted and divided by the length of the segment to get units in driveways per mile. Two columns were added to the final spreadsheet: driveway count and driveways per mile. The crash data are used in this same way; however, since the crash data used in this process covers from 2010 to 2014, the annual number of crashes per mile were calculated. Three columns are in the final spreadsheet: Crash Count, Crashes per Mile per 5 years, and Crashes per Mile per Year.

3.3.3 Output

The output for the roadway segmentation, both the original and the modified workbook, is a single Excel sheet that has many different data columns compiled from all of the input datasets. Data included in the original output are the beginning and ending mile points of the segment, Route, Region, seven years of AADT data, functional class, urban code, number of through lanes, and speed limit. The original output also included single and combination truck percentages; however, these were not included in the modified output. The modified output includes the majority of the data included in the original output as well as AC, four different lane types, top four predominate medians on the segment, driveway count and density, and crash count and density. Table 3-8 shows all of the column headers that are in the amended output and an example value for each header. The modified segmentation output has 3,758 segments while the original has 6,091 segments.

Table 3-8: Modified Workbook Output

Column Header	Example
Label	0006P
Beg_Milepoint	0
End_Milepoint	24.5
Route_Name	6
Route_ID	6
Direction	P
County	Millard
Region	4
AADT_2014	350
AADT_2013	330
AADT_2012	325
AADT_2011	330
AADT_2010	340
AADT_2009	355
AADT_2008	345
AC	2
AC_Type	(S-R)
Speed_Limit	65
Thru_Lanes	2
RtLns	0
LftLns	2
TWLTL	0
Dominant_Median	Undivided
Median2	Painted Median
Median3	No Median
Median4	-
FC_Code	3
FC_Type	Other Principal Arterial
Urban_Rural	99999
Urban_Ru_1	Rurall
Driveway_Count	3
Driveway/Mile	0.12
Crash_Count/5yrs	43
Crashes/Mile/5yrs	1.76
Crashes/Mile/Yr	0.35

3.3.4 Short Segment Discrepancies

It became apparent that many of the segments from the segmented data were less than 0.5 miles in length. Researchers became interested in seeing how much of an impact these short segments, less than 0.5 miles, were having on the analysis results. Many short segments have the same characteristics as the nearby segment except when one characteristic changes. AADT, AC, and speed limit change within a few tenths of each other much of the time, therefore it may be inferred that these changes are meant to happen simultaneously and that combining these segments would not substantially affect segment characteristics. Thus, the roadway segmentation workbook was revisited and modified to include a minimum segment length constraint. Figure 3-9 shows the updated segmentation user interface for roadway data. The minimum length specified for this analysis was 0.5 miles. Roadway data were segmented as previously discussed, then, segments with lengths below the minimum length were combined with a segment nearby with the same route and the same AADT. Combining segments this way reduced the accuracy of segmenting the data on homogeneous characteristics; however, many segments were less than 0.1 miles which did not change the segment length substantially. It was originally expected that adding a minimum length requirement would eliminate short segments entirely; however, if the short segment did not share an equal AADT value with the adjacent segments it could not be combined, thus several short segments remained.

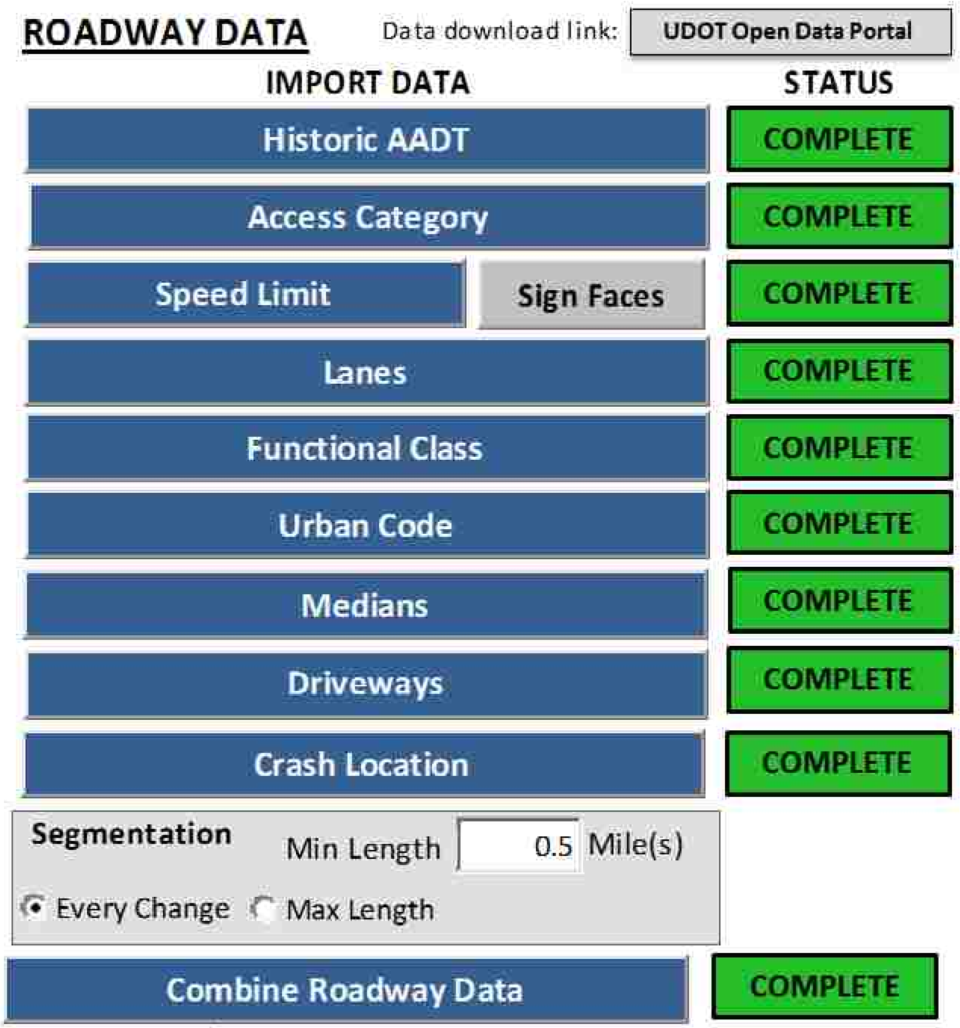

Figure 3-9: Updated segmentation user interface for roadway data.

Combining segments based on route and AADT showed a reduction in the overall number of short segments. Initially, 3,605 total segments were created with 1,746 segments shorter than 0.5 miles. After adding a minimum segment length of 0.5 miles, 2,291 segments were created with only 304 segments shorter than 0.5 miles, a drastic reduction from the segmentation run without a minimum specified segment length. Figure 3-10 displays the number of segments less than and greater than 0.5 miles, before and after the minimum segment length requirement was added.

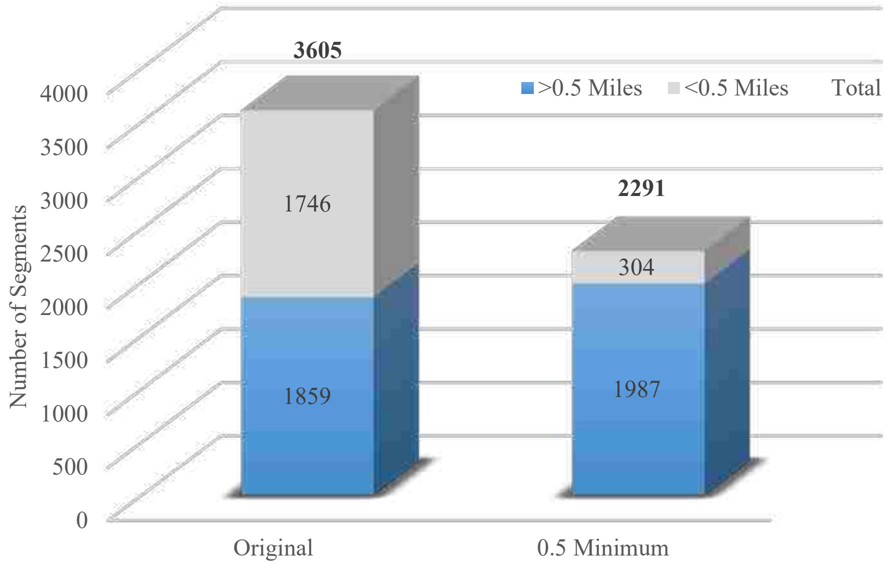

Figure 3-10: Comparision of the number of segments before and after the minimum segment length buffer.

To continue to eliminate short segments, the AADT of the short segment was used to find a buffer that was compared with the AADT of the adjacent segments. If the AADT of the adjacent segments was within the buffer, the segments were combined. The maximum and minimum value calculations are shown in Equations 3-3 and 3-4.

$$Short\ Segment\ AADT * Percentage + Short\ Segment\ AADT = Max\ AADT \quad (3\text{-}3)$$

$$Short\ Segment\ AADT - Short\ Segment\ AADT * Percentage = Min\ AADT \quad (3\text{-}4)$$

Three different percentages were compared to find the percentage that would reduce short segments while maintaining the integrity of the data. A comparison of the number of short segments and the number of segments greater than 0.5 miles for each AADT percentage buffer is shown in Figure 3-11. Using a 10 percent buffer yielded 2,187 segments, of which 180 were short segments. A 15 percent buffer gave 2,147 segments where 136 were short segments, while the 20 percent buffer gave 2,116 segments, of which 107 were short segments. The 10 percent buffer was determined to be the best percentage after sensitivity analysis because it had the desired effect of reducing short segments under 0.5 miles while keeping segments homogeneous.

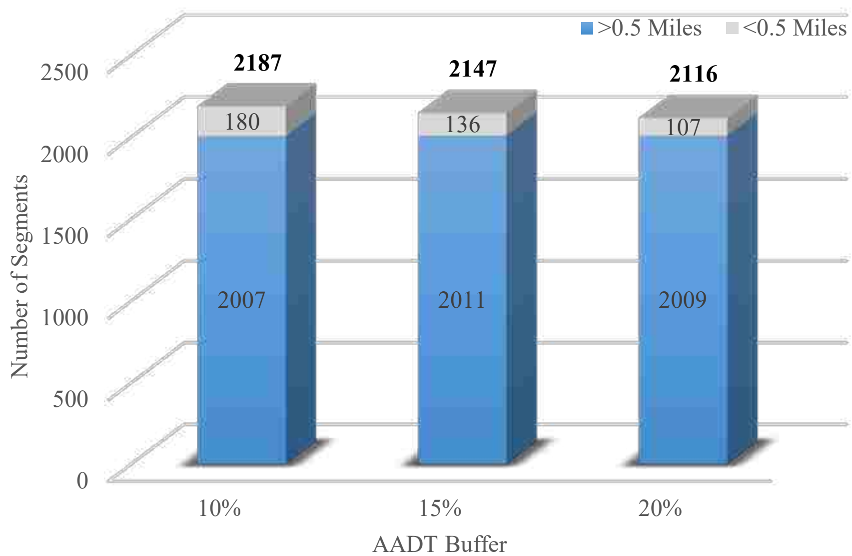

Figure 3-11: Comparison of AADT percentage buffers.

A third and final buffer was created to eliminate all segments less than 0.1 miles. This buffer combined all short segments less than 0.1 miles with an adjacent segment automatically. Since the segment lengths were so short, researchers were not concerned with creating non-homogeneous segments when combining with an adjacent segment. This buffer eliminated all remaining segments less than 0.1 miles. Figure 3-12 depicts the number of segments less than 0.1 miles that remained after each buffer was applied to the data.

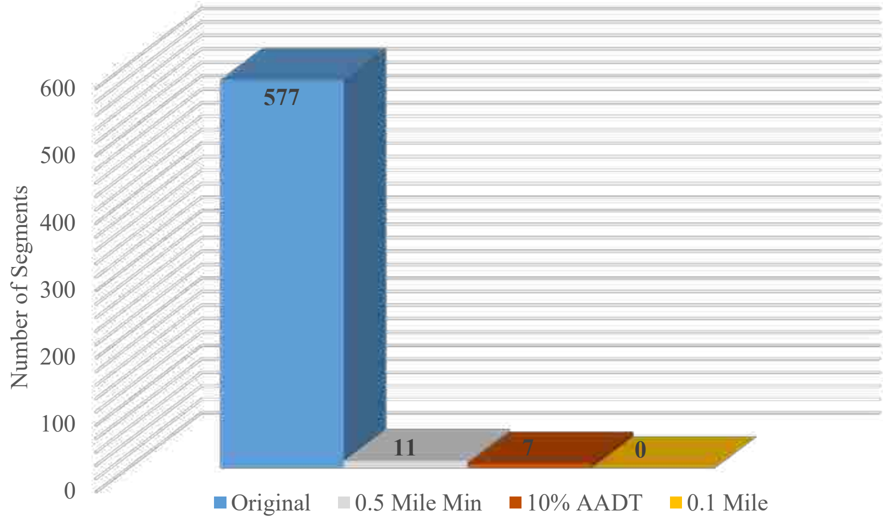

Figure 3-12: Comparison of the number of segments less than 0.1 miles for all buffers.

After the addition of the minimum length buffer, the AADT percentage buffer, and the 0.1-mile buffer, the number of short segments decreased dramatically. There are, however, still some segments less than 0.5 miles because these segments did not meet the requirements of the buffers and therefore could not combine with adjacent segments. Researchers decided to leave these segments in the data instead of removing all segments less than 0.5 miles to keep the segments homogeneous.

3.3.5 Removing Gated/Utility Driveways

After an initial analysis was run, researchers found that many of the AC 3 segments fell outside the Administrative Rule R930-6 criteria of zero driveways on the roadway. Some sensitivity analysis was completed on these AC 3 segments and it was found that the dataset included utility driveways. These driveways are not widely used and do not have a profound effect on safety; therefore, the driveways that were specified as a gated/utility driveway type were removed from the driveway dataset and a new analysis of segments that fell outside of the AC criteria were found.

Figure 3-13 and Figure 3-14 show a visual comparison of the segments found outside of the current AC criteria in Salt Lake County, Utah. With the gated/utility driveway type included in the analysis, there are more segments found outside of the AC criteria, meaning these segments have more access on the roadway than the criteria guidelines suggest. Therefore, the gated/utility driveway types, though counted as an access on the roadway, were removed for this study.

3.4 Chapter Summary

This chapter outlines the datasets used in this project, different ways researchers visually examined the data in ArcMap 10.3, and an automated technique used to segment roadway datasets in Microsoft Excel. A crash density was created which made possible hotspot areas easier to identify. Driveway densities were produced using two different methods. The first used line density to create a density similar to the crash density hotspot maps, while spatial join created a linear access density that was segmented based on AADT. Both methods were useful in identifying possible areas to analyze further and multiple maps showing hotspots were created. An automated Excel workbook was created to segment roadway data based on homogeneous characteristics and to combine crash data. This workbook was modified to fit the needs of this project. The output generated after modifications were made was presented.

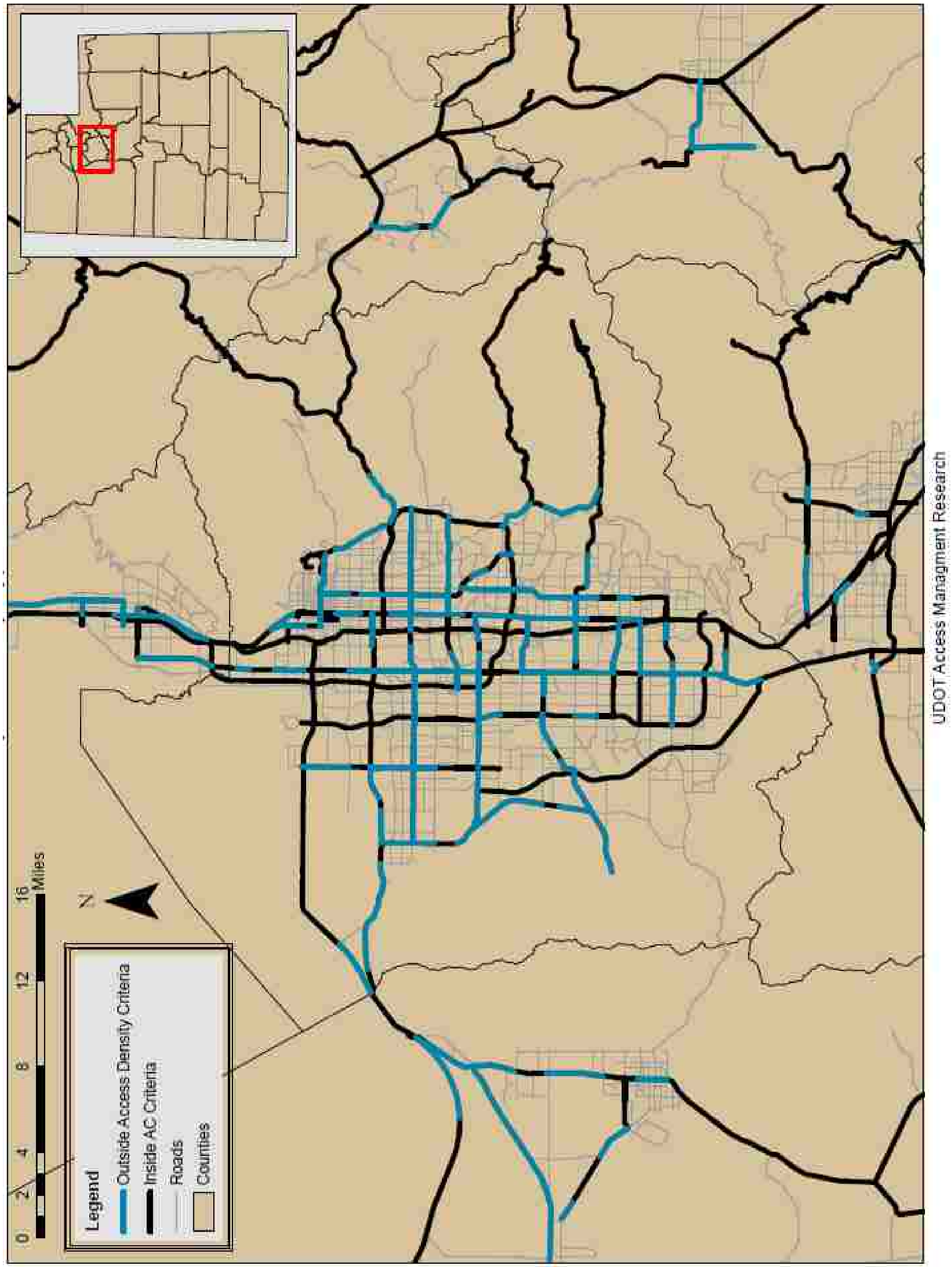

Figure 3-13: Segments outside access density criteria with gated/utility driveways included.

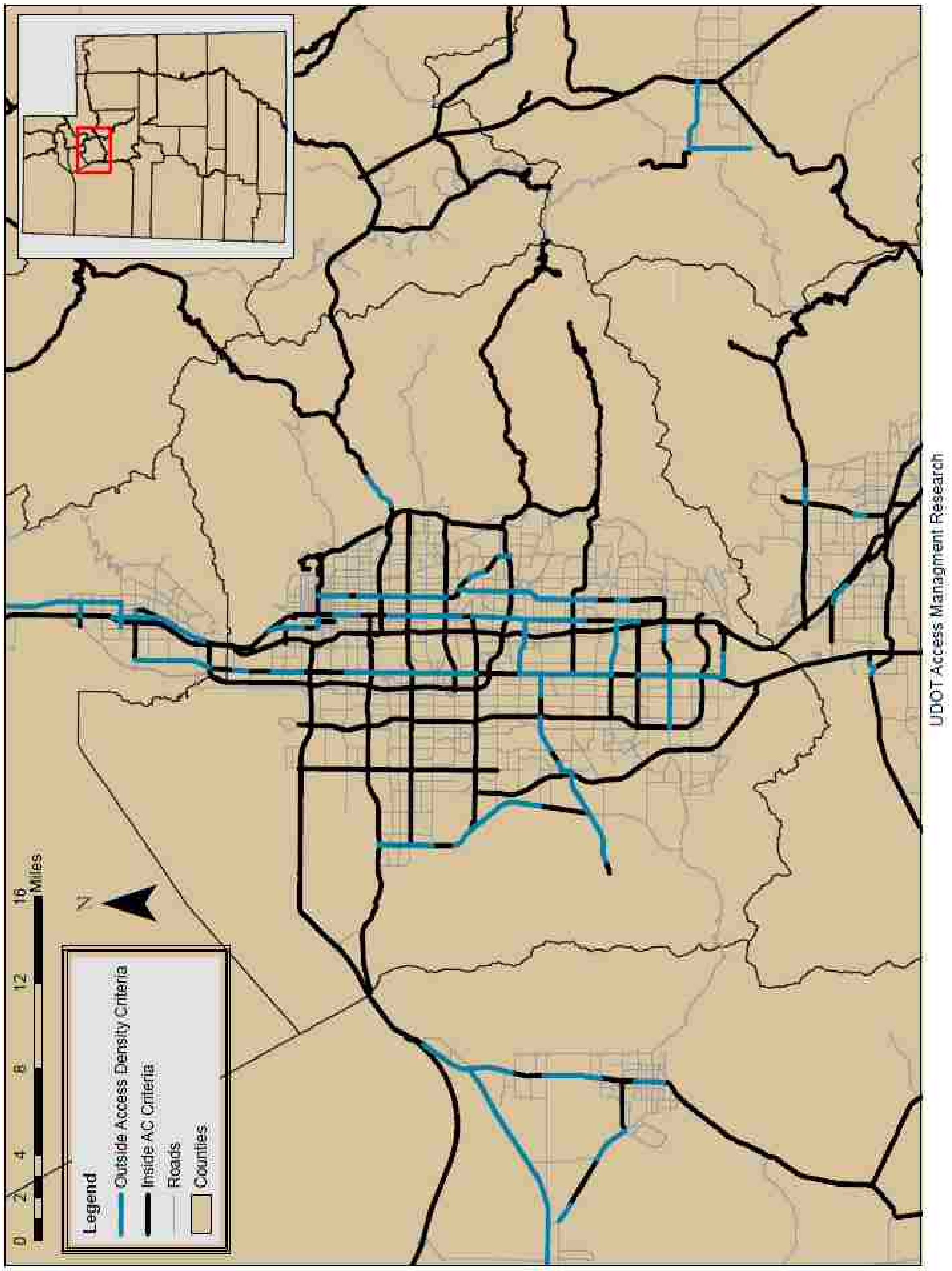

Figure 3-14: Segments outside access density criteria with gated/utility driveways removed.

4 ANALYSIS

Several analyses were performed using the modified roadway segmentation output. These included analyzing AC and different characteristics of the roadway that determine the AC; and raised median installation using a before-after model. Each of these scenarios and the findings associated with them will be explained in this chapter.

4.1 AC Criteria Analysis

AC is a categorization for a roadway based on speed limit, driveway density, signal spacing, and functional class. BYU researchers explored the AC data to determine how Utah roads are currently categorized and if these categorizations meet the specifications outlined in the Administrative Rule R930-6. Using the modified segmentation output, the segments where the access density did not meet the AC specifications were identified and then categorized based on their current roadway characteristics.

4.1.1 Finding Segments Outside AC Criteria

Table 4-1 shows each AC, the number of segments in the category, and the number of segments and the percentage of segments that do not meet the driveway density conditions. As outlined previously in Table 2-3, AC 1, 3, and 10 are categorized such that they do not have any access. However, as displayed in Table 4-1, there are segments classified as an AC 1 and 3 that have access and do not meet the specification of zero access. AC 3 has the highest percentage of segments that fall outside of the existing category than any other category at 45.8 percent. Of all 2,180 segments, 14.5 percent have a higher driveway density count than the AC allows.

Table 4-1: Segments Outside the Access Density Criteria

AC	Total Segments	Crash/Mile/Year	Segments Outside Access Density Guidelines		
			Number of Segments	Percentage	Crash/Mile/Year
1	336	21.9	5	1.5%	5.3
2	331	2.0	7	2.1%	2.2
3	203	18.7	93	45.8%	12.1
4	484	2.4	42	8.7%	3.9
5	313	28.2	119	38.0%	31.3
6	145	21.8	31	21.4%	23.6
7	274	2.1	11	4.0%	3.4
8	82	16.5	7	8.5%	27.2
9	12	0.5	0	0.0%	0.0
10	0	0.0	0	0.0%	0.0
Total	2180	12.3	315	14.5%	19.1

AC and speed limit were also compared. Only eight of the 10 AC have approximated speed limit values identified in the R930-6; AC 1, 2, 3, 4, 5, 6, 7, and 8. These approximated speed limits were used as the recommended speed for this analysis. Table 4-2 displays the number of segments that exceed the speed limit values outlined previously in Table 2-3. Of the categories that specify a speed limit, 18.2 percent of the total number of segments did not meet the speed limit specification for the AC that the segment was classified as. AC 5 has the highest number of segments that had a speed limit outside the existing speed limit outlined for that category at 52.7 percent. Several segments, shown in Table 4-3, fall outside both access density and speed limit guidelines given in the R930-6. AC 5 has by far the most segments that fall outside both characteristic criteria at 25.2 percent.

Table 4-2: Segments Outside the Speed Limit Criteria

AC	Total Segments	Crash/Mile/Year	Segments Outside Speed Limit Guidelines		
			Number of Segments	Percentage	Crash/Mile/Year
1	336	21.9	2	0.6%	45.2
2	331	2.0	15	4.5%	1.2
3	203	18.7	13	6.4%	26.9
4	484	2.4	75	15.5%	1.8
5	313	28.2	165	52.7%	40.2
6	145	21.8	49	33.8%	10.4
7	274	2.1	70	25.6%	1.4
8	82	16.5	7	8.5%	6.0
9	12	0.5	0	0.0%	0.0
10	0	0.0	0	0.0%	0.0
Total	2180	12.3	396	18.2%	19.9

Table 4-3: Segments Outside Both Access Density and Speed Limit Criteria

AC	Total Segments	Crash/Mile/Year	Segments Outside Access Density and Speed Limit Guidelines		
			Number of Segments	Percentage	Crash/Mile/Year
1	336	21.9	0	0.0%	0.0
2	331	2.0	0	0.0%	0.0
3	203	18.7	9	4.4%	20.3
4	484	2.4	13	2.7%	2.6
5	313	28.2	79	25.2%	35.9
6	145	21.8	4	2.8%	8.5
7	274	2.1	0	0.0%	0.0
8	82	16.5	0	0.0%	0.0
9	12	0.5	0	0.0%	0.0
10	0	0.0	0	0.0%	0.0
Total	2180	12.3	105	4.8%	29.4

4.1.2 Placing Segments into a New AC

According to the previous analysis, several segments fell outside the Administrative Rule R930-6 guidelines for the AC that segments are currently assigned. BYU researchers wanted to determine which category those segments follow based on existing roadway characteristics determined using the LiDAR data. This was accomplished using urban code and access density; and using urban code, access density, and speed limit. Each procedure will be explained in this section.

4.1.2.1 Urban Code and Access Density

The first procedure used to place segments into a new AC was based on urban code and access density. Table 4-4 shows the number of segments that were allocated to a new category based on those two parameters. The green cells in the table show the number of segments that currently fall within the existing AC criteria and were not changed to a different AC. The red cells show the number of segments placed into a different AC than the original. Cells were colored light red if the number of segments that changed AC is less than 10 percent of the total number of segments in each AC, while cells were colored dark red if the number of segments that changed AC is greater than 10 percent of the total number of segments in each AC. Row one in Table 4-4 shows that the total number of segments currently classified as an AC 1 is 336 segments. The R930-6 criteria, outlined previously in Table 2-3, was used compare those guidelines to the current data of the segment. Of the 336 total segments, 329 segments fit the AC 1 guidelines, however, five segments fit the criteria of an AC 2 and two segments fit the criteria of an AC 5. Both of those cells are light pink since the number of segments that fit into a different AC were less than 10 percent of 336, the total number of segments in AC 1. If a segment had over 70.4 driveways per mile, then it exceeded the maximum number of accesses per mile allowed according to the R930-6 guidelines. After careful consideration, these segments were recommended to be assigned to an AC 9 which is a category called other importance.

Table 4-4: New AC Assignments Based on Urban Code and Access Density.

AC	Total AC	New Access Category									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	336	329	5	0	0	2	0	0	0	0	0
2	331	0	321	0	4	5	0	1	0	0	0
3	203	0	11	106	4	67	3	5	4	3	0
4	484	0	50	0	385	19	7	19	2	2	0
5	313	0	1	0	0	193	53	2	40	24	0
6	145	0	3	0	3	26	78	5	16	14	0
7	274	0	43	0	11	9	0	200	0	11	0
8	82	0	1	0	0	6	0	0	68	7	0
9	12	0	0	0	0	0	0	0	0	12	0
10	-	-	-	-	-	-	-	-	-	-	-
Key:		Green: Current AC Matches Field Data			Light Red Cells: <10% Total AC Segments			Dark Red Cells: >10% Total AC Segments			

4.1.2.2 Urban Code, Access Density, and Speed Limit

The second procedure placed segments into a AC based on urban code, access density, and speed limit. Table 4-5 depicts the new AC assignments based on these three roadway characteristics. The colors are the same as described in the previous section. Upon comparing Table 4-4 with Table 4-5, there are a lot of similarities between the number of segments that received new AC assignments, however, more segments are given a new AC when the speed limit criterion was used. Upon comparing the row for AC 5 in both tables, 193 segments are not given a new AC using urban code and access density and only 109 segments keep the current AC when speed limit is added. In addition, the segments that are given a new AC of 6 with urban code, access density, and speed limit criteria are double the number when urban code and access density are used. The number of segments that exceeded the criteria and were assigned to an AC 9 was 24 segments when just urban code and access density were used and 59 segments when speed limit was added. This method assigns more segments to a new AC than the previous method because the segment must meet an additional characteristic criterion.

Table 4-5: New AC Assignments: Urban Code, Access Density, and Speed Limit

AC	Total AC	New Access Category									
		1	2	3	4	5	6	7	8	9	10
1	336	329	5	0	0	0	2	0	0	0	0
2	331	0	309	0	4	2	3	12	0	1	0
3	203	0	11	106	4	53	15	3	4	7	0
4	484	0	0	0	380	11	10	64	0	19	0
5	313	0	0	0	0	109	120	1	24	59	0
6	145	0	3	0	3	26	69	1	12	31	0
7	274	0	43	0	11	9	0	193	0	18	0
8	82	0	1	0	0	6	0	0	68	7	0
9	12	0	0	0	0	0	0	0	0	12	0
10	-	-	-	-	-	-	-	-	-	-	0
Key:		Green: Current AC Matches Field Data			Light Red Cells: <10% Total AC Segments			Dark Red Cells: >10% Total AC Segments			

Depending on the segment, the AC may not need to change even if the above analysis indicates that the AC is not in accordance with current roadway characteristics. UDOT can take the list of segments that fall outside of the current AC guidelines and analyze each segment to see if the AC on the roadway needs to change or if new accesses allowed on the roadway need to be limited. Upon determining whether AC guidelines need to change, the understanding of how UDOT wants the roadway to grow in the future is important to consider. Having that understanding will allow UDOT to either limit the number of access on a roadway or allow new accesses to be added.

4.2 Raised Median Safety Performance Analysis

A before-after model created previously by BYU researchers for UDOT, analyzes segments of roadway for a specific change that occurred on them. The change being used in this study is the installation of raised medians between the years of 2002 and 2014. The before-after model uses a hierarchical Bayesian linear regression analysis to statistically determine the probability that the number of crashes increase or decrease with the installation of raised medians. Since the data are in the form of number of crashes over a specified segment of road, a Poisson likelihood was used as is common for count data. This section will explain the input data that were used in the model, the specifications of the model, the results upon running the model, and a description of the CMF values from the results.

4.2.1 Input Data

Using the segmented data, roadways with a raised median as dominant median type or second dominant median type were viewed using Google Earth to find where the raised medians were located and when they were installed. Google Earth has a database of satellite imagery that was used to find a range of years that raised medians were installed. Of the raised medians that were analyzed, 35 segments were found where raised medians were installed between 2002 and 2014. Researchers then traveled to UDOT and viewed the segments using historic Roadview Explorer data to find the precise year the raised median was installed. Of these 35 segments, 20 were determined to be acceptable to use for the before-after model (Google Earth 2016, UDOT 2017).

A sample of the original input data for this model is shown in Table 4-6. The route and mile points for each segment are listed for each year of crash data, from 2002 to 2014. A weighted AADT was calculated using Equation 4-1 for each year of crash data. The percentage is the proportion of the median length with a changed AADT value. For example, if a raised median segment had multiple AADT values over its length, then the percentage would be the proportion of the median within that AADT value. Calculating a weighted average created a more accurate AADT for each year. Other input data included number of crashes that occurred for each year and the AC of the segment. Three categories of access were identified over all of the raised median segments: AC 3, 5, and 6. AC 6 had the least number of raised median segments in the before-after input data.

$$Weighted\ AADT = Percentage_1 * AADT_1 + Percentage_2 * AADT_2 + \ldots \tag{4-1}$$

The first run of the model with this input gave posterior distribution plots for each AC involved. Though each plot gave a 100 percent probability that crashes decrease with the addition of a raised median, the accuracy of the model was determined to be low. To increase accuracy of the model, the year the raised median was installed on each segment was removed from the input data. This was done because it allowed time for the public to get used to the new configuration of the roadway and the exact dates of change was not included in the analysis.

Driveway count was a dataset that BYU researchers thought would be a very useful predictor variable in the before-after model; however, UDOT has only one year of driveway data as opposed to every year from 2002 to 2014. One way researchers found to be able to use driveway count in the model was to manually count the driveways on each raised median segment using historic data from UDOT's Roadview Explorer and Google Earth for every year used in the before-after model (Google Earth 2016, UDOT 2017). Additionally, crash severity and intersection counts were added to the input data. For every year in a segment, a crash count for each crash severity was added. The model was rerun using the updated input data file, a portion of which is shown in Table 4-7, and the results received were similar to the previous model runs with a higher level of accuracy. The full updated input data and the regression and posterior plots that were created for each severity and AC are shown in Appendix C.

Table 4-6: Sample Data Input for the Before-After Model

Seg_Num	Label	BegMP	EndMP	Year	AADT	AC	BA	Crash
1	0009P	8.47	8.67	2002	16080	5	0	7
1	0009P	8.47	8.67	2003	16210	5	0	8
1	0009P	8.47	8.67	2004	17645	5	0	5
1	0009P	8.47	8.67	2005	20725	5	0	7
1	0009P	8.47	8.67	2006	20435	5	0	16
1	0009P	8.47	8.67	2007	21110	5	0	9
1	0009P	8.47	8.67	2008	20055	5	0	5
1	0009P	8.47	8.67	2009	22185	5	0	6
1	0009P	8.47	8.67	2010	20055	5	0	7
1	0009P	8.47	8.67	2010	22055	5	1	7
1	0009P	8.47	8.67	2011	22140	5	1	1
1	0009P	8.47	8.67	2012	26840	5	1	6
1	0009P	8.47	8.67	2013	28075	5	1	10
1	0009P	8.47	8.67	2014	28330	5	1	9
2	0018P	0.2	0.5	2002	25123	5	0	24
2	0018P	0.2	0.5	2003	26380	5	0	24
2	0018P	0.2	0.5	2004	26355	5	0	33
2	0018P	0.2	0.5	2005	24660	5	0	42
2	0018P	0.2	0.5	2006	24750	5	0	39
2	0018P	0.2	0.5	2007	25465	5	0	36
2	0018P	0.2	0.5	2008	24245	5	0	25
2	0018P	0.2	0.5	2008	24245	5	1	25
2	0018P	0.2	0.5	2009	23855	5	1	26
2	0018P	0.2	0.5	2010	24310	5	1	36
2	0018P	0.2	0.5	2011	24215	5	1	9
2	0018P	0.2	0.5	2012	24335	5	1	5
2	0018P	0.2	0.5	2013	24455	5	1	15
2	0018P	0.2	0.5	2014	24870	5	1	6

Table 4-7: Updated Before-After Model Input

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4,5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
1	0009P	8.47	8.67	2002	16080	5	0	5	2	6	1	7	3	1	1
1	0009P	8.47	8.67	2003	16210	5	0	5	3	7	1	8	3	1	1
1	0009P	8.47	8.67	2004	17645	5	0	3	2	5	0	5	3	1	1
1	0009P	8.47	8.67	2005	20725	5	0	6	1	7	0	7	3	1	1
1	0009P	8.47	8.67	2006	20435	5	0	14	2	14	2	16	3	1	1
1	0009P	8.47	8.67	2007	21110	5	0	9	0	9	0	9	3	1	1
1	0009P	8.47	8.67	2008	20055	5	0	5	0	5	0	5	3	1	1
1	0009P	8.47	8.67	2009	22185	5	0	4	2	5	1	6	3	2	1
1	0009P	8.47	8.67	2010	20055	5	0	4	3	6	1	7	3	2	1
1	0009P	8.47	8.67	2010	22055	5	1	4	3	6	1	7	3	2	1
1	0009P	8.47	8.67	2011	22140	5	1	1	0	1	0	1	3	2	1
1	0009P	8.47	8.67	2012	26840	5	1	2	4	5	1	6	3	2	1
1	0009P	8.47	8.67	2013	28075	5	1	8	2	10	0	10	3	2	1
1	0009P	8.47	8.67	2014	28330	5	1	7	2	9	0	9	3	2	1

4.2.2 Model Specifications

A hierarchical Bayesian model was constructed for the analysis. The model used crash data and AADT data of selected analysis sites as inputs. Other covariates were also included in the input data as outlined in Section 4.2.1. It was assumed that the number of crashes y_i is Poisson distributed as outlined in Equation 4-2.

$$y_i \sim Poisson(\lambda_i). \tag{4-2}$$

The Poisson distribution was used due to the randomness of crash occurrence. This distribution is easily able to include the exposure parameter, AADT, associated with the number of miles in a given segment. To account for segment length, VMT was calculated using Equation 4-3.

$$\text{VMT} = \text{AADT x Segment Length} \tag{4-3}$$

After executing the model, it was found that the only significant covariates included in the model were VMT and VMT^2. The estimation of the mean number of crashes within the functional area of a given intersection was then calculated using Equation 4-4.

$$\log(\lambda_i) = \beta_{0j} + \beta_{1j}\,(BA_{ij}) + \beta_{2j}\,VMT_{ij} + \beta_{3j}\,VMT^2_{ij}, \qquad (4\text{-}4)$$

Where, i = the roadway segment

j = AC

λ_i = the mean number of crashes within the functional area,

VMT_{ij} = Vehicle Miles Traveled for the i^{th} observation in the j^{th} AC, and

BA_{ij} = an indicator variable stating which category the i^{th} observation is of the roadway before or after the installation of a raised median for the j^{th} AC.

This result is the consideration of six intercepts: one for the before and one for after median installation for AC 3, 5 and 6. VMT is constrained to be the same for each category. Note that the analysis is restricted to AC 3, 5, and 6 to perform a specific before-after analysis for each AC. The log transformation was chosen as part of the standard Poisson regression procedures.

The prior for each β_j is normally distributed as defined in Equation 4-5 for each k corresponding to coefficient number, k = 1, 2, 3, and 4, and each AC, j = 3, 5, and 6.

$$\beta_{kj} \sim Normal\,(\mu_k, \sigma_k^2) \qquad (4\text{-}5)$$

Furthermore, priors are set on hyperparameters, μ_k and σ_k^2.These hyperparameters are shown for the intercept term β_0 in Equations 4-6 and 4-7.

$\mu_0 \sim Normal(10,100)$ (4-6)

$\sigma_0^2 \sim IG(0.01, 0.01)$ (4-7)

The hyperparameters for all other β_k are outlined in Equations 4-8 and 4-9.

$\mu_k \sim Normal(0, 100)$ (4-8)

$\sigma_k^2 \sim IG(0.01, 0.01)$ (4-9)

These priors, after sensitivity analysis, were found to be quite uninformative, which reflects the lack of convincing evidence to suggest more specific priors.

The posterior distribution for the parameter θ_i is expressed in Equation 4-10.

$$f(\theta_i|x) \propto f(x|\theta_i)\pi(X_i\beta) = \prod_{i=1}^{n} \frac{e^{-\theta_i}\theta_i^{y_i}}{y_i!} e^{-X_i\beta} \quad (4\text{-}10)$$

Where, X_i = matrix containing appropriate covariates to satisfy the model, and

n = total number of observations

Due to the complexity of the posterior distribution, rather than deriving the distribution theoretically, it was determined to sample from the posterior using the Markov Chain Monte Carlo (MCMC) methodology. This involves beginning with initial values and sampling each of the β_k parameters one at a time from the complete conditional distributions, using the newly sampled value in ensuing complete conditional calculation.

The results of the algorithm are a number of random draws from the posterior distribution for each of the β_k parameters. In this study, each site was modeled with its own set of β parameters for both overall and severe crashes.

4.2.3 Model Results

Several plots were created as output of the before-after model. This section will describe and interpret regression plot and CMF results.

4.2.3.1 Regression Plot Results

Regression plots were created for each AC. The regression plot for AC 3 is illustrated in Figure 4-1. This plot shows the mean number of crashes and the 95 percent confidence interval for both the existing crashes and predicted crashes. As shown in Figure 4-1 the number of crashes that will occur are predicted to decrease after the installation of a raised median with a 95 percent certainty for VMT values between 16,000 and 25,000. Despite the fact that the after median installation value of crashes is well below the before median installation value, inference to a decrease in crashes due to an installation of a raised median cannot be made because the 95 percent confidence intervals for the before and after means overlap. The confidence interval widths are based on the amount of data available. Similar regression plots for all AC combined and for AC 5 and 6 individually are shown in Appendix C. Note that all crash severities are included in this analysis.

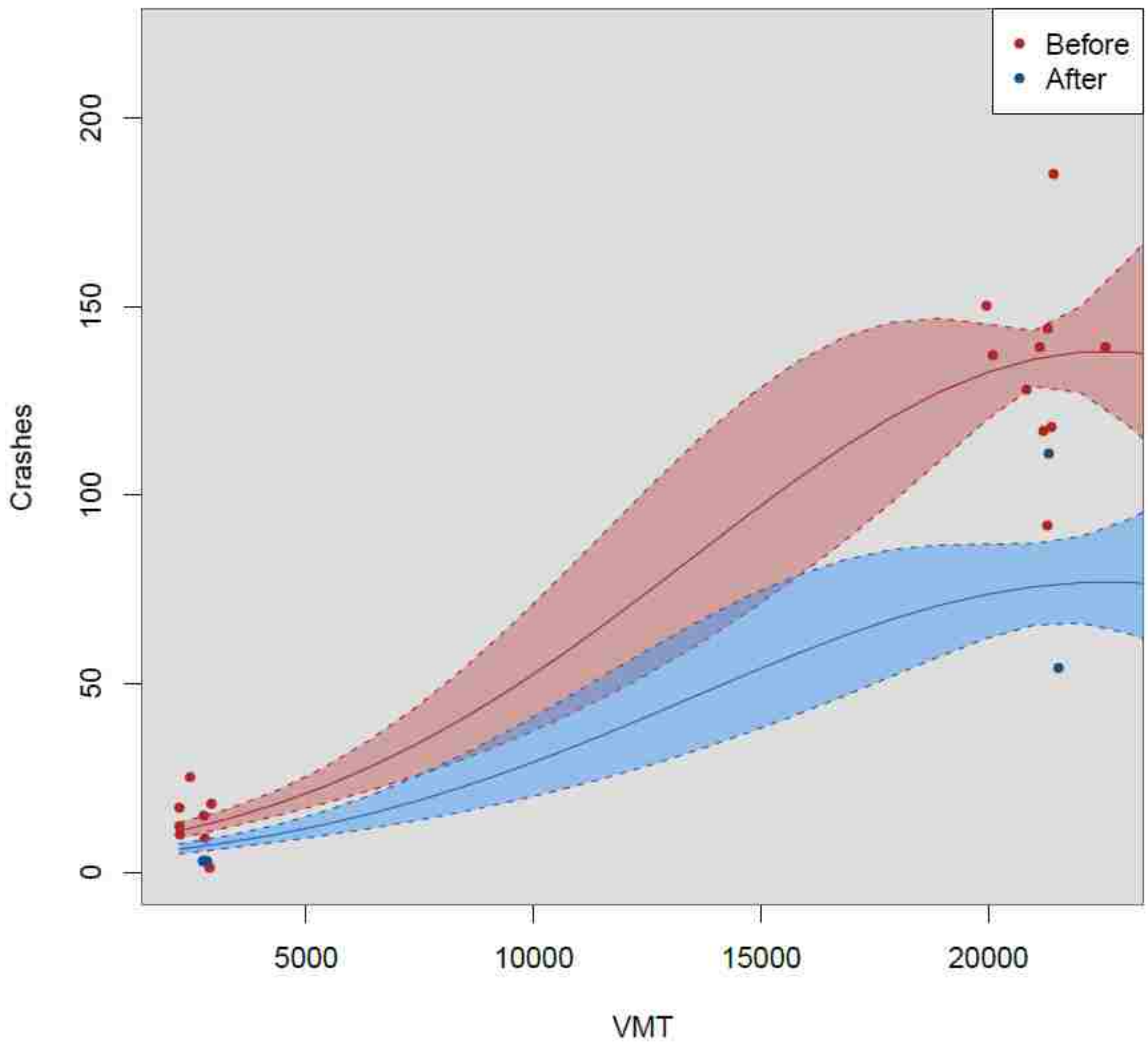

Figure 4-1: Regression plot for AC 3.

Crash severities by AC were also analyzed. The crash severities were grouped together four different ways to see how effective raised medians are at reducing severe crashes. The crash severity groups are as follows: crash severity 1 and 2; crash severity 1, 2, and 3; crash severity 3, 4, and 5; and crash severity 4 and 5. Each crash severity group was run with all AC together and each AC separately. Regression plots for AC 3 will be presented for each crash severity group in this section while the plots for the rest of the AC can be found in Appendix C.

The before-after model results for AC 3 ran with only crashes with a severity 1 or 2 is shown in Figure 4-2. This plot shows, with a 95 percent confidence, that installing a raised median decreases crashes with a severity 1 or 2 between 17,000 and 24,000 VMT. Other results cannot be assumed since the 95 percent confidence intervals of the before mean and after mean overlap. These results are similar and comparable to those in Figure 4-1.

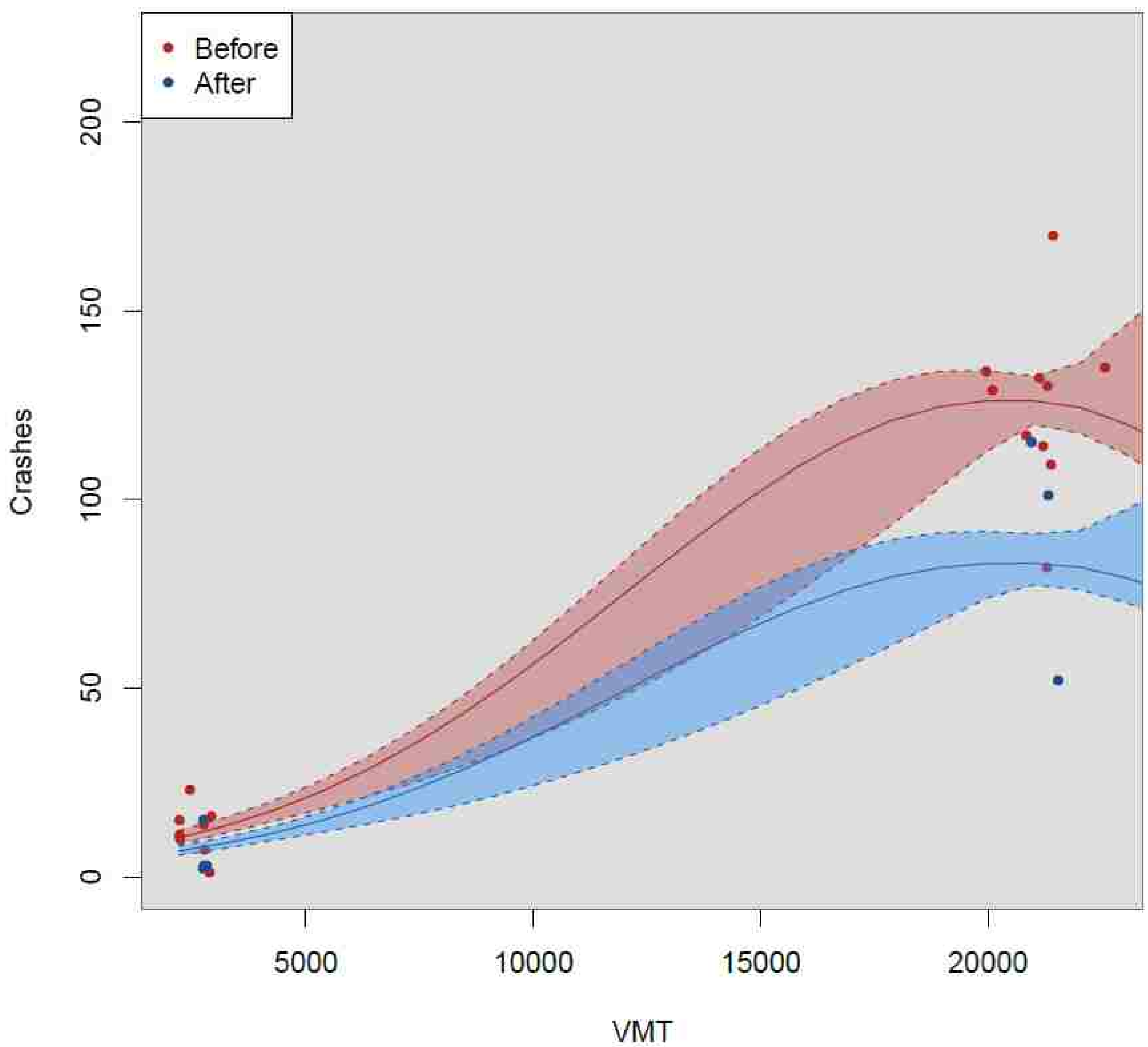

Figure 4-2: Regression plot for AC 3 only including crashes with severity 1 and 2.

AC 3 with severity 1, 2 and 3 crashes were run in the before-after model as well. Figure 4-3 shows, with 95 percent confidence, that installing a raised median decreases crashes with a severity 1, 2, or 3 between 18,000 and 24,000 VMT. These results are almost identical to the results shown in Figure 4-2. Again other results cannot be assumed because the 95 percent confidence intervals overlap. Since the plots with severity 1 and 2 and the regression with severity 1, 2 and 3 are comparable, it can be said that number of crashes with a severity 3 is not large enough to change the results of the model. This aligns with the concept that crashes with severity 1 or 2 occur more frequently and in larger numbers than the other severities.

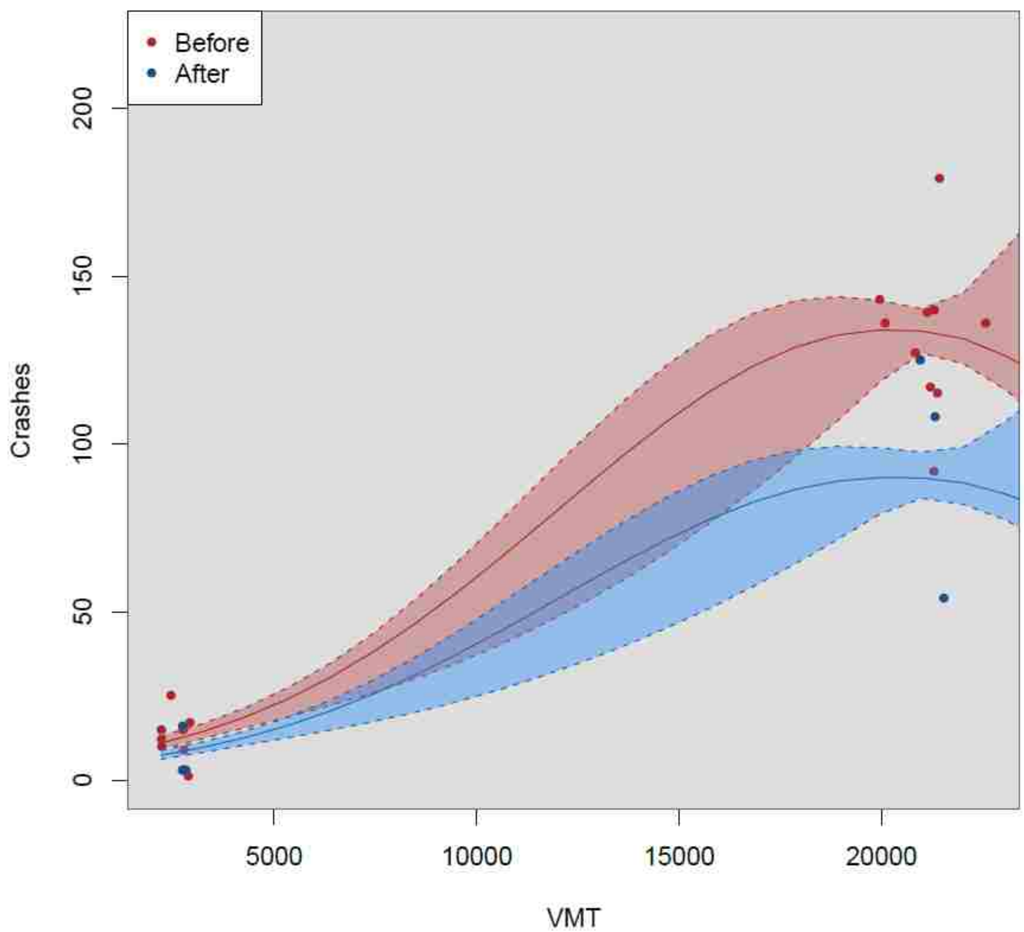

Figure 4-3: Regression plot for AC 3 only including crashes with severity 1, 2, and 3.

Crashes with a severity of 3, 4, and 5 were run together for AC 3 and the results are shown in Figure 4-4. Since the 95 percent confidence intervals overlap, no inference that the installation of a raised median reduces crashes with a severity 3, 4 or 5 on AC 3 roadways can be made. Figure 4-5 shows the regression plot for AC 3 using only crashes with severity 4 and 5. An inference to a reduction in crashes due to a raised median installation can only be made from this plot between 12,000 and 24,000 VMT. Note that the y-axis scales between when crash severity 4 and 5 are included is drastically different than when the other severity groupings are run. This is because crashes with a severity of 1, 2, and 3 occur more frequently than the more severe crashes.

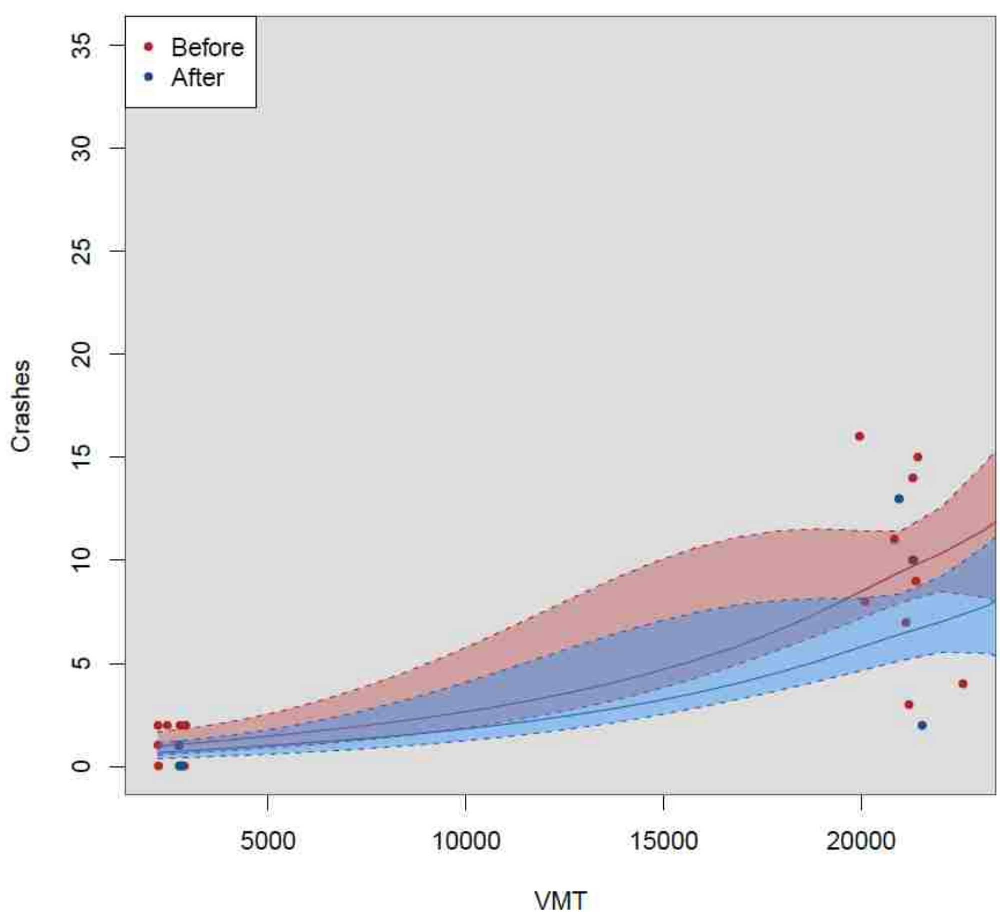

Figure 4-4: Regression plot for AC 3 only including crashes with severity 3, 4, and 5.

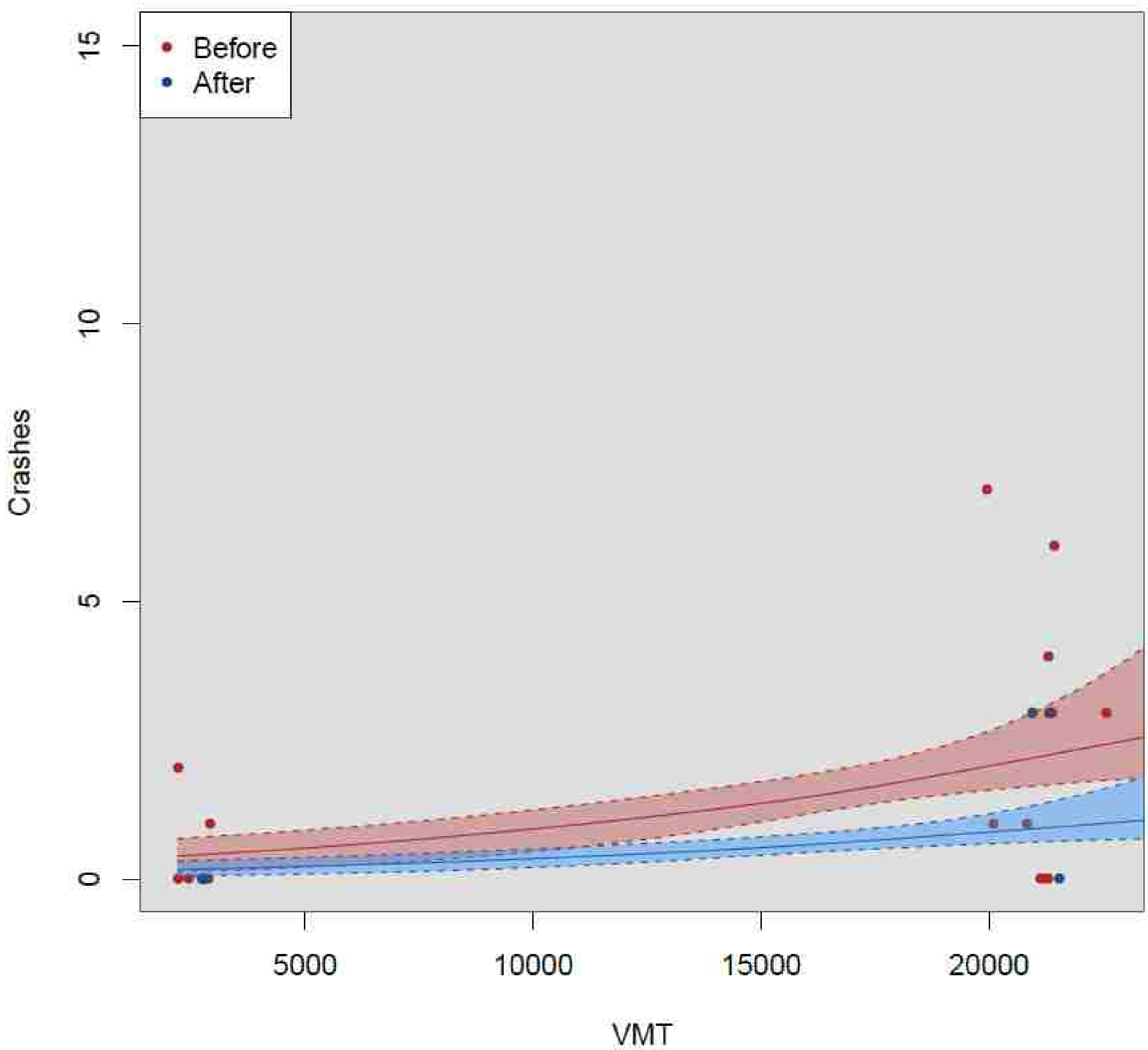

Figure 4-5: Regression plot for AC 3 only including crashes with severity 4 and 5.

4.2.3.2 CMF Results

Part of the output given by the before-after model included a plot of the CMF for any given VMT value. An overview of the meaning of a CMF, the CMF plots for AC 3 for each crash severity grouping, and mean CMF values for each AC and crash severity grouping is explained and outlined in this section.

4.2.3.2.1 CMF Overview. Using equations outlined in the HSM (AASHTO 2010), a mean CMF and a crash reduction factor (CRF) were calculated. A CMF "represents the relative change in crash frequency due to a change in a specific condition" (AASHTO 2010). Equation 4-11 shows the equation to calculate CMFs. Condition A is the roadway without the raised median, while condition B is the segment with the raised median implementation. A CMF less than 1.0 indicates the alternative treatment decreases the estimated crash frequency. A CMF greater than 1.0 indicates the alternative treatment increases the estimated crash frequency (AASHTO 2010). This value can be multiplied by the number of before crashes to get the predicted number of crashes after the implementation of the treatment. CRFs are calculated by taking 1.0 minus the CMF. These values approximate the average percent in reduction in crashes that can be expected after the roadway treatment is implemented.

$$CMF = \frac{Expected\ Average\ Crash\ Frequency\ with\ Site\ Condition\ B}{Expected\ Average\ Crash\ Frequency\ with\ Site\ Condition\ A} \qquad (4\text{-}11)$$

4.2.3.2.2 CMF Plots. Figure 4-6 shows the CMF for all given VMT values and all crash severity types for AC 3. This plot shows that the mean CMF value is approximately 0.56 for all VMT. Figure 4-7 shows the CMF plot for crash severity 1 and 2. The mean CMF value for AC 3 and the 95 percent confidence intervals for this mean value are shown in this plot. The average CMF value is 0.66. When crash severity 3 is added with crash severity 1 and 2, the confidence intervals are nearly identical, as shown in Figure 4-8. The average however, is 0.67, a slight difference between the results without crash severity 3. Similar CMF plots for all AC combined, and AC 5 and 6 can be found in Appendix C for all severity groups.

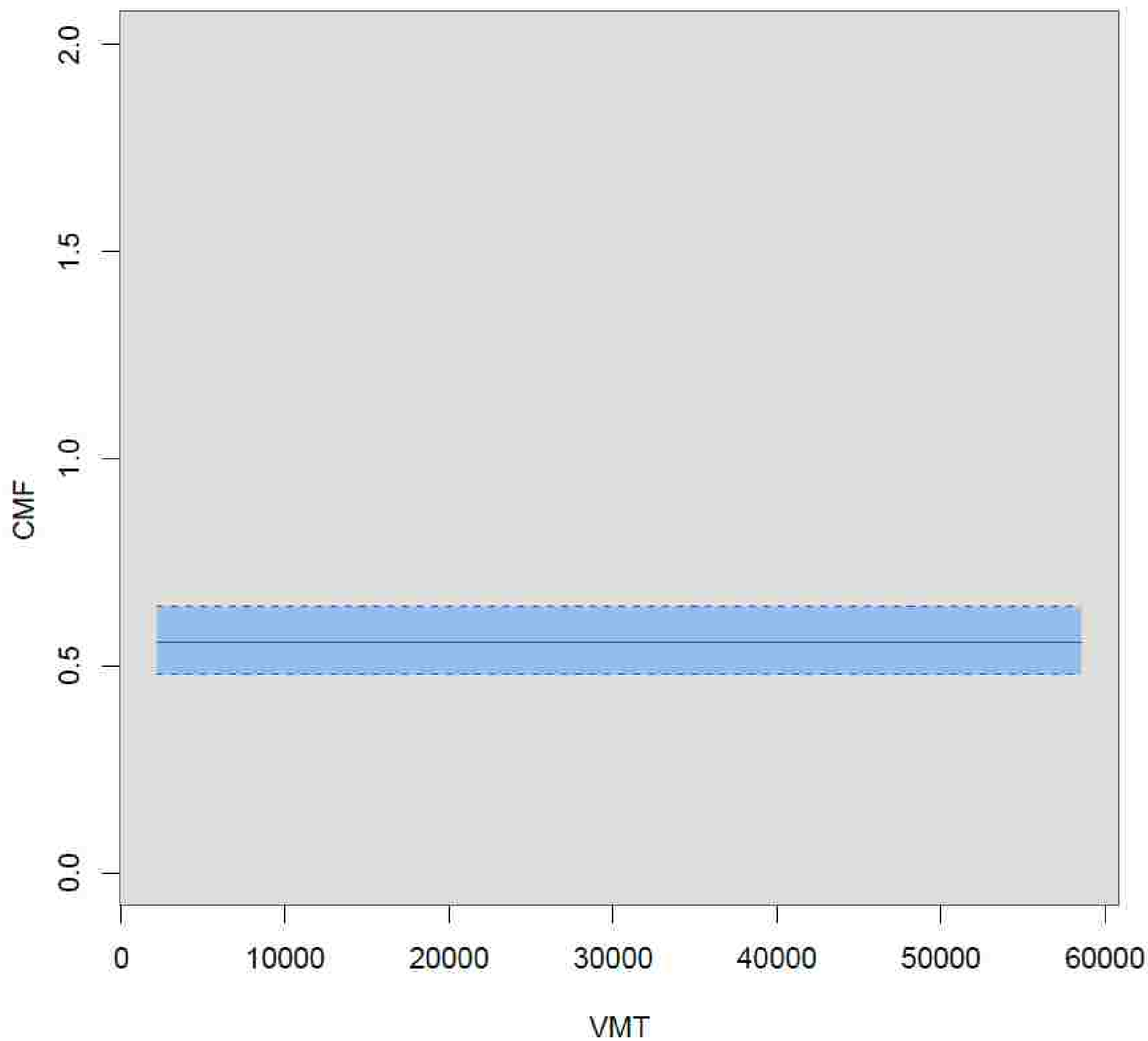

Figure 4-6: Plot of CMF values for any given VMT for AC 3.

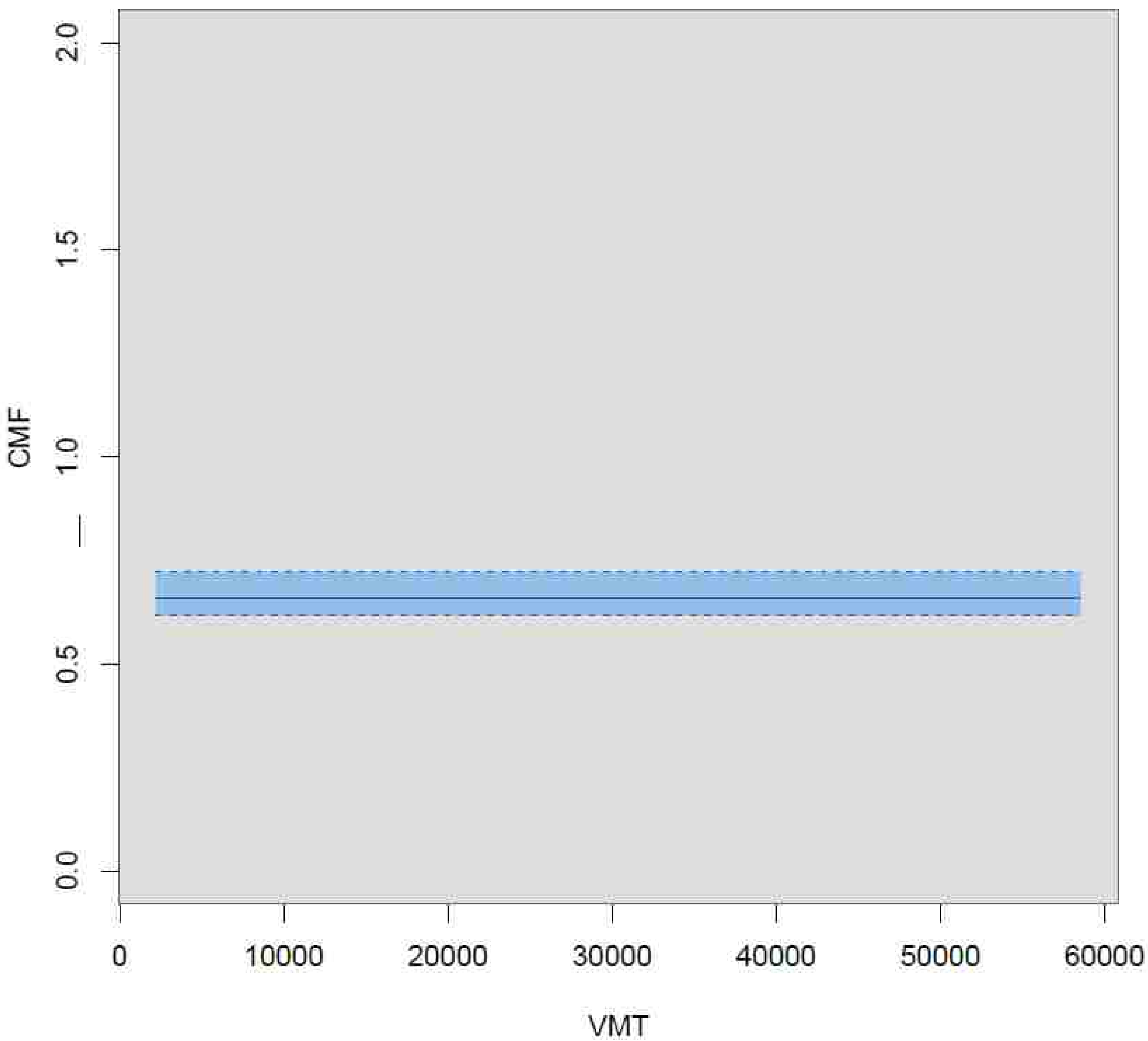

Figure 4-7: Plot of CMF values for any given VMT for AC 3, only including crashes with severity 1 and 2.

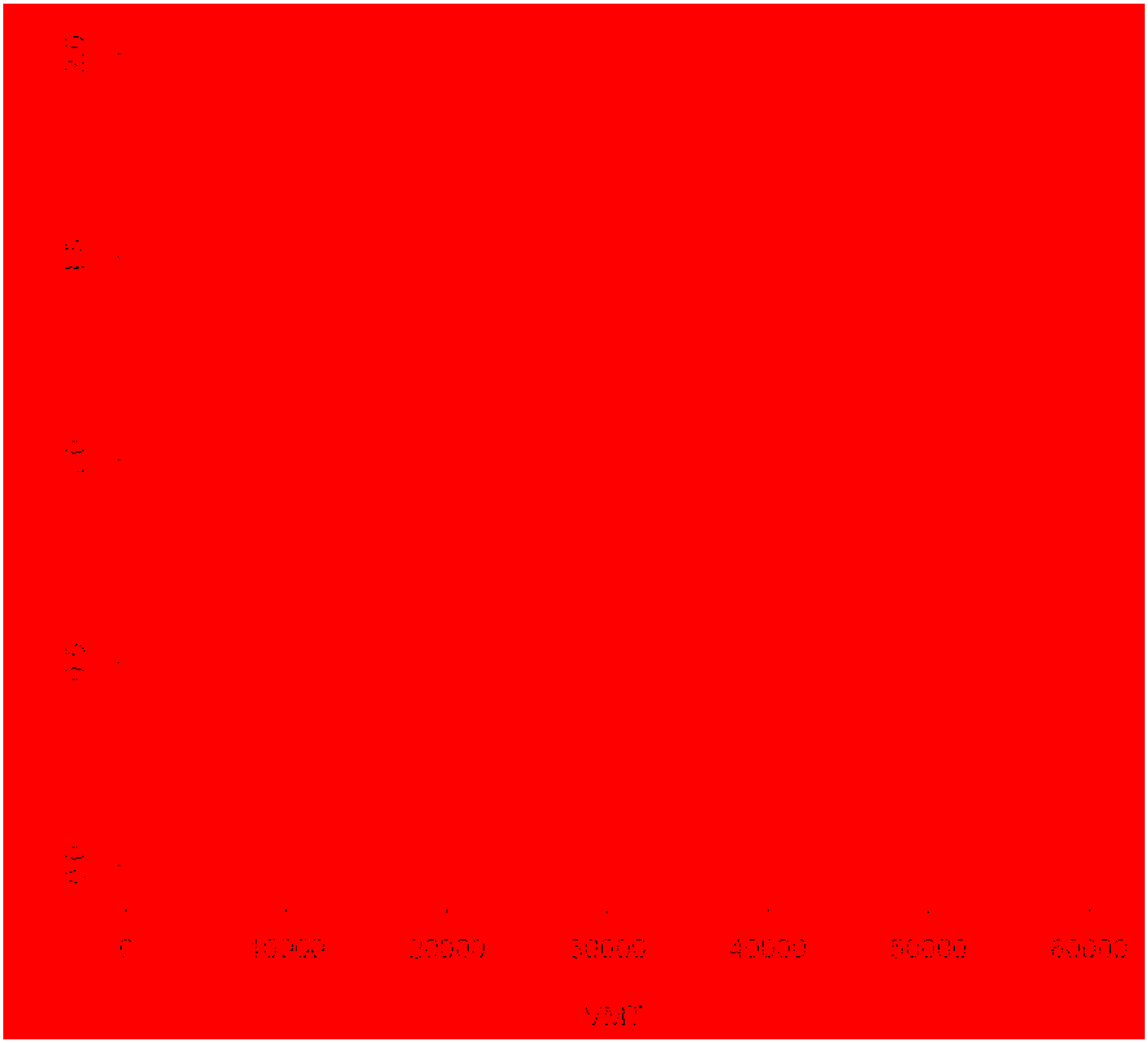

Figure 4-8: Plot of CMF values for any given VMT for AC 3, only including crashes with severity 1, 2, and 3.

CMF plots for AC 3 using severity 3, 4 and 5 crashes and severity 4 and 5 crashes are shown in Figure 4-9 and Figure 4-10 respectively. For crashes with severity 3, 4 and 5, the mean CMF value is similar to Figure 4-8 except that it has wider confidence intervals. For crashes with severity 4 and 5, the CMF value dramatically decreases without the severity 3 crashes which means a higher reduction of severity 4 and 5 crashes.

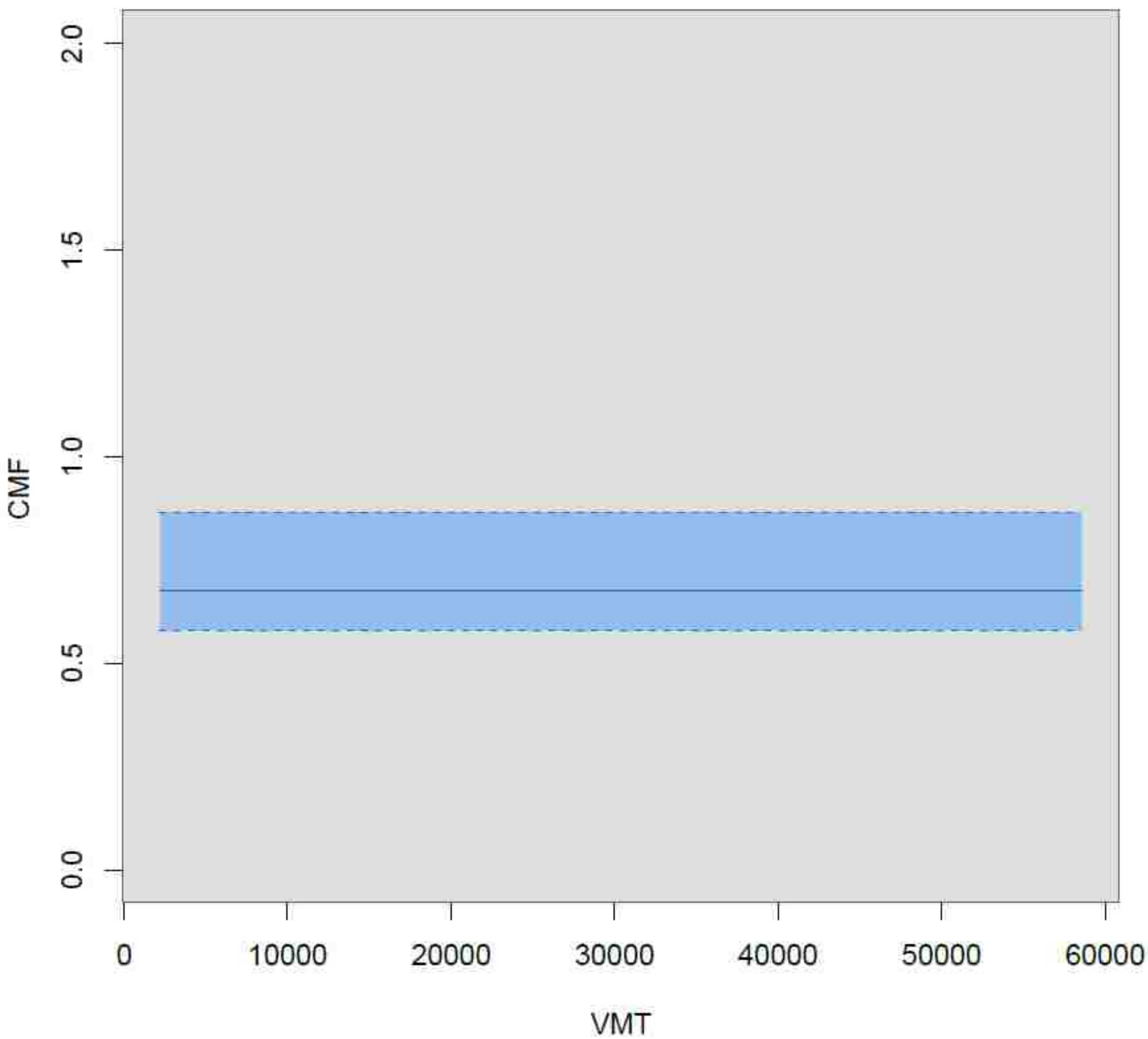

Figure 4-9: Plot of CMF values for any given VMT for AC 3, only including crashes with severity 3, 4, and 5.

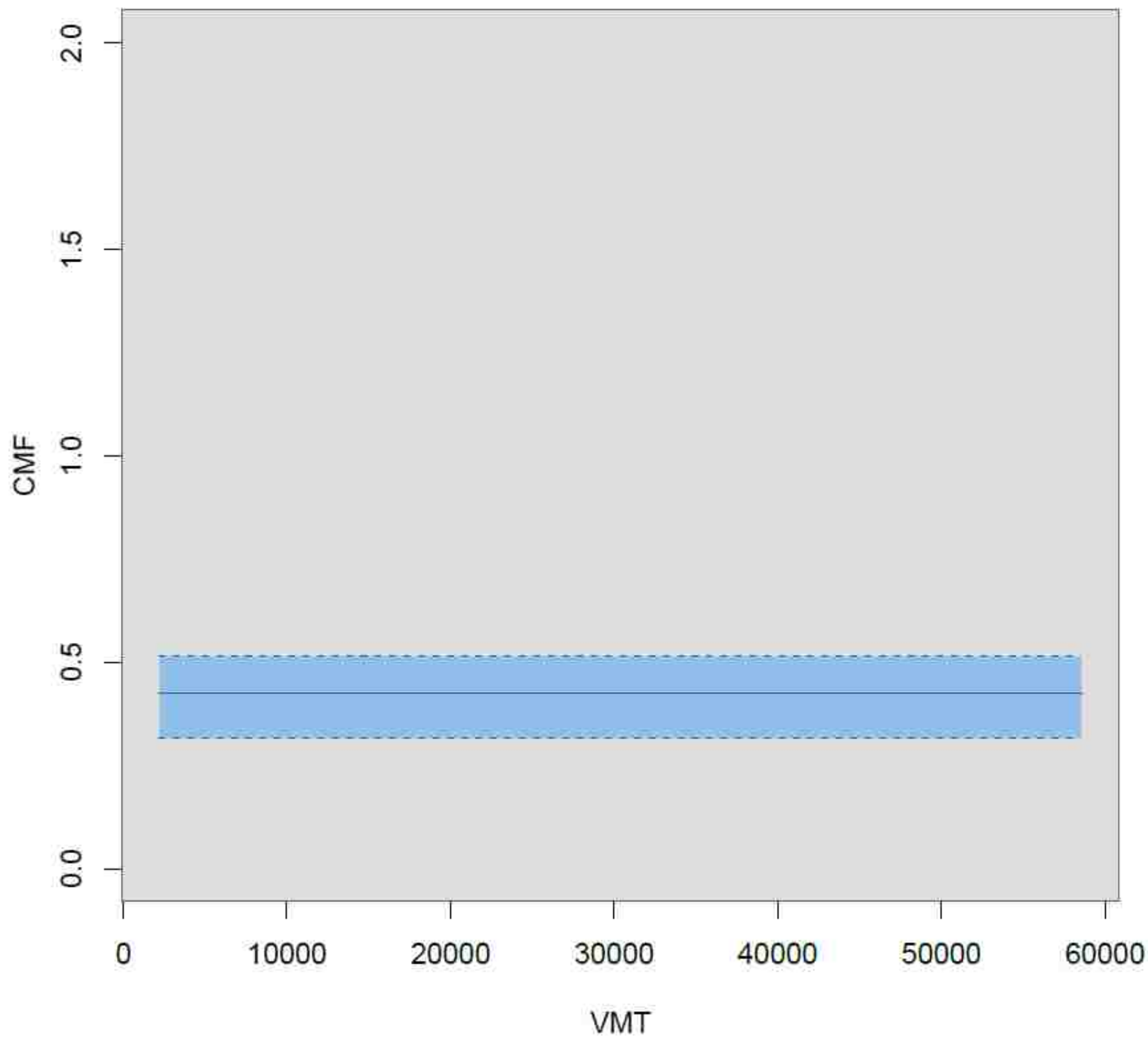

Figure 4-10: Plot of CMF values for any given VMT for AC 3, only including crashes with severity 4 and 5.

4.2.3.2.3 Mean CMF Values Table 4-8 shows the mean CMF values for each AC for different crash severity combinations. Using AC 5 and crashes of only severities 3, 4, and 5 as an example, the mean CMF value is 0.67. If there were 100 crashes that occurred before a raised median was implemented, then it would be expected that an average of 67 crashes would occur after the raised median was installed with a 33 percent reduction in crashes with a severity of 3, 4 and 5.

Table 4-8: Mean CMF Values for Each AC and Different Crash Severities

CMFs	All AC	AC3	AC5	AC6
All Crashes	0.47	0.56	0.61	0.67
Severity 1,2	0.52	0.66	0.65	0.66
Severity 1,2,3	0.54	0.67	0.67	0.68
Severity 3,4,5	0.62	0.68	0.67	0.67
Severity 4,5	0.41	0.43	0.43	0.42

The mean crash severity values show that between AC 3, 5, and 6 raised median segments, the CMF values are very similar to each other. A 32 to 44 percent reduction of crashes should be expected for all crashes (when analyzing each AC separately) regardless of severity. Three of the four severity groups analyzed in the model had a similar predicted reduction in crashes: severity 1 and 2; severity 1, 2 and 3; and severity 3, 4, and 5. When analyzing only severity 4 and 5 crashes, there is a much greater reduction of those crashes. AC 3 and 5 see a 57 percent reduction in severe crashes while AC 6 sees a 58 percent reduction in severe crashes. Overall, with all raised median segments regardless of AC and for all crashes despite severity, there is expected to be a 53 percent reduction in crashes.

4.3 Chapter Summary

An explanation of two different analyses was given in this chapter. In the first analysis, AC standards, outlined in the R930-6, were used as guidelines to find segments that fell outside the recommended values. In addition, these standards were used to gives these segments a new AC that matched the existing data of the segment. This analysis does not mean the current AC is incorrect, it simply means that the assigned AC does not meet current roadway characteristics based on the LiDAR data analysis. Further analysis can be done to determine whether the AC needs to be changed on a roadway, or if the roadway needs to be changed to meet the current category.

In the second analysis, raised median segments were analyzed using a hierarchical Bayesian linear regression before-after model created in previous BYU research. Accuracy in the model was improved with the addition of predictor variables that included crash severity, intersection count, and driveway counts. CMF values were calculated to find the impact that installing a raised median had on reducing crashes. Different crash severity groups were run in the before-after model to find whether raised medians reduce high severity crashes after installation. All crash severity groups and all AC saw a reduction in crashes after the installation of a raised median. Individual AC analysis yielded results ranging from 32 to 44 percent for all severity groups except severity 4 and 5. The reduction in crashes for severity 4 and 5 ranged from 57 percent for AC 3 and 5 to 58 percent for AC 6.

5 CONCLUSIONS

The purpose of this research was to use the LiDAR dataset to perform a safety analysis of the state related to access management, specifically related to driveway spacing and raised medians. The preceding chapters have discussed the procedures used to complete the analysis. Two analyses have been run using the LiDAR data: an AC criteria analysis and a raised median safety performance analysis.

Initially, ArcMap 10.3 was used to visualize the data and to find hotspot locations around the state regarding crash data, driveways, and AC. Next, an automated Excel workbook was modified to analyze roadway data in segments based on a change in roadway characteristics. This was used in an AC analysis to find whether roadways throughout Utah follow the guidelines outlined in Administrative Rule R930-6. A second analysis was performed regarding raised median installation and the effect this access management technique has on safety. With the use of a hierarchal Bayesian statistical model, the impact of installing a raised median was evaluated. This chapter summarizes the findings of the AC analysis and the raised median analysis and provides suggestions for future research opportunities.

5.1 AC Criteria Analysis Summary

After initially visualizing the data in ArcMap 10.3, an automated workbook created in previous BYU research was modified to segment the data using several roadway characteristics.

Access density was calculated to find the number of driveways on each segment. This density was compared with the number of driveways per mile permitted on each AC. The lowest speed limit guidelines outlined in Administrative Rule R930-6 were compared with the speed limit on each segment. Of all of the segments, approximately 14 percent fell outside of the access density guidelines and 18 percent fell outside the speed limit guidelines. Five percent of all segments fell outside both the access density and speed limit guidelines. Comparing each AC showed that AC 5 had the most segments outside of the access density, speed, and both access density and speed guidelines than the rest of the ACs. These results show that segments in AC 5 could be evaluated more closely to see whether the existing AC classification should be changed to a different category that better fits the segment. Again, this analysis does not mean the current AC is incorrect, it simply means that the assigned AC does not meet current roadway characteristic based on the LiDAR data analysis. UDOT can decide what this roadway will become in the future and help shape each segment using the AC categories outlined in the Administrative Rule R930-6.

After segments were identified that fell outside the guidelines, segments were placed into a new AC that better fit the segment and its current characteristics. If segments had over 70.4 access per mile, the segment was considered an AC 9 because it had more than the maximum number of accesses recommended by the Administrative Rule R930-6. Segments were placed into a new AC first based on the number of accesses per mile on that segment and the urban code of the segment, and then again by accesses per mile, speed limit, and the urban code of the segment. The first method showed that less segments were placed into a new AC than the second method. AC 5 showed the most drastic difference in the second method with 120 of the 313 segments in AC 5 being assigned to AC 6. Placing segments into a new AC was a good way to visualize how the current characteristics of each segment fit into the AC guidelines in the Administrative Rule R930-6. Note that the reassignment of segments into a new AC is not a rigid action; however, the information can be used to evaluate the current conditions of the ACs on roadways in Utah.

5.2 Raised Median Safety Performance Analysis Summary

Twenty raised median segments were found through the use of Roadview Explorer and Google Earth. The raised medians on these segments were installed between 2002 and 2014, which is within the crash data used for this analysis. Characteristics for each of the segments were gathered including route, beginning and ending mile point, and number of crashes. All of these 20 segments fell into either an AC 3, 5, or 6 and this analysis specifically looked at each AC separately. The before-after model was executed for different crash severity types as well. Output from the model included regression plots which show the mean number of existing crashes before a raised median was installed and predicted crashes after a raised median was installed for any given VMT and CMF plots which show the mean CMF value for any given VMT.

A mean CMF value was found for each run of the before-after model. These values were then used to compare the severity groupings and each AC. Overall, all AC and all crash severity groupings see a reduction in crashes when a raised median is installed. AC analysis yielded results ranging from 32 to 44 percent for all severity groups except severity 4 and 5. When analyzing only severe crashes with a severity of 4 and 5, a larger reduction beginning at a 57 percent reduction was found. AC 6 for these severe crashes gave a reduction of 58 percent.

5.3 Recommendations and Future Research

UDOT LiDAR data were used in this study to conduct all analyses. All of this data worked well in every use except for the 2014 median data. This dataset had a few discrepancies with the mile points, as discussed in section 3.3.2.2. It is recommended that this dataset be revised and uploaded again to the UDOT Data Portal (UDOT 2016). Only one year of driveway data has been collected as part of the UDOT LiDAR data collection. This dataset was extremely useful in this research; however, if driveway data would have been collected in previous years, finding changes in the number of driveways on each raised median segment would have been more accurate and easier to determine. Driveway studies will be completed more effectively in the future with the new LiDAR driveway data; therefore, it is recommended that driveway data be collected approximately once every four years since driveways do not change very often.

Access management techniques assist in reducing crashes and increasing safety. Research efforts in this area are important as they provide a better understanding of the safety benefits of access management. Utah's Administrative Rule R930-6 is an important document that provides guidance on where access is allowed on a roadway and can be used to assist UDOT in shaping roadways for the future. This research has used AC guidelines to find segments of Utah roadways that are outside of those guidelines. Future research may include using these guidelines in conjunction with UDOT's vision for the roadways to provide a specific in-depth analysis of access management improvements, specifically related to driveways, that can be made in the future to help identify and eliminate high conflict areas, improve safety, and help UDOT toward their goal of zero fatalities. Future research could also analyze driveway spacing and intersections, with the use of Administrative Rule R930-6, to find locations in Utah where driveways located too close to intersections are increasing the number of crashes that occur there. Finally, future research could use the before-after model on other access management techniques and the Utah Crash Severity Model (UCSM) to find how using both models can yield more accurate results.

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APPENDIX A CRITICAL DATA COLUMNS

Appendix A is a collection of tables that provide a list of the critical data columns needed for each dataset. These columns are used in the automated Excel workbook to segment data or combine crash data files.

A.1 UDOT Data Portal Datasets

The critical columns for each of the datasets downloaded from the UDOT Data Portal are shown in Table A-1 through Table A-7. These columns are crucial in the use of the Roadway Segmentation portion of the automated Excel workbook.

Table A-1: Critical Data Columns for Driveway Data

Heading	Description
ROUTE	Route ID: numeric route number for a given roadway segment
START_ACCUM	Beginning Mile point: beginning milepost of the roadway segment
END_ACCUM	End Mile point: end milepost of the roadway segment
DRIVEWAY_TYPE	Driveway Type

Table A-2: Critical Data Columns for Median Data

Heading	Description
ROUTE_NAME	Route ID: numeric route number for a given roadway segment
START_ACCUM	Beginning Mile point: beginning milepost of the roadway segment
END_ACCUM	End Mile point: end milepost of the roadway segment
MEDIAN_TYPE	Median Type

Table A-3: Critical Data Columns for Lanes

Heading	Description
ROUTE_NAME	Route ID: numeric route number for a given roadway segment
START_ACCUM	Beginning Mile point: beginning milepost of the roadway segment
END_ACCUM	End Mile point: end milepost of the roadway segment
THRU_LANE	Thru Lanes: number of thru lanes
RIGHT_TURN	Thru Lanes: number of left lanes
LEFT_TURN	Thru Lanes: number of right lanes
TWO_WAY_LE	Thru Lanes: number of TWLTL lanes

Table A-4: Critical Data Columns for AC

Heading	Description
LABEL	Route ID: numeric route number for a given roadway segment
BEG_MP	Beginning Mile point: beginning milepost of the roadway segment
END_MP	End Mile point: end milepost of the roadway segment
AC	AC: number representing the access category type of the roadway
AC_Type	AC: code representing the access category type of the roadway

Table A-5: Critical Data columns for Speed Limit

Heading	Description
Route	Route ID: Route ID number with direction letter (i.e., 0089N)
Direction	Direction: Route direction (P, N)
Beg_MP	Beginning Mile point: The milepost where the sign appears
End_MP	End Mile point: The end milepost of the roadway segment
Speed_Limit	Speed Limit: number signifying the speed limit (in mph) of a particular segment.

Table A-6: Critical Data Columns for Functional Class

Heading	Description
LABEL	Route ID: numeric route number for a given roadway segment
BEGIN_MP	Beginning Mile point: beginning milepost of the roadway segment
END_MP	End Mile point: end milepost of the roadway segment
FC_CODE	FC_CODE: number representing the functional class type of the roadway
FC_Type	FC_Type: name of the functional class of the roadway

Table A-7: Critical Data Columns for Urban Code

Heading	Description
ROUTE_NAME	Route ID: numeric route number for a given roadway segment
START_ACCUM	Beginning Mile point: beginning milepost of the roadway segment
END_ACCUM	End Mile point: end milepost of the roadway segment
URBAN_CODE	Urban Code: number that represents a description of the surrounding area
URBAN_DESC	Urban Description: description of the surrounding area (i.e., Small-Urban, St. George, Logan, Ogden-Layton, Provo-Orem, Salt Lake City, rural, unknown)

A.2 Crash Datasets

The critical columns for each of the datasets received from the UDOT Traffic & Safety Division are outlined in Table A-8 through Table A-11. These data columns are crucial in the use of the Crash Data portion of the automated Excel workbook.

Table A-8: Crash Data Critical Columns

Heading	Description
CRASH_ID	Crash ID: unique crash ID number for each crash
CRASH_DATETIME	Crash Date/Time: date and time of crash
CRASH_SEVERITY_ID	Crash Severity ID: numerical severity level of crash (i.e., 1-5)
LIGHT_CONDITION_ID	Light Condition: ID for light condition at time of crash (i.e., 1-6, 88-99)
WEATHER_CONDITION_ID	Weather Condition: ID for weather condition at time of crash (i.e., 1-9, 88-99)
MANNER_COLLISION_ID	Manner Collision: ID for manner of collision in crash (i.e., 1-8, 88-99)
PAVEMENT_ID	Pavement: ID for pavement type (i.e., 1-4, 88-99)
ROADWAY_SURF_CONDITION_ID	Roadway Surface Condtion: ID for roadway surface conditions (i.e., 1-9, 88-99)
ROADWAY_JUNCT_FEATURE_ID	Roadway Junction Feature: ID for roadway junction feature (i.e.,1-10, 20-26, 88-99)
HORIZONTAL_ALIGNMENT_ID	Horizontal Alignment: ID for horizontal curvature of roadway (i.e., 1-2, 88-99)

Table A-8: Continued

Heading	Description
VERTICAL_ALIGNMENT_ID	Vertical Alignment: ID for vertical curvature of roadway (i.e., 1-4. 88-99)
ROADWAY_CONTRIB_CIRCUM_ID	Roadway Contributing Circumstance: ID for vehicle contributing circumstance related to the crash (i.e., 0-18, 88-99)
FIRST_HARMFUL_EVENT_ID	First Harmful Event: ID for first harmful event resulting from the crash (i.e., 0-62, 88-99)

Table A-9: Critical Data Columns for Crash Location

Heading	Description
CRASH_ID	Crash ID: unique crash ID number for each crash
ROUTE	Route ID: numeric route number for a given roadway segment
ROUTE_DIRECTION	Direction: route direction (i.e., P, N, or X)
RAMP_ID	Ramp ID: ID indicating a ramp and the type (i.e., 1-4, CD)
MILEPOINT	Mile point: mile point location of the crash

Table A-10: Crash Rollup Critical Data Columns

Heading	Description
CRASH_ID	Crash ID: unique crash ID number for each crash
NUMBER_VEHICLES_INVOLVED	Number Vehicles Involved: number of vehicles involved in the given accident
NUMBER_FATALITIES	Number of Fatalities: number of person-fatalities resulting from a given crash
NUMBER_FOUR_INJURIES	Number of incapacitating injuries: number of person-incapacitating injuries resulting from a given crash
NUMBER_THREE_INJURIES	Number of injuries: number of person-injuries resulting from a given crash
NUMBER_TWO_INJURIES	Number of possible injuries: number of person-possible injuries resulting from a given crash
NUMBER_ONE_INJURIES	Number of property damage only events: number of events for property damage only resulting from a given crash
PEDESTRIAN_INVOLVED	Pedestrian Involved: Y/N to determine whether a pedestrian was involved in the crash

Table A-10 Continued

Heading	Description
BICYCLIST_INVOLVED	Bicyclist Involved: Y/N to determine whether a bicyclists was involved in the crash
MOTORCYCLE_INVOLVED	Motorcycle Involved: Y/N to determine whether a motorcycle was involved in the crash
IMPROPER_RESTRAINT	Improper Restraint: Y/N to determine whether improper restraint was a factor in the crash
UNRESTRAINED	Unrestrained: Y/N to determine whether a driver/passenger was unrestrained in the crash
DUI	DUI: Y/N to determine whether driving under the influence was a factor in the crash
AGGRESSIVE_DRIVING	Aggressive Driving: Y/N to determine whether aggressive driving was a factor in the crash
DISTRACTED_DRIVING	Distracted Driving: Y/N to determine whether distracted driving was a factor in the crash
DROWSY_DRIVING	Drowsy Driving: Y/N to determine whether drowsy driving was a factor in the crash
SPEED_RELATED	Speed Related: Y/N to determine whether speed was a factor in the crash
INTERSECTION_RELATED	Intersection Related: Y/N to determine whether the crash occurred at an intersection
ADVERSE_WEATHER	Adverse Weather: Y/N to determine whether adverse weather was a factor in the crash
ADVERSE_ROADWAY_SURF_CONDITION	Adverse Roadway Surface Conditions: Y/N to determine whether adverse roadway surface conditions were a factor in the crash
ROADWAY_GEOMETRY_RELATED	Roadway Geometry Related: Y/N to determine whether roadway geometry was a factor in the crash
WILD_ANIMAL_RELATED	Wild Animal Related: Y/N to determine whether a wild animal was involved in the crash
DOMESTIC_ANIMAL_RELATED	Domestic Animal Related: Y/N to determine whether a domestic animal was involved in the crash

Table A-10 Continued

Heading	Description
ROADWAY_DEPARTURE	Roadway Departure: Y/N to determine whether a vehicle departed the roadway as a result of the crash
OVERTURN_ROLLOVER	Overturn/Rollover: Y/N to determine whether a vehicle overturned and/or rolled over as a result of a crash
COMMERCIAL_MOTOR_VEH_INVOLVED	Commercial Motor Vehicle Involved: Y/N to determine whether a commercial motor vehicle was involved in the crash
INTERSTATE_HIGHWAY	Interstate Highway: Y/N to determine whether the crash occurred on an interstate roadway
TEENAGE_DRIVER_INVOLVED	Teenage Driver Involved: Y/N to determine whether a teenage driver was involved in the crash
OLDER_DRIVER_INVOLVED	Older Driver Involved: Y/N to determine whether an older driver was involved in the crash
URBAN_COUNTY	Urban County: Y/N to determine whether the crash occurred in an urban area
ROUTE_TYPE	Route Type (L/S/U):
NIGHT_DARK_CONDITION	Night/Dark Condition: Y/N to determine whether night or dark conditions was a factor in the crash
SINGLE_VEHICLE	Single Vehicle: Y/N to determine whether a single vehicle was involved in a crash (i.e., not a collision involving multiple vehicles)
TRAIN_INVOLVED	Train Involved: Y/N to determine whether a train was involved in the crash
RAILROAD_CROSSING	Railroad Crossing: Y/N to determine whether the crash occurred at a railroad crossing
TRANSIT_VEHICLE_INVOLVED	Transit Vehicle Involved: Y/N to determine whether a transit vehicle was involved in the crash
COLLISION_WITH_FIXED_OBJECT	Collision with Fixed Object: Y/N to determine whether the crash involved a fixed object (i.e., not another vehicle, nor a person)

Table A-11: Crash Vehicle Critical Data Columns

Heading	Description
CRASH_ID	Crash ID: Specific crash ID number for each crash
VEHICLE_NUM	Vehicle Number: Number assigned to each vehicle involved in a given crash
CRASH_DATETIME	Crash Date/Time: Date and time of crash
TRAVEL_DIRECTION_ID	Travel Direction: Direction value of route at the location of the crash (i.e., 1-5)
EVENT_SEQUENCE_1_ID	Event Sequence #1: ID for first crash sequence for non-collision and colllision events (i.e., 0-99)
EVENT_SEQUENCE_2_ID	Event Sequence #2: ID for second crash sequence for non-collision and colllision events (i.e., 0-99)
EVENT_SEQUENCE_3_ID	Event Sequence #3: ID for third crash sequence for non-collision and colllision events (i.e., 0-99)
EVENT_SEQUENCE_4_ID	Event Sequence #4: ID for fourth crash sequence for non-collision and colllision events (i.e., 0-99)
MOST_HARMFUL_EVENT_ID	Most Harmful Event: ID for most harmful event resulting from the crash (i.e., 0-99)
VEHICLE_MANEUVER_ID	Vehicle Maneuver: ID for the controlled maneuver prior to the crash (i.e., 1-14, 88-99)
VEHICLE_DETAIL_ID	Vehicle Detail ID: 8-digit ID number that is specific to a vehicle involved in a crash amongst all other vehicle involved in crashes

APPENDIX B HOT SPOT ANALYSIS

This appendix includes maps depicting hot spot locations found during the preliminary analysis of the data. Figure B-1 through Figure B-9 compare the line density and spatial join access density methods, crash density, and median type for different locations throughout Utah. Each characteristic is shown in the inset maps from left to right respectively. Refer back to Chapter 3 for details on the creation of these densities.

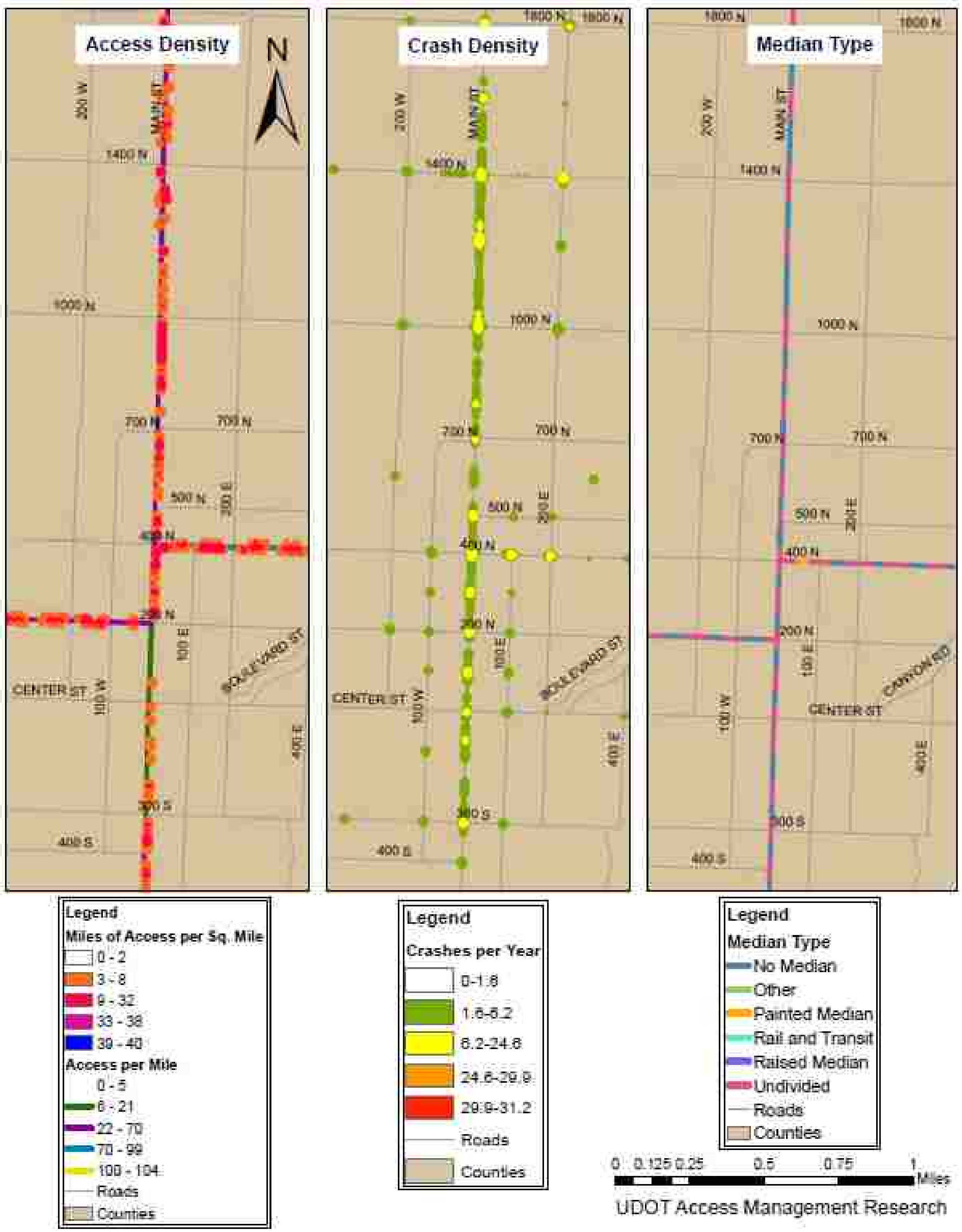

Figure B-1 Map comparing access density methods, crash density, and median type for Main St. in Cache County, Utah.

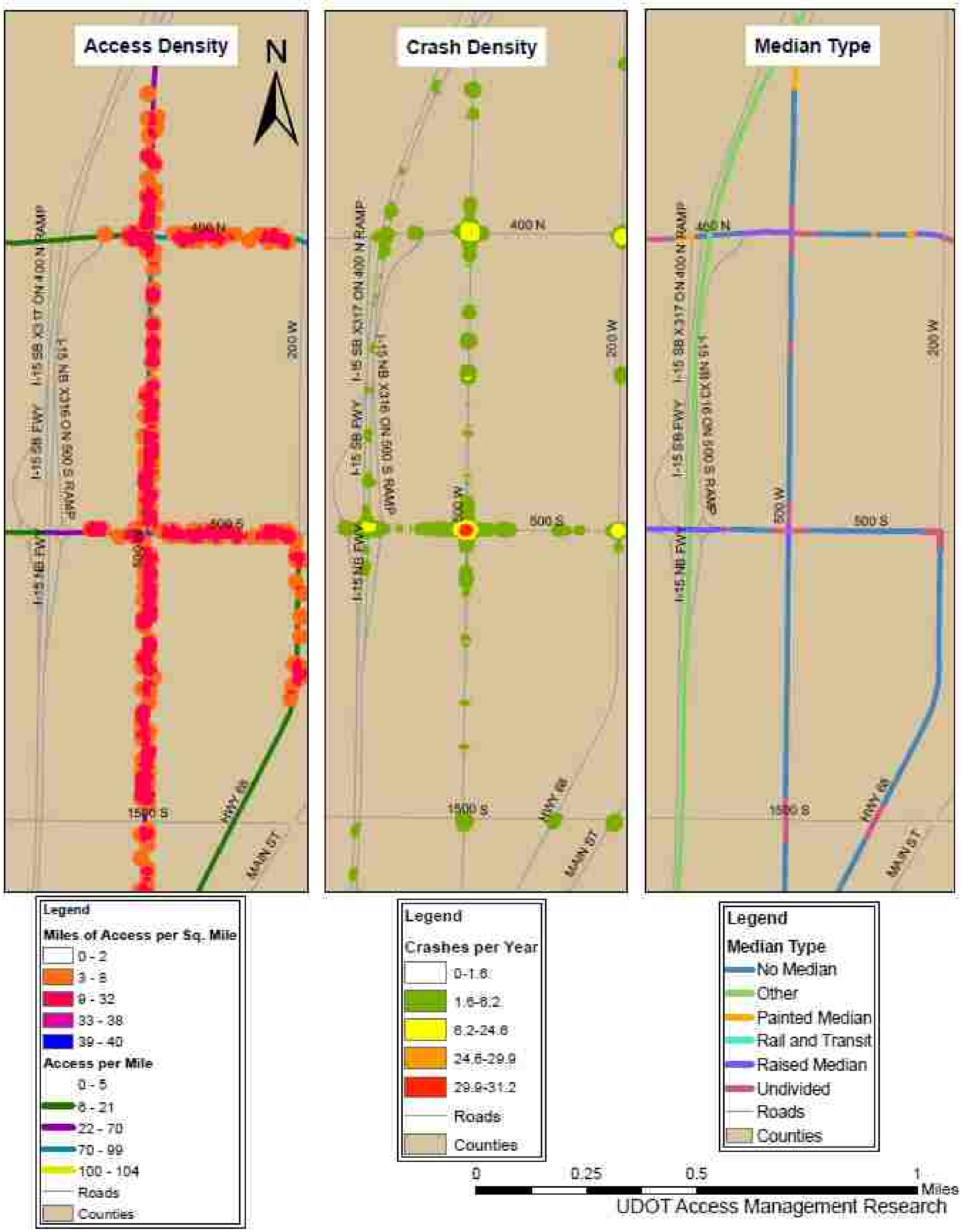

Figure B-2: Map comparing access density methods, crash density, and median type for 500 W. in Davis County, Utah.

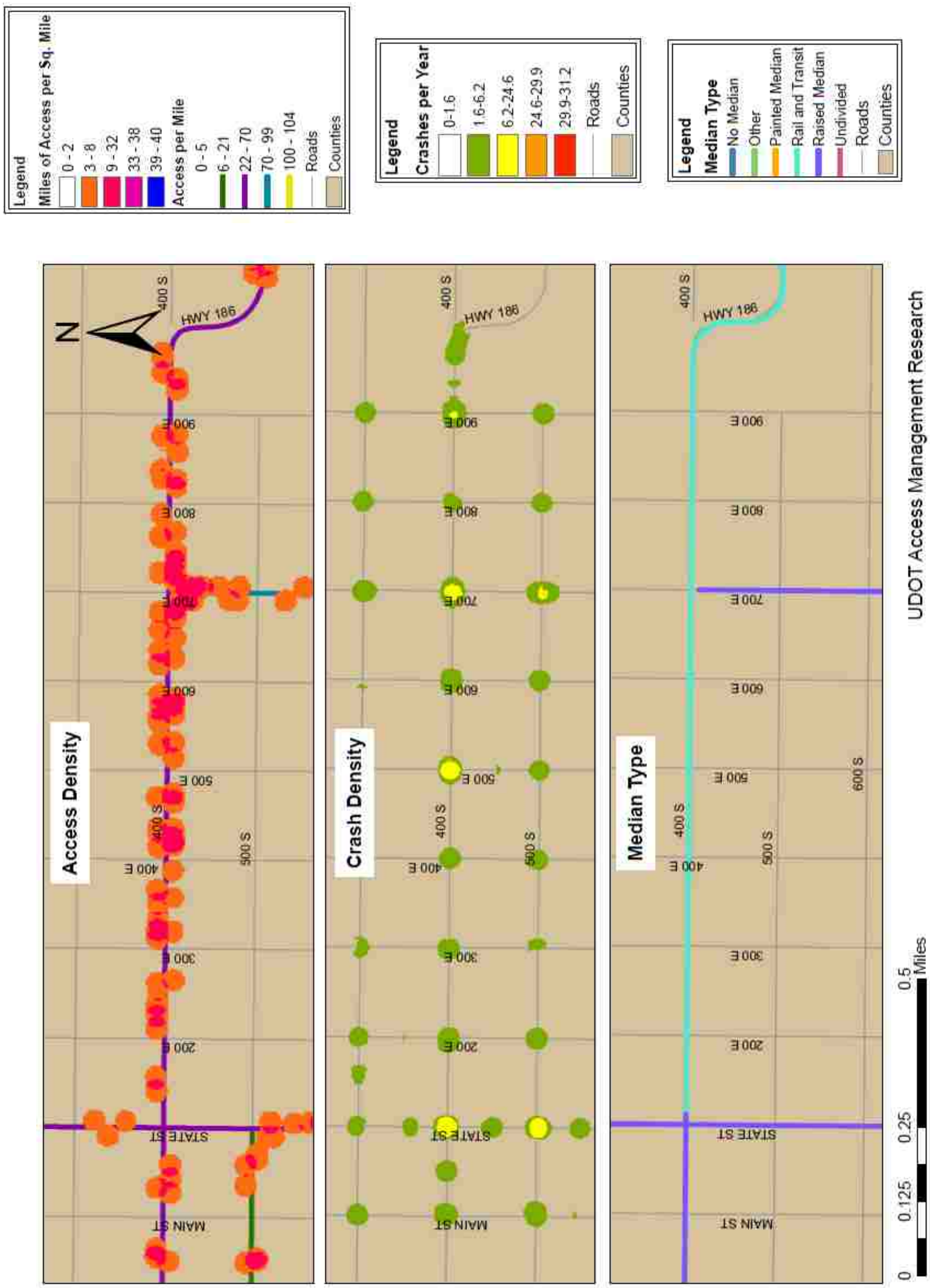

Figure B-3: Map comparing access density methods, crash density, and median type for 400 S. in Salt Lake City, UT.

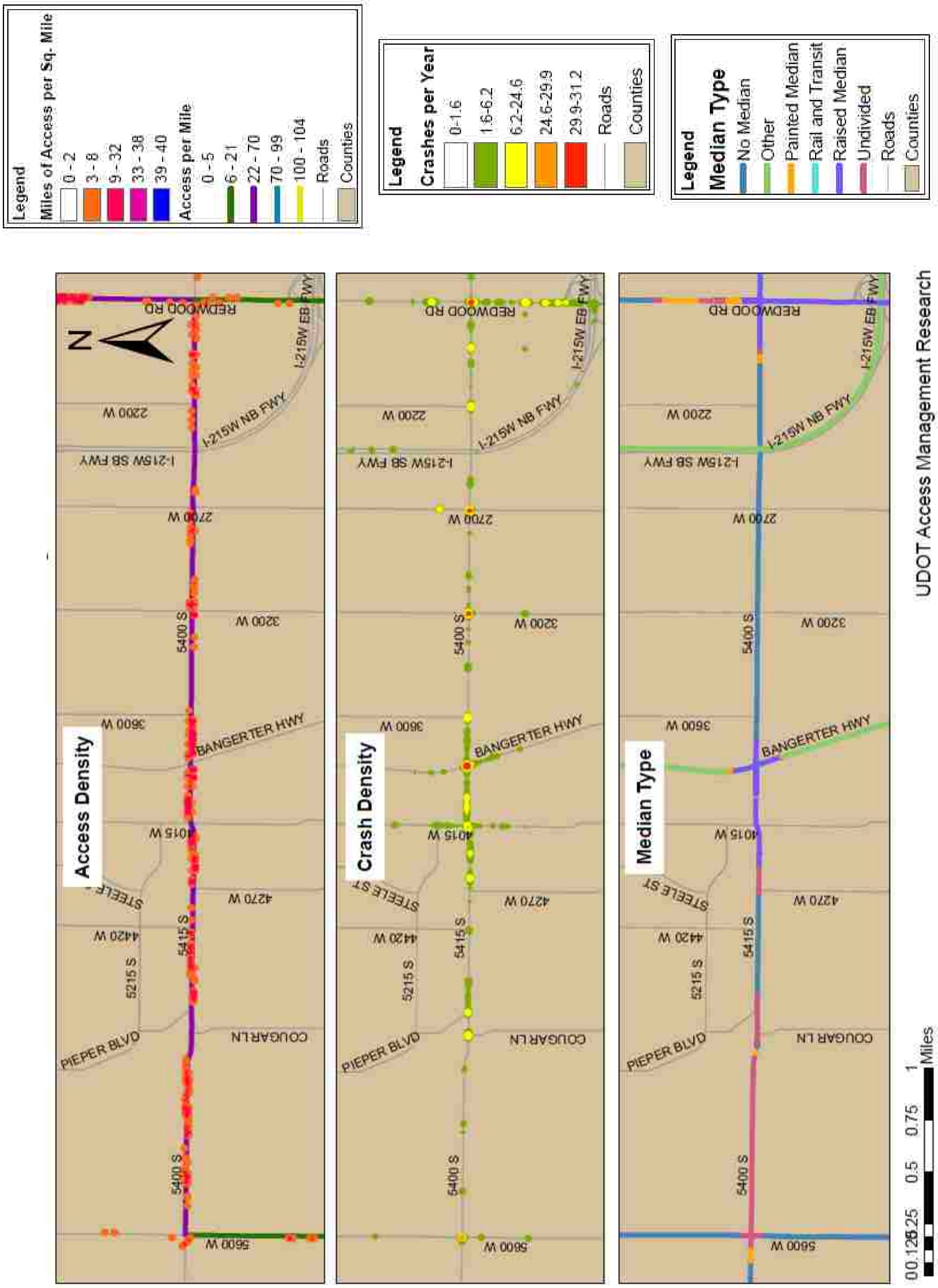

Figure B-4: Map comparing access density methods, crash density, and median type for 5400 S. in Salt Lake City, UT.

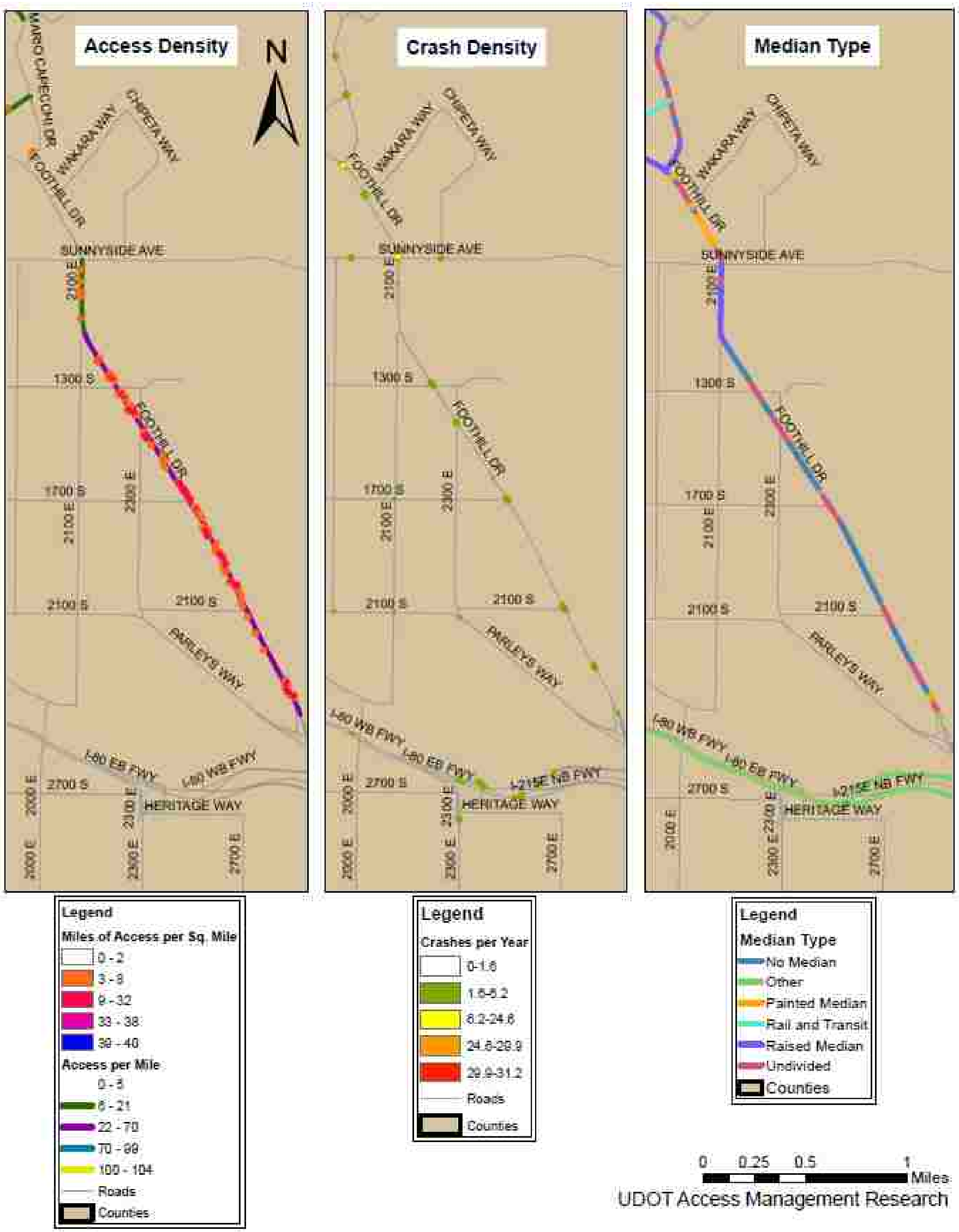

Figure B-5: Map comparing access density methods, crash density, and median type for Foothill Dr. in Salt Lake County, UT.

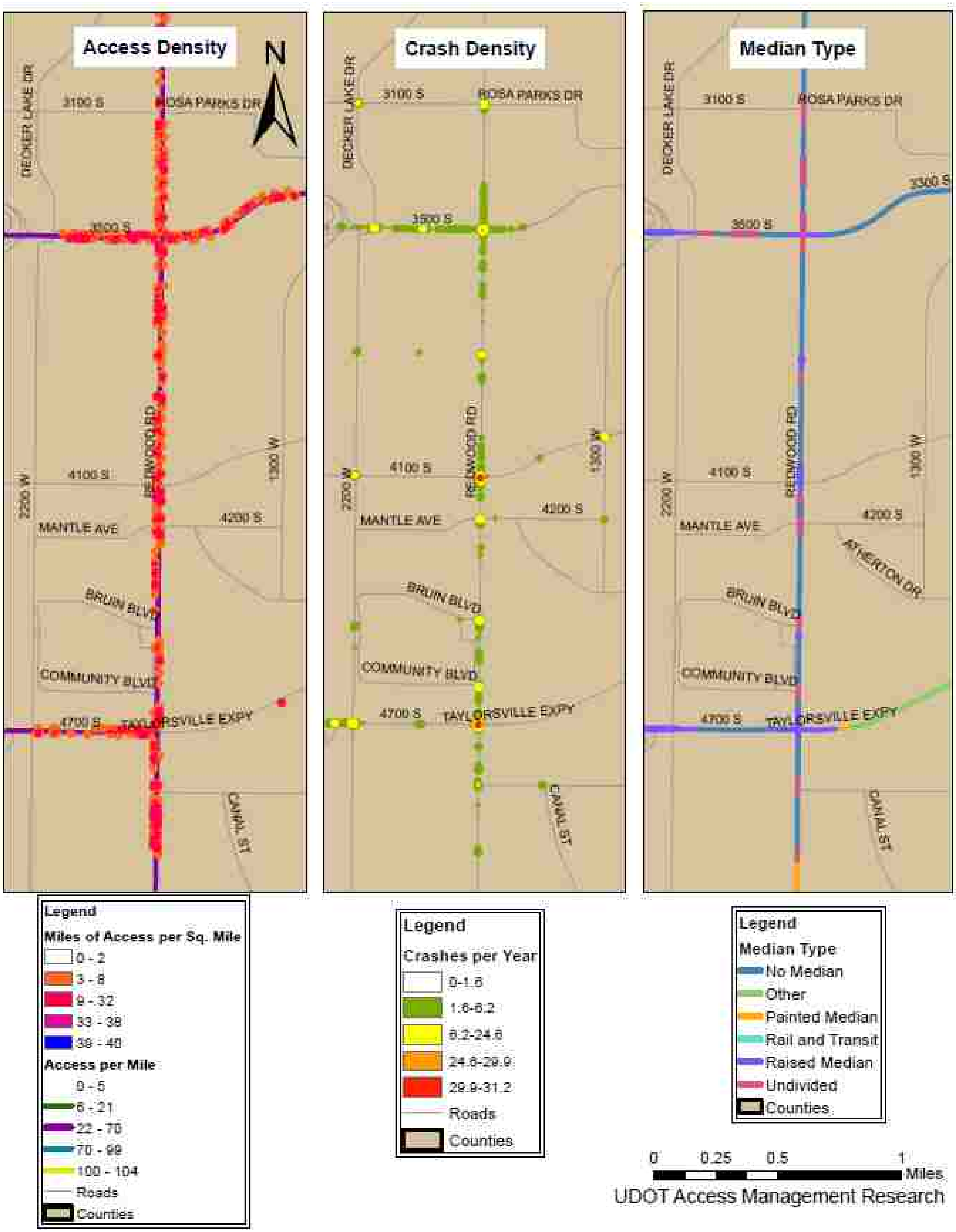

Figure B-6: Map comparing access density methods, crash density, and median type for Redwood Rd. in Salt Lake City, UT.

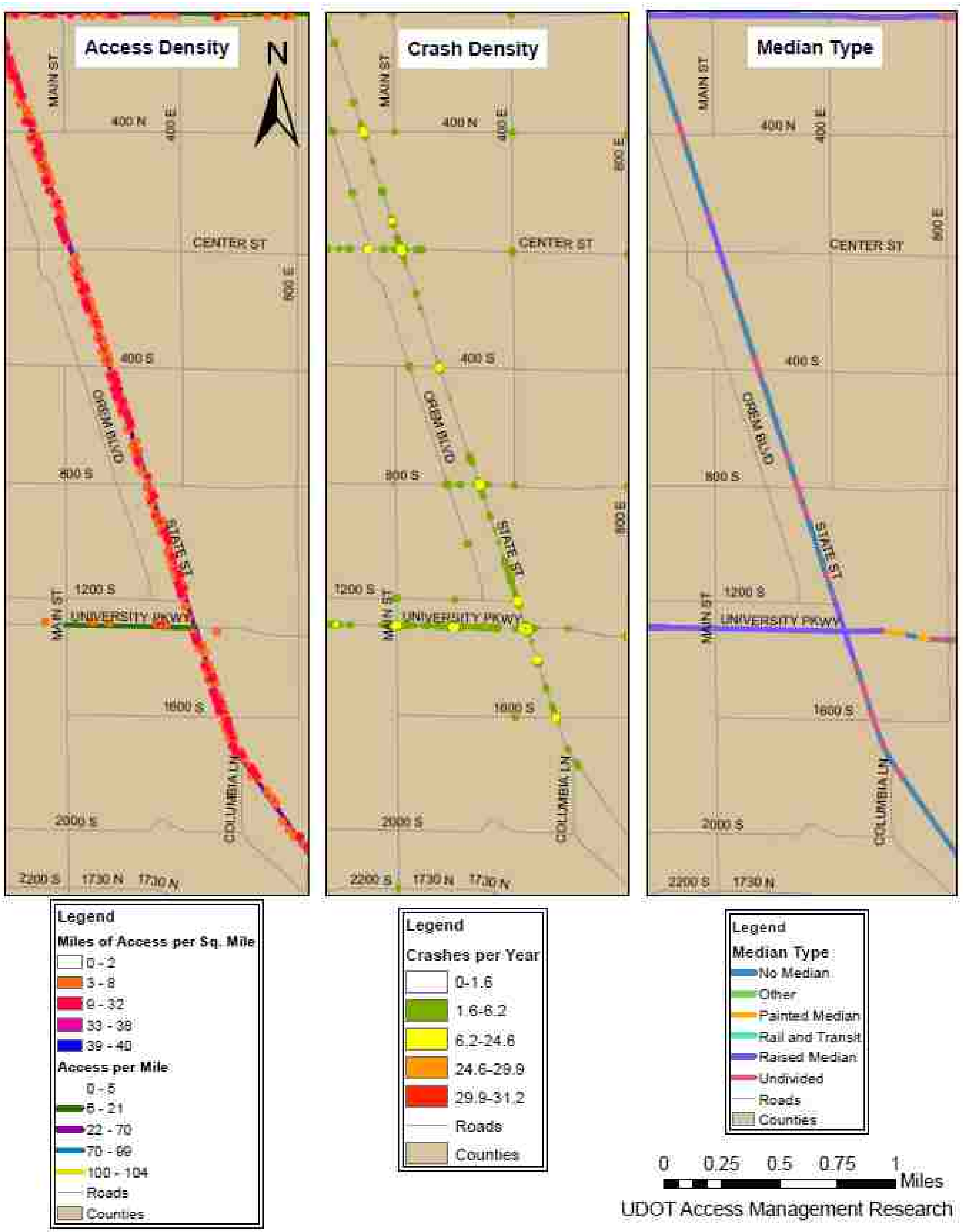

Figure B-7: Map comparing access density methods, crash density, and median type for State St. in Orem, UT.

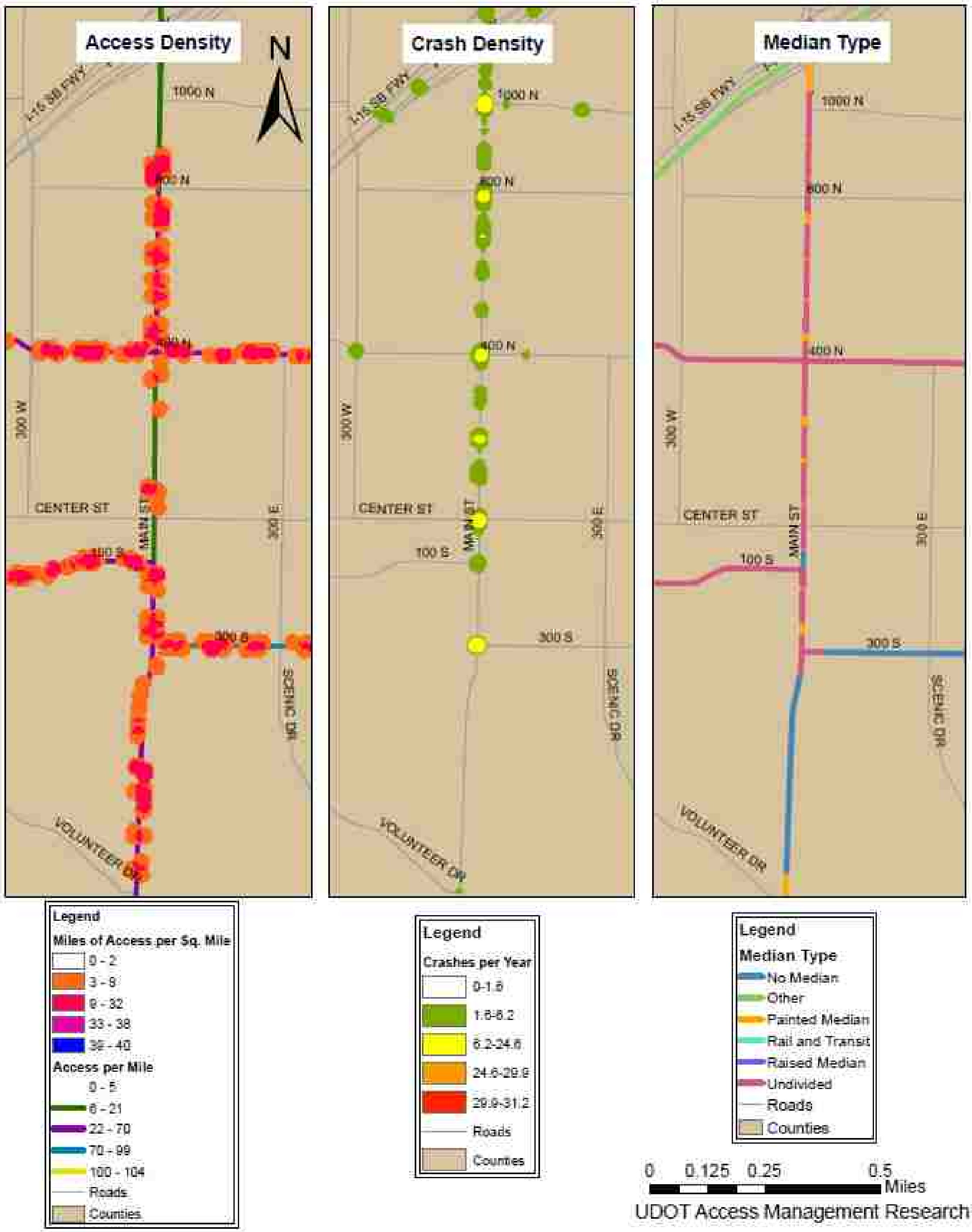

Figure B-8: Map comparing access density methods, crash density, and median type for N. Main St. in Spanish Fork, UT.

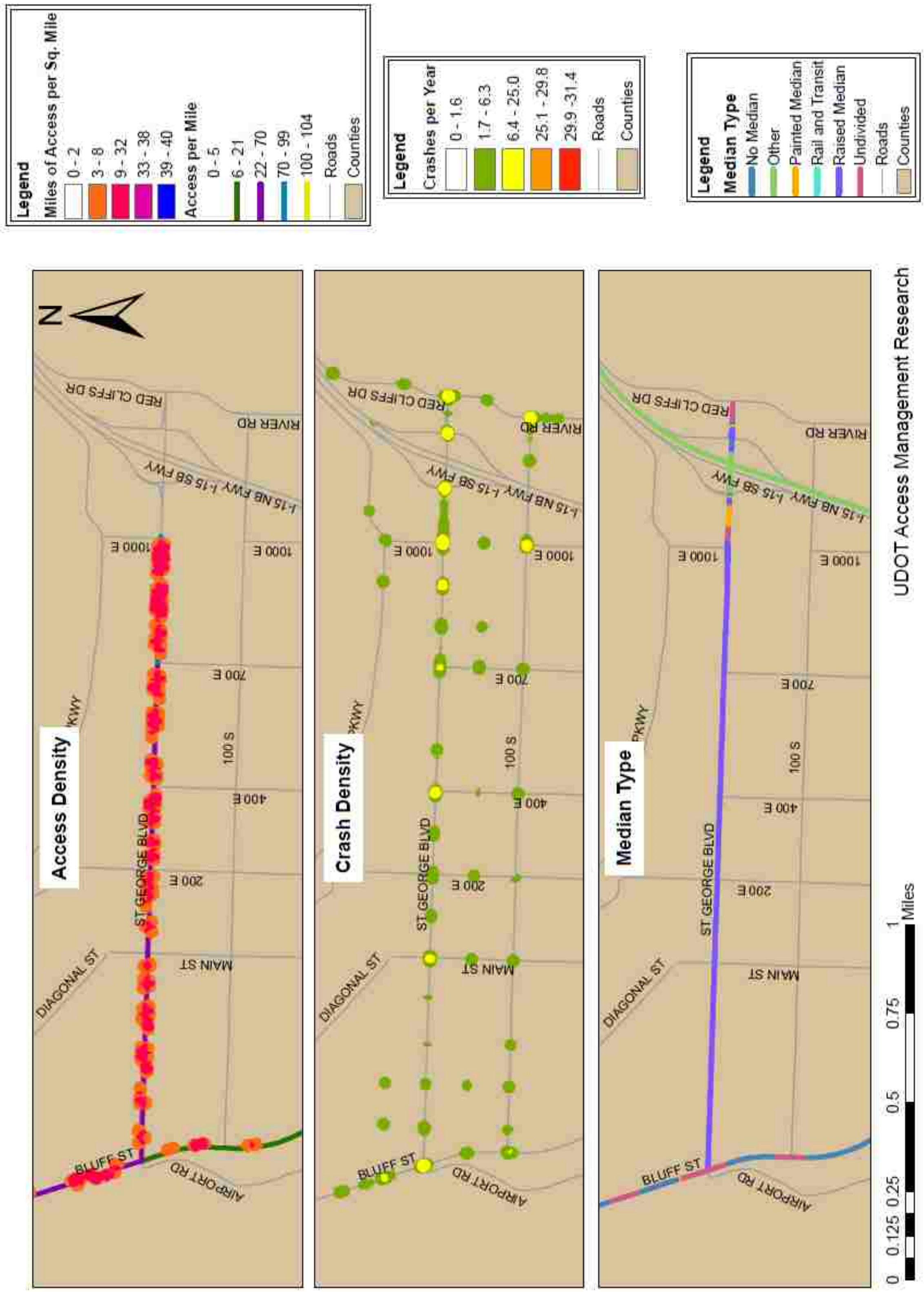

Figure B-9: Map comparing access density methods, crash density, and median type for St. George Blvd. in Washington County, UT.

APPENDIX C BEFORE-AFTER ANALYSIS

Appendix C contains input data used in the raised median safety performance analysis and output from the before-after hierarchal Bayesian analysis, including regression and CMF plots.

C.1 Input Data

This section shows the entire input data used in the hierarchal Bayesian model. Table C-1 shows the data for each raised median segment including segment number, label, mile points, AADT, and crashes that occurred.

Table C-1: Before-After Input Data

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
1	0009P	8.47	8.67	2002	16080	5	0	5	2	6	1	7	3	1	1
1	0009P	8.47	8.67	2003	16210	5	0	5	3	7	1	8	3	1	1
1	0009P	8.47	8.67	2004	17645	5	0	3	2	5	0	5	3	1	1
1	0009P	8.47	8.67	2005	20725	5	0	6	1	7	0	7	3	1	1
1	0009P	8.47	8.67	2006	20435	5	0	14	2	14	2	16	3	1	1
1	0009P	8.47	8.67	2007	21110	5	0	9	0	9	0	9	3	1	1
1	0009P	8.47	8.67	2008	20055	5	0	5	0	5	0	5	3	1	1
1	0009P	8.47	8.67	2009	22185	5	0	4	2	5	1	6	3	2	1
1	0009P	8.47	8.67	2010	20055	5	0	4	3	6	1	7	3	2	1
1	0009P	8.47	8.67	2010	22055	5	1	4	3	6	1	7	3	2	1
1	0009P	8.47	8.67	2011	22140	5	1	1	0	1	0	1	3	2	1
1	0009P	8.47	8.67	2012	26840	5	1	2	4	5	1	6	3	2	1
1	0009P	8.47	8.67	2013	28075	5	1	8	2	10	0	10	3	2	1

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
1	0009P	8.47	8.67	2014	28330	5	1	7	2	9	0	9	3	2	1
2	0018P	0.2	0.5	2002	25123	5	0	21	3	23	1	24	4	1	1
2	0018P	0.2	0.5	2003	26380	5	0	20	4	21	3	24	4	1	1
2	0018P	0.2	0.5	2004	26355	5	0	31	2	31	2	33	4	1	1
2	0018P	0.2	0.5	2005	24660	5	0	40	2	41	1	42	4	1	1
2	0018P	0.2	0.5	2006	24750	5	0	37	2	39	0	39	4	1	1
2	0018P	0.2	0.5	2007	25465	5	0	34	2	36	0	36	4	1	1
2	0018P	0.2	0.5	2008	24245	5	0	24	1	25	0	25	4	1	1
2	0018P	0.2	0.5	2008	24245	5	1	24	1	25	0	25	4	1	1
2	0018P	0.2	0.5	2009	23855	5	1	23	3	26	0	26	4	1	1
2	0018P	0.2	0.5	2010	24310	5	1	34	2	36	0	36	4	1	1
2	0018P	0.2	0.5	2011	24215	5	1	8	1	9	0	9	4	1	1
2	0018P	0.2	0.5	2012	24335	5	1	4	1	5	0	5	4	1	1
2	0018P	0.2	0.5	2013	24455	5	1	14	1	15	0	15	4	1	1
2	0018P	0.2	0.5	2014	24870	5	1	6	0	6	0	6	4	1	1
3	0034P	0	1.75	2002	33462	5	0	152	8	159	1	160	116	14	5
3	0034P	0	1.75	2003	27272	5	0	189	17	202	4	206	116	14	5
3	0034P	0	1.75	2004	26982	5	0	184	16	198	2	200	116	14	5
3	0034P	0	1.75	2005	26141	5	0	132	14	145	1	146	116	14	5
3	0034P	0	1.75	2005	26141	5	1	132	14	145	1	146	116	14	5
3	0034P	0	1.75	2006	5299	5	1	64	8	71	1	72	116	14	5
3	0034P	0	1.75	2007	26939	5	1	97	23	118	2	120	117	14	5
3	0034P	0	1.75	2008	25420	5	1	102	8	110	0	110	117	14	5
3	0034P	0	1.75	2009	24886	5	1	91	8	99	0	99	117	14	5
3	0034P	0	1.75	2010	24736	5	1	81	6	87	0	87	117	14	5
3	0034P	0	1.75	2011	24839	5	1	72	12	84	0	84	117	14	5
3	0034P	0	1.75	2012	24983	5	1	109	15	124	0	124	117	14	5
3	0034P	0	1.75	2013	25108	5	1	95	7	100	2	102	117	14	5
3	0034P	0	1.75	2014	25536	5	1	76	7	82	1	83	117	14	5
4	0039P	5.8	6.1	2002	31667	5	0	18	1	19	0	19	15	1	1
4	0039P	5.8	6.1	2003	23286	5	0	20	3	22	1	23	13	1	1
4	0039P	5.8	6.1	2004	23576	5	0	19	4	21	2	23	13	1	1
4	0039P	5.8	6.1	2005	23544	5	0	12	1	13	0	13	13	1	1
4	0039P	5.8	6.1	2006	23895	5	0	14	4	17	1	18	13	1	1
4	0039P	5.8	6.1	2007	22779	5	0	18	5	23	0	23	13	1	1
4	0039P	5.8	6.1	2008	21915	5	0	15	5	20	0	20	13	1	1

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
4	0039P	5.8	6.1	2009	22068	5	0	28	3	30	1	31	13	1	1
4	0039P	5.8	6.1	2009	22068	5	1	28	3	30	1	31	13	1	1
4	0039P	5.8	6.1	2010	22093	5	1	15	2	16	1	17	13	1	1
4	0039P	5.8	6.1	2011	21451	5	1	13	6	17	2	19	13	1	1
4	0039P	5.8	6.1	2012	25938	5	1	16	5	20	1	21	13	1	1
4	0039P	5.8	6.1	2013	26612	5	1	13	1	14	0	14	13	1	1
4	0039P	5.8	6.1	2014	27786	5	1	15	5	20	0	20	13	1	1
5	0039P	6.3	6.5	2002	28925	5	0	19	7	22	4	26	10	1	1
5	0039P	6.3	6.5	2003	24235	5	0	23	0	23	0	23	10	1	1
5	0039P	6.3	6.5	2004	24553	5	0	22	4	23	3	26	10	1	1
5	0039P	6.3	6.5	2005	23745	5	0	20	4	24	0	24	10	1	1
5	0039P	6.3	6.5	2006	24102	5	0	12	7	19	0	19	10	1	1
5	0039P	6.3	6.5	2007	22894	5	0	19	4	23	0	23	10	1	1
5	0039P	6.3	6.5	2008	22114	5	0	18	6	24	0	24	10	1	1
5	0039P	6.3	6.5	2009	22269	5	0	10	0	10	0	10	10	1	1
5	0039P	6.3	6.5	2009	22269	5	1	10	0	10	0	10	10	1	1
5	0039P	6.3	6.5	2010	22291	5	1	16	4	20	0	20	10	1	1
5	0039P	6.3	6.5	2011	20143	5	1	11	1	11	1	12	10	1	1
5	0039P	6.3	6.5	2012	20080	5	1	15	5	19	1	20	10	1	1
5	0039P	6.3	6.5	2013	20602	5	1	13	5	18	0	18	10	1	1
5	0039P	6.3	6.5	2014	21511	5	1	16	3	17	2	19	10	1	1
6	0048P	8.5	8.6	2002	24490	3	0	23	2	25	0	25	3	0	0
6	0048P	8.5	8.6	2003	22120	3	0	11	1	12	0	12	3	0	0
6	0048P	8.5	8.6	2004	22255	3	0	10	0	10	0	10	3	0	0
6	0048P	8.5	8.6	2005	22185	3	0	15	2	15	2	17	3	0	0
6	0048P	8.5	8.6	2006	28765	3	0	1	0	1	0	1	3	0	0
6	0048P	8.5	8.6	2007	29170	3	0	16	2	17	1	18	3	0	0
6	0048P	8.5	8.6	2008	27740	3	0	7	2	9	0	9	3	0	0
6	0048P	8.5	8.6	2009	27575	3	0	14	1	15	0	15	3	0	0
6	0048P	8.5	8.6	2010	27465	3	0	15	1	16	0	16	3	0	0
6	0048P	8.5	8.6	2010	27465	3	1	15	1	16	0	16	3	0	0
6	0048P	8.5	8.6	2011	27380	3	1	2	1	3	0	3	3	0	0
6	0048P	8.5	8.6	2012	28205	3	1	3	0	3	0	3	3	0	0
6	0048P	8.5	8.6	2013	27500	3	1	3	0	3	0	3	3	0	0
6	0048P	8.5	8.6	2014	27805	3	1	3	0	3	0	3	3	0	0
7	0052P	0.3	0.6	2002	18355	6	0	14	2	15	1	16	0	2	2

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4,5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
7	0052P	0.3	0.6	2003	18128	6	0	10	2	11	1	12	0	2	2
7	0052P	0.3	0.6	2004	17996	6	0	35	1	36	0	36	0	2	2
7	0052P	0.3	0.6	2005	17630	6	0	27	2	27	2	29	0	2	2
7	0052P	0.3	0.6	2006	18060	6	0	12	1	13	0	13	0	2	2
7	0052P	0.3	0.6	2007	14960	6	0	22	4	25	1	26	0	2	2
7	0052P	0.3	0.6	2008	14617	6	0	18	1	18	1	19	0	2	2
7	0052P	0.3	0.6	2009	14682	6	0	18	4	21	1	22	0	2	2
7	0052P	0.3	0.6	2010	14685	6	0	21	2	23	0	23	0	2	2
7	0052P	0.3	0.6	2010	14685	6	1	21	2	23	0	23	0	2	2
7	0052P	0.3	0.6	2011	16787	6	1	35	3	37	1	38	0	2	2
7	0052P	0.3	0.6	2012	16692	6	1	20	2	22	0	22	0	2	2
7	0052P	0.3	0.6	2013	17702	6	1	15	0	15	0	15	0	1	1
7	0052P	0.3	0.6	2014	18368	6	1	11	2	13	0	13	0	1	1
8	0052P	1.55	2.05	2002	31743	6	0	38	10	45	3	48	18	4	1
8	0052P	1.55	2.05	2003	31195	6	0	48	6	51	3	54	18	4	1
8	0052P	1.55	2.05	2004	30782	6	0	48	5	52	1	53	18	4	1
8	0052P	1.55	2.05	2005	30052	6	0	60	6	66	0	66	18	4	1
8	0052P	1.55	2.05	2006	30500	6	0	16	3	18	1	19	18	4	1
8	0052P	1.55	2.05	2007	30926	6	0	49	6	54	1	55	18	4	1
8	0052P	1.55	2.05	2008	30432	6	0	38	4	42	0	42	17	4	1
8	0052P	1.55	2.05	2008	30432	6	1	38	4	42	0	42	17	4	1
8	0052P	1.55	2.05	2009	31347	6	1	27	1	28	0	28	17	4	1
8	0052P	1.55	2.05	2010	32916	6	1	16	8	24	0	24	17	4	1
8	0052P	1.55	2.05	2011	31962	6	1	37	4	41	0	41	17	4	1
8	0052P	1.55	2.05	2012	31868	6	1	22	1	23	0	23	17	4	1
8	0052P	1.55	2.05	2013	32029	6	1	25	3	28	0	28	17	4	1
8	0052P	1.55	2.05	2014	33438	6	1	22	1	23	0	23	17	4	1
9	0071P	8.83	9.7	2002	23407	5	0	54	6	58	2	60	35	7	1
9	0071P	8.83	9.7	2003	23135	5	0	64	7	68	3	71	35	7	1
9	0071P	8.83	9.7	2004	23387	5	0	60	10	67	3	70	35	7	1
9	0071P	8.83	9.7	2005	23354	5	0	64	6	67	3	70	35	7	1
9	0071P	8.83	9.7	2006	23704	5	0	39	11	50	0	50	35	7	1
9	0071P	8.83	9.7	2006	23704	5	1	39	11	50	0	50	35	7	1
9	0071P	8.83	9.7	2007	24036	5	1	37	6	41	2	43	36	8	1
9	0071P	8.83	9.7	2008	23124	5	1	31	6	33	4	37	36	8	1
9	0071P	8.83	9.7	2009	23286	5	1	25	3	28	0	28	36	8	1

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
9	0071P	8.83	9.7	2010	22473	5	1	25	2	25	2	27	36	8	1
9	0071P	8.83	9.7	2011	21821	5	1	14	3	16	1	17	36	8	1
9	0071P	8.83	9.7	2012	23069	5	1	15	2	16	1	17	37	8	1
9	0071P	8.83	9.7	2013	23670	5	1	14	3	17	0	17	37	8	1
9	0071P	8.83	9.7	2014	24712	5	1	10	6	15	1	16	37	8	1
10	0077P	7.45	8.54	2002	17531	5	0	17	3	19	1	20	6	2	0
10	0077P	7.45	8.54	2003	18335	5	0	16	4	19	1	20	6	2	0
10	0077P	7.45	8.54	2004	19140	5	0	15	4	18	1	19	6	2	0
10	0077P	7.45	8.54	2005	19080	5	0	40	11	46	5	51	6	3	0
10	0077P	7.45	8.54	2006	19924	5	0	52	7	56	3	59	6	3	0
10	0077P	7.45	8.54	2007	18965	5	0	47	7	52	2	54	6	3	0
10	0077P	7.45	8.54	2007	18965	5	1	47	7	52	2	54	6	3	0
10	0077P	7.45	8.54	2008	20333	5	1	38	1	38	1	39	6	3	0
10	0077P	7.45	8.54	2009	20208	5	1	1	0	1	0	1	6	2	0
10	0077P	7.45	8.54	2010	20128	5	1	8	0	8	0	8	6	2	0
10	0077P	7.45	8.54	2011	20068	5	1	6	0	6	0	6	6	2	0
10	0077P	7.45	8.54	2012	19668	5	1	24	1	25	0	25	6	2	0
10	0077P	7.45	8.54	2013	29649	5	1	37	3	39	1	40	6	2	0
10	0077P	7.45	8.54	2014	29974	5	1	16	0	16	0	16	6	2	1
11	0089P	364.78	366.28	2002	31714	5	0	7	1	8	0	8	38	6	4
11	0089P	364.78	366.28	2003	30653	5	0	10	0	10	0	10	38	6	4
11	0089P	364.78	366.28	2004	29630	5	0	4	0	4	0	4	38	6	4
11	0089P	364.78	366.28	2005	33218	5	0	18	0	18	0	18	38	6	4
11	0089P	364.78	366.28	2005	33218	5	1	18	0	18	0	18	38	6	4
11	0089P	364.78	366.28	2006	32756	5	1	102	18	119	1	120	38	6	4
11	0089P	364.78	366.28	2007	33216	5	1	91	15	103	3	106	38	6	4
11	0089P	364.78	366.28	2008	31586	5	1	49	10	55	4	59	38	6	4
11	0089P	364.78	366.28	2009	28283	5	1	42	8	49	1	50	38	7	4
11	0089P	364.78	366.28	2010	31246	5	1	53	3	55	1	56	38	7	4
11	0089P	364.78	366.28	2011	28886	5	1	45	10	53	2	55	38	7	4

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
11	0089P	364.78	366.28	2012	27009	5	1	51	15	63	3	66	38	7	5
11	0089P	364.78	366.28	2013	28080	5	1	56	13	66	3	69	38	7	5
11	0089P	364.78	366.28	2014	30127	5	1	39	11	49	1	50	38	7	5
12	0091P	25.45	25.6	2002	17680	5	0	5	1	5	1	6	9	0	0
12	0091P	25.45	25.6	2003	17365	5	0	8	1	8	1	9	9	0	0
12	0091P	25.45	25.6	2004	17405	5	0	7	2	9	0	9	9	0	0
12	0091P	25.45	25.6	2005	17380	5	0	7	0	7	0	7	9	0	0
12	0091P	25.45	25.6	2006	18025	5	0	18	4	21	1	22	9	0	0
12	0091P	25.45	25.6	2007	18275	5	0	21	2	23	0	23	9	0	0
12	0091P	25.45	25.6	2008	17580	5	0	18	0	18	0	18	9	0	0
12	0091P	25.45	25.6	2009	18645	5	0	5	1	6	0	6	9	0	0
12	0091P	25.45	25.6	2010	18665	5	0	18	2	20	0	20	9	0	0
12	0091P	25.45	25.6	2010	18665	5	1	18	2	20	0	20	9	0	0
12	0091P	25.45	25.6	2011	18125	5	1	2	0	2	0	2	9	0	0
12	0091P	25.45	25.6	2012	18070	5	1	1	0	1	0	1	9	0	0
12	0091P	25.45	25.6	2013	18540	5	1	2	0	2	0	2	9	0	0
12	0091P	25.45	25.6	2014	19355	5	1	1	0	1	0	1	9	0	0
13	0108P	0.28	0.43	2002	36670	5	0	28	4	31	1	32	0	0	0
13	0108P	0.28	0.43	2003	29070	5	0	23	4	25	2	27	0	0	0
13	0108P	0.28	0.43	2004	29245	5	0	30	4	34	0	34	0	0	0
13	0108P	0.28	0.43	2005	29160	5	0	22	2	24	0	24	0	0	0
13	0108P	0.28	0.43	2006	35130	5	0	11	0	11	0	11	0	0	0
13	0108P	0.28	0.43	2006	35130	5	1	11	0	11	0	11	0	0	0
13	0108P	0.28	0.43	2007	35620	5	1	21	1	22	0	22	0	0	0
13	0108P	0.28	0.43	2008	36655	5	1	11	1	11	1	12	0	0	0
13	0108P	0.28	0.43	2009	36435	5	1	11	3	13	1	14	0	0	0
13	0108P	0.28	0.43	2010	36290	5	1	9	1	10	0	10	0	0	0
13	0108P	0.28	0.43	2011	42610	5	1	10	1	11	0	11	0	0	0

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4,5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
13	0108P	0.28	0.43	2012	41755	5	1	12	1	13	0	13	0	0	0
13	0108P	0.28	0.43	2013	40715	5	1	8	0	8	0	8	0	0	0
13	0108P	0.28	0.43	2014	41160	5	1	9	0	9	0	9	0	0	0
14	0171P	6.02	7.25	2002	42480	5	0	148	31	168	11	179	74	8	4
14	0171P	6.02	7.25	2003	41736	5	0	153	24	166	11	177	74	8	4
14	0171P	6.02	7.25	2004	41028	5	0	139	24	152	11	163	74	8	4
14	0171P	6.02	7.25	2005	40970	5	0	200	61	249	12	261	74	8	4
14	0171P	6.02	7.25	2006	42720	5	0	139	16	153	2	155	74	8	4
14	0171P	6.02	7.25	2007	43317	5	0	134	31	163	2	165	75	8	4
14	0171P	6.02	7.25	2008	41691	5	0	93	24	115	2	117	75	8	4
14	0171P	6.02	7.25	2008	41691	5	1	93	24	115	2	117	75	8	4
14	0171P	6.02	7.25	2009	41982	5	1	67	6	72	1	73	75	8	4
14	0171P	6.02	7.25	2010	38924	5	1	63	10	73	0	73	77	8	4
14	0171P	6.02	7.25	2011	35220	5	1	43	6	49	0	49	77	8	4
14	0171P	6.02	7.25	2012	35113	5	1	67	4	70	1	71	77	8	4
14	0171P	6.02	7.25	2013	35191	5	1	90	9	99	0	99	77	8	4
14	0171P	6.02	7.25	2014	36739	5	1	86	8	93	1	94	77	8	4
15	0173P	4.55	5.15	2002	35723	3	0	170	15	179	6	185	43	3	2
15	0173P	4.55	5.15	2003	35510	3	0	130	14	140	4	144	43	3	2
15	0173P	4.55	5.15	2004	37632	3	0	135	4	136	3	139	43	3	2
15	0173P	4.55	5.15	2005	33264	3	0	134	16	143	7	150	43	3	2
15	0173P	4.55	5.15	2006	34733	3	0	117	11	127	1	128	43	3	2
15	0173P	4.55	5.15	2007	35220	3	0	132	7	139	0	139	43	3	2
15	0173P	4.55	5.15	2008	33495	3	0	129	8	136	1	137	43	3	2
15	0173P	4.55	5.15	2009	35488	3	0	82	10	92	0	92	43	3	2
15	0173P	4.55	5.15	2010	35346	3	0	114	3	117	0	117	43	3	2
15	0173P	4.55	5.15	2011	35636	3	0	109	9	115	3	118	43	3	2
15	0173P	4.55	5.15	2012	34918	3	0	115	13	125	3	128	41	3	3
15	0173P	4.55	5.15	2012	34918	3	1	115	13	125	3	128	41	3	3
15	0173P	4.55	5.15	2013	35548	3	1	101	10	108	3	111	41	3	3
15	0173P	4.55	5.15	2014	35898	3	1	52	2	54	0	54	41	3	3
16	0204P	3.45	3.65	2002	22402	5	0	18	2	19	1	20	8	1	1
16	0204P	3.45	3.65	2003	22643	5	0	15	0	15	0	15	8	1	1
16	0204P	3.45	3.65	2004	22630	5	0	12	0	12	0	12	8	1	1
16	0204P	3.45	3.65	2005	23891	5	0	14	6	19	1	20	8	1	1
16	0204P	3.45	3.65	2006	26068	5	0	12	5	16	1	17	8	1	1

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
16	0204P	3.45	3.65	2007	26433	5	0	21	1	22	0	22	7	1	1
16	0204P	3.45	3.65	2008	25138	5	0	13	4	17	0	17	7	1	1
16	0204P	3.45	3.65	2008	25138	5	1	13	4	17	0	17	7	1	1
16	0204P	3.45	3.65	2009	24985	5	1	9	2	10	1	11	7	1	1
16	0204P	3.45	3.65	2010	24885	5	1	7	2	9	0	9	7	1	1
16	0204P	3.45	3.65	2011	24501	5	1	3	2	5	0	5	7	1	1
16	0204P	3.45	3.65	2012	25362	5	1	11	6	17	0	17	7	1	1
16	0204P	3.45	3.65	2013	24729	5	1	8	0	8	0	8	7	1	1
16	0204P	3.45	3.65	2014	24998	5	1	9	6	15	0	15	7	1	1
17	0209P	7.6	8	2002	40817	5	0	68	6	72	2	74	14	3	1
17	0209P	7.6	8	2003	41017	5	0	53	5	56	2	58	14	3	1
17	0209P	7.6	8	2004	40482	5	0	51	3	53	1	54	14	3	1
17	0209P	7.6	8	2005	40364	5	0	62	5	66	1	67	14	3	1
17	0209P	7.6	8	2006	37283	5	0	50	7	56	1	57	14	3	1
17	0209P	7.6	8	2007	36337	5	0	55	6	61	0	61	14	3	1
17	0209P	7.6	8	2007	36337	5	1	55	6	61	0	61	14	3	1
17	0209P	7.6	8	2008	34957	5	1	48	7	55	0	55	14	3	1
17	0209P	7.6	8	2009	35204	5	1	42	6	48	0	48	14	3	1
17	0209P	7.6	8	2010	35238	5	1	37	8	43	2	45	14	3	1
17	0209P	7.6	8	2011	34215	5	1	50	11	59	2	61	14	3	1
17	0209P	7.6	8	2012	35462	5	1	49	10	56	3	59	14	3	1
17	0209P	7.6	8	2013	36382	5	1	39	8	46	1	47	14	3	1
17	0209P	7.6	8	2014	37984	5	1	47	3	49	1	50	14	3	1
18	0209P	9.3	9.74	2002	20085	5	0	9	1	10	0	10	0	0	0
18	0209P	9.3	9.74	2003	19730	5	0	9	1	10	0	10	0	0	0
18	0209P	9.3	9.74	2004	19470	5	0	1	0	1	0	1	0	0	0
18	0209P	9.3	9.74	2005	19445	5	0	9	0	9	0	9	0	0	0
18	0209P	9.3	9.74	2006	19735	5	0	4	0	4	0	4	0	0	0
18	0209P	9.3	9.74	2006	19735	5	1	4	0	4	0	4	0	0	0
18	0209P	9.3	9.74	2007	20010	5	1	14	1	15	0	15	0	3	1
18	0209P	9.3	9.74	2008	19250	5	1	13	1	14	0	14	0	3	1
18	0209P	9.3	9.74	2009	19385	5	1	6	0	6	0	6	0	3	1
18	0209P	9.3	9.74	2010	19405	5	1	6	1	7	0	7	0	3	1
18	0209P	9.3	9.74	2011	20980	5	1	2	1	3	0	3	0	3	1
18	0209P	9.3	9.74	2012	20915	5	1	9	1	10	0	10	0	3	1
18	0209P	9.3	9.74	2013	21460	5	1	4	0	4	0	4	0	3	1

Table C-1 Continued

Seg Num	Label	Beg MP	End MP	Year	AADT	AC	BA	Sev 1,2	Sev 3,4, 5	Sev 1,2,3	Sev 4,5	All Sev	Dwy	Int	Sig Int
18	0209P	9.3	9.74	2014	22405	5	1	3	1	4	0	4	0	3	1
19	0068P	56.32	57.1	2002	19087	5	0	20	11	24	7	31	34	3	1
19	0068P	56.32	57.1	2003	18262	5	0	24	6	27	3	30	34	3	1
19	0068P	56.32	57.1	2003	18262	5	1	24	6	27	3	30	34	3	1
19	0068P	56.32	57.1	2004	18494	5	1	23	5	25	3	28	34	3	1
19	0068P	56.32	57.1	2005	17328	5	1	20	6	23	3	26	34	3	1
19	0068P	56.32	57.1	2006	17517	5	1	18	10	23	5	28	34	3	1
19	0068P	56.32	57.1	2007	17762	5	1	26	3	28	1	29	34	3	1
19	0068P	56.32	57.1	2008	24505	5	1	31	16	46	1	47	34	3	1
19	0068P	56.32	57.1	2009	24066	5	1	27	4	30	1	31	34	3	1
19	0068P	56.32	57.1	2010	23586	5	1	24	6	30	0	30	34	3	1
19	0068P	56.32	57.1	2011	23326	5	1	15	6	19	2	21	34	3	1
19	0068P	56.32	57.1	2012	23326	5	1	7	8	14	1	15	34	3	1
19	0068P	56.32	57.1	2013	29002	5	1	19	10	26	3	29	34	3	1
19	0068P	56.32	57.1	2014	27549	5	1	25	4	29	0	29	34	3	1
20	0009P	9.42	10.8	2002	16696	5	0	27	0	27	0	27	42	12	2
20	0009P	9.42	10.8	2003	17408	5	0	37	9	44	2	46	42	12	2
20	0009P	9.42	10.8	2004	18940	5	0	41	3	44	0	44	42	12	2
20	0009P	9.42	10.8	2005	21051	5	0	39	7	45	1	46	42	12	2
20	0009P	9.42	10.8	2006	21912	5	0	49	3	51	1	52	49	12	2
20	0009P	9.42	10.8	2006	21912	5	1	49	3	51	1	52	49	12	2
20	0009P	9.42	10.8	2007	22635	5	1	53	2	54	1	55	49	12	2
20	0009P	9.42	10.8	2008	21502	5	1	30	0	30	0	30	49	12	2
20	0009P	9.42	10.8	2009	21792	5	1	29	2	30	1	31	49	12	2
20	0009P	9.42	10.8	2010	21662	5	1	15	3	17	1	18	49	12	2
20	0009P	9.42	10.8	2011	21747	5	1	9	4	13	0	13	49	12	2
20	0009P	9.42	10.8	2012	23282	5	1	13	3	16	0	16	52	13	2
20	0009P	9.42	10.8	2013	24350	5	1	17	3	20	0	20	52	13	2
20	0009P	9.42	10.8	2014	24572	5	1	20	4	24	0	24	52	13	2

C.2 Before-After Analysis Output Plots

This section has regression plots and CMF plots for all of the AC together (AC 3, 5 and 6) and for AC 5 and 6 separately. In this section, plots for all crash severity types will be presented first and then separate crash severity group plots will be presented.

C.2.1 Plots for All Crash Severity Types

Figure C-1 and Figure C-2 show, with a 95 percent confidence interval, that installing a raised median reduces the number of crashes that occur 100 percent of the time. Figure C-3 shows that installing a raised median reduces crashes with a 95 percent confidence between 0 and 8,000 VMT, and 12,000 and 18,000 VMT. Figure C-4 shows that the average CMF value for all VMT is 0.47. Figure C-5 and Figure C-6 show that the mean CMF values for both AC 5 and 6 are 0.61 and 0.67.

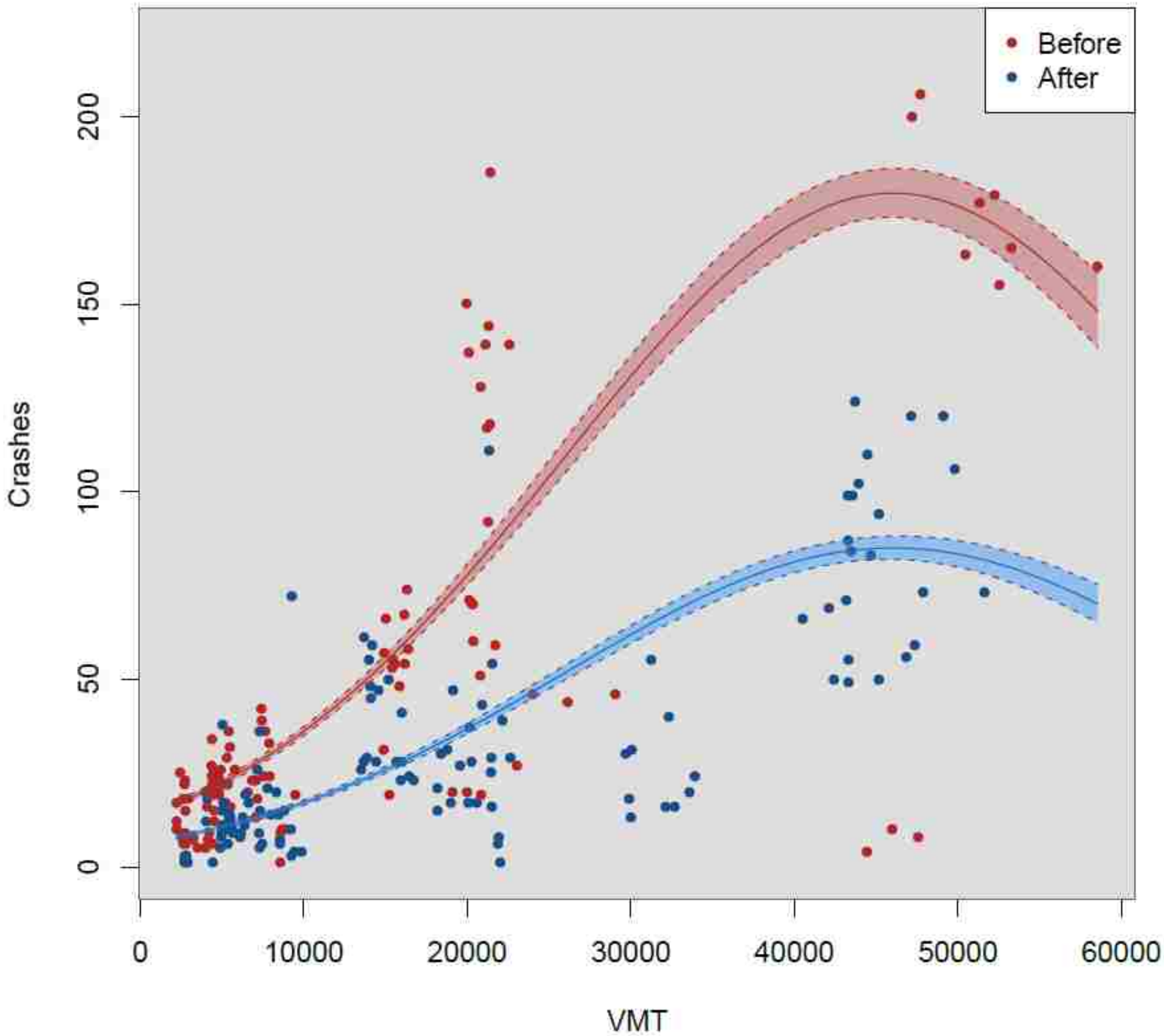

Figure C-1: Regression plot for all AC.

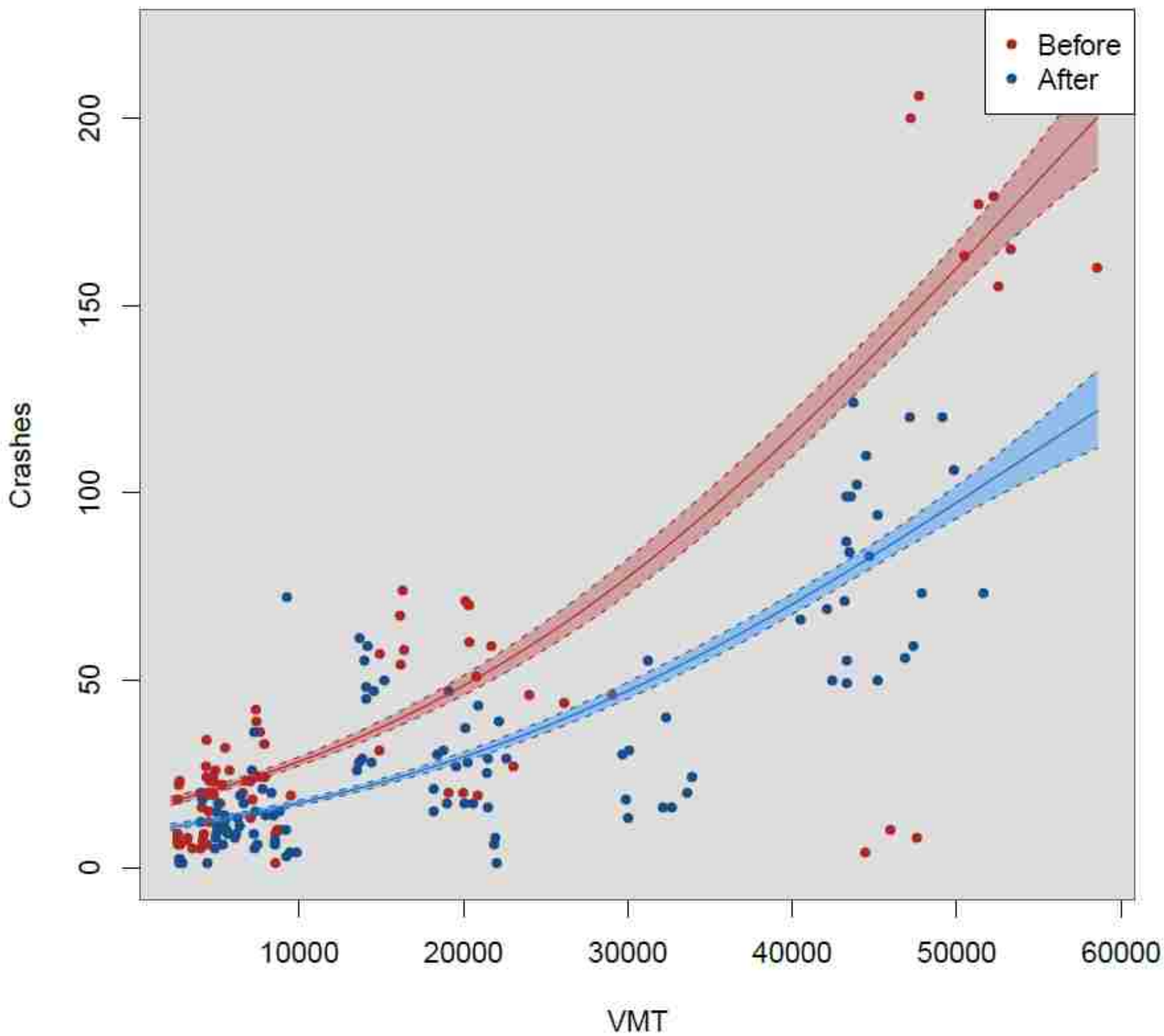

Figure C-2: Regression plot for AC 5.

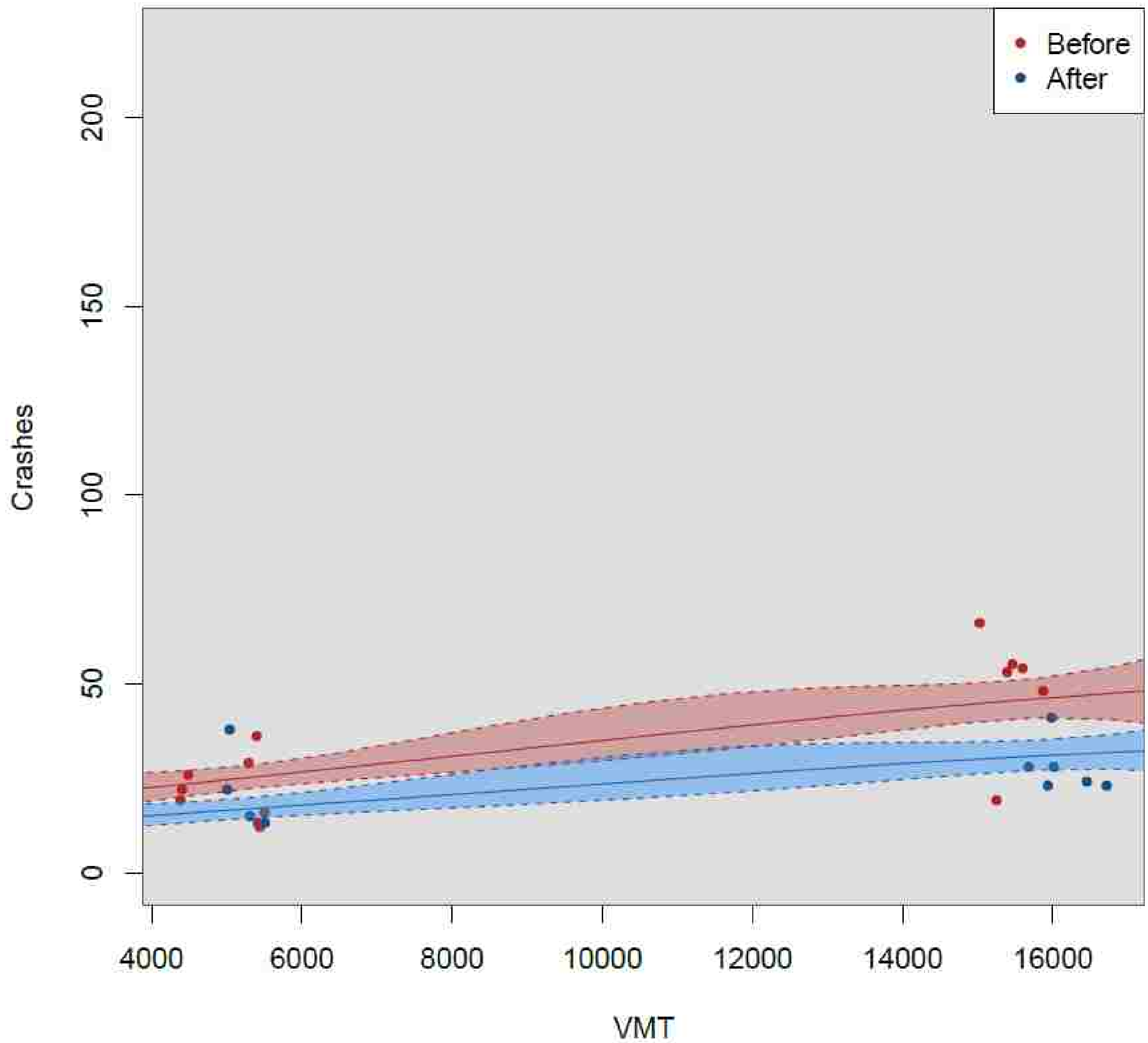

Figure C-3: Regression plot AC6.

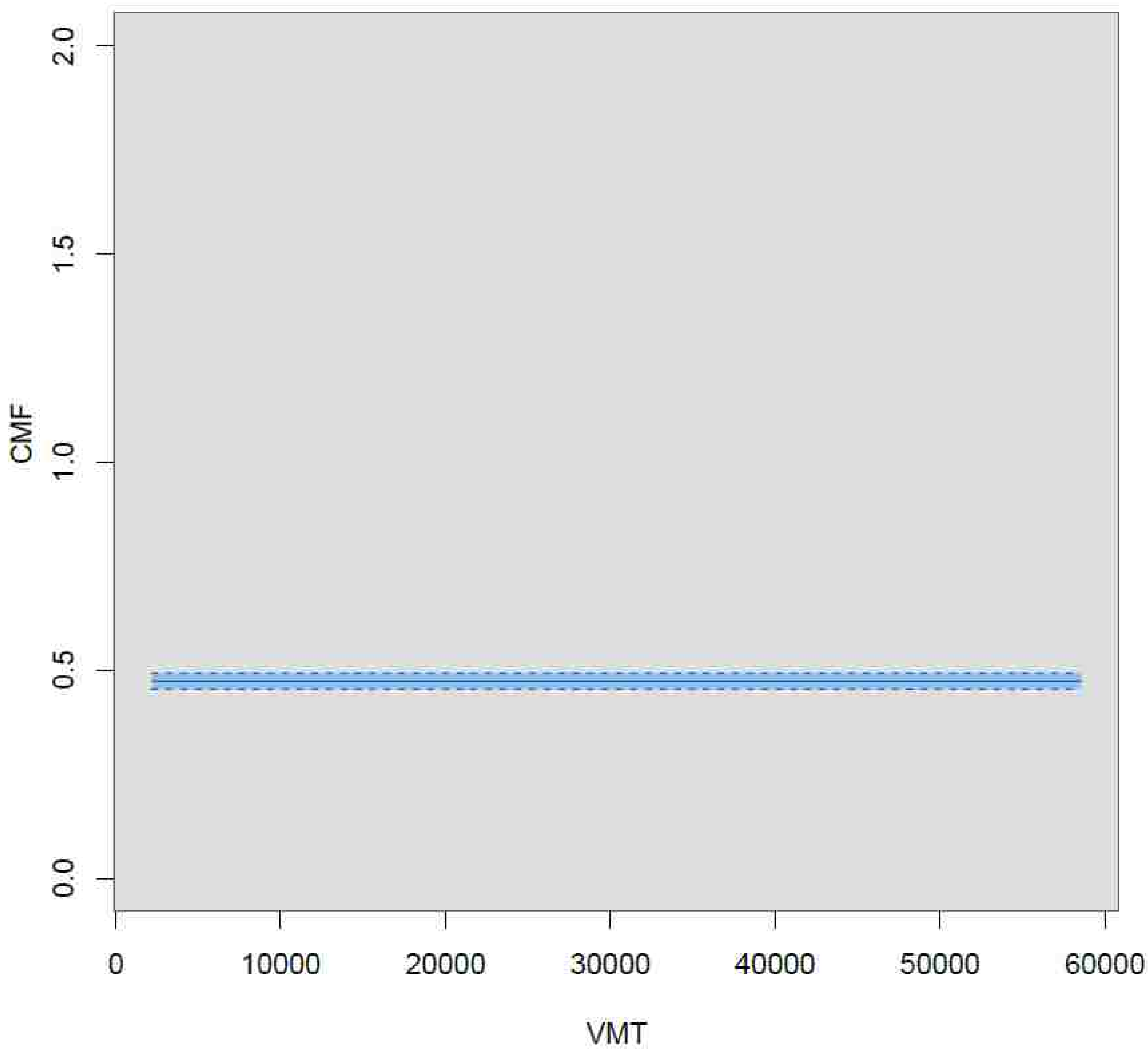

Figure C-4: Plot of CMF values for any given VMT for all AC.

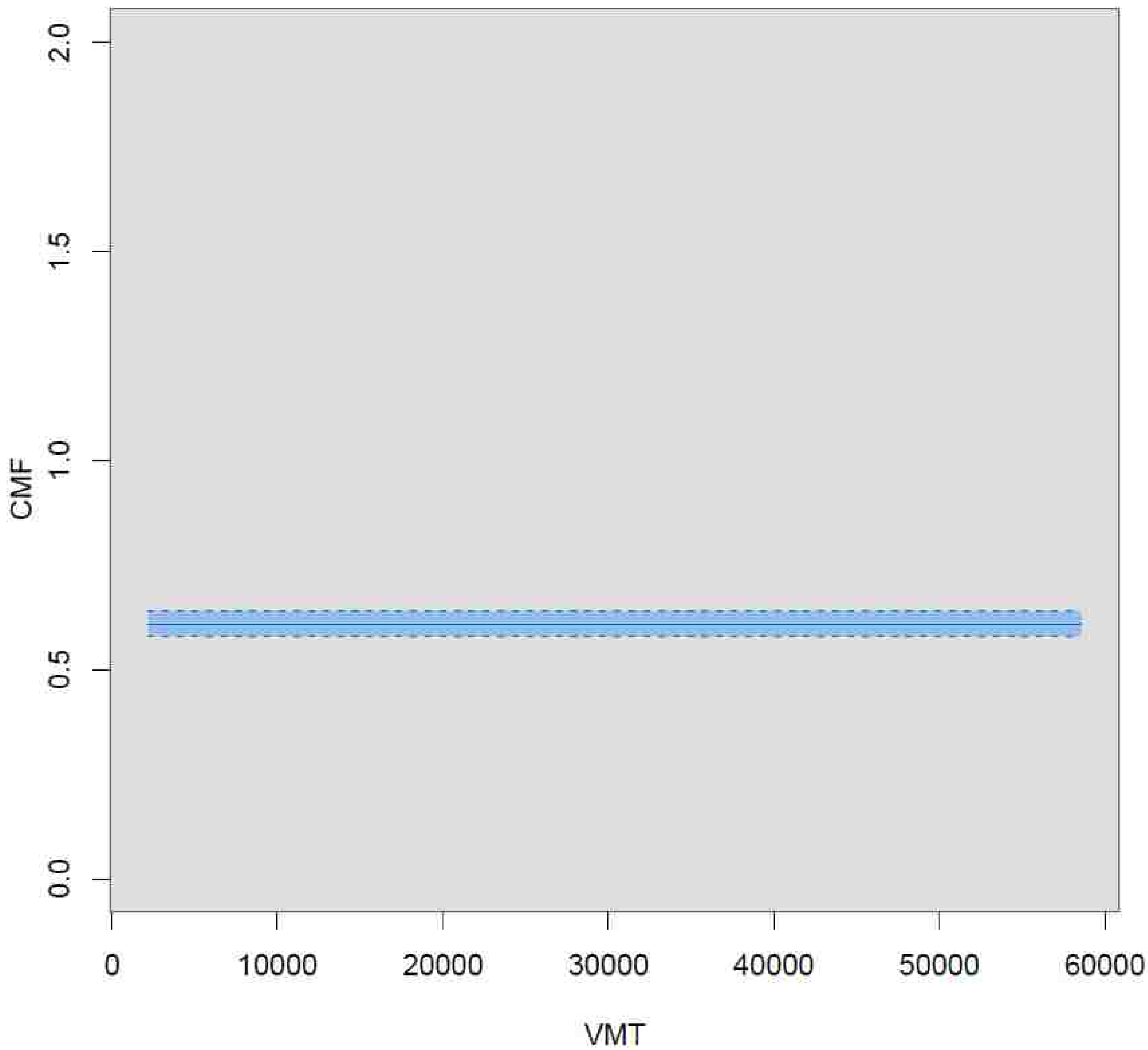

Figure C-5: Plot of CMF values for any given VMT for AC 5.

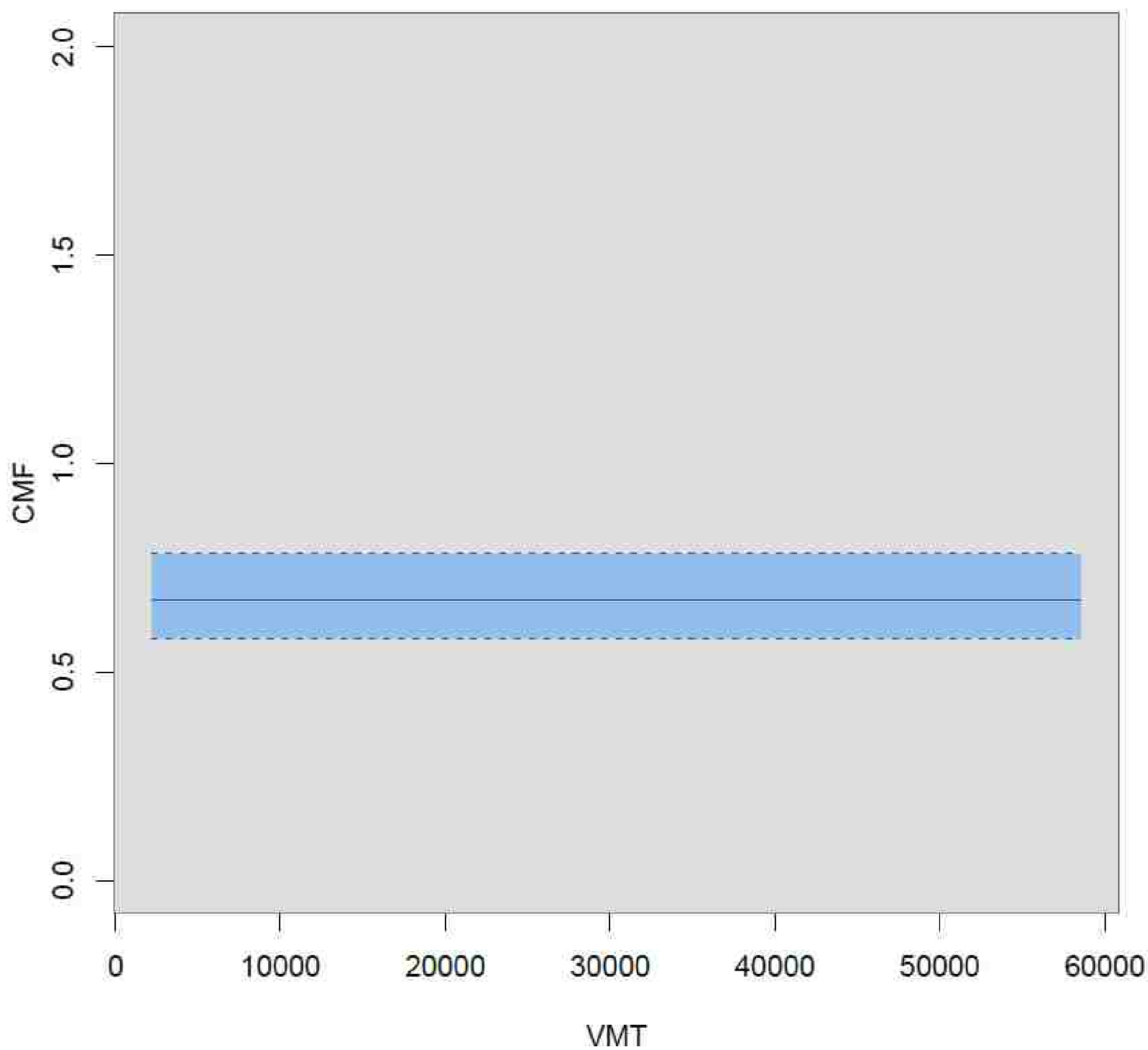

Figure C-6: Plot of CMF values for any given VMT for AC 6.

C.2.2 Plots by Crash Severity Groups

Four different crash severity groups were used in the before-after model to find how different crash severity types decrease with the installation of a raised median. First plots for severity 1 and 2 will be presented, followed by plots for severity 1, 2, and 3. Next, plots depicting results for crash severity 3, 4, and 5 will be shown and lastly, plots for crash severity 4 and 5 will be presented.

C.2.2.1 Crash Severity 1 and 2

Only crashes with a severity of 1 and 2 were included in the before-after model. Figure C-7, Figure C-8, and Figure C-9, which coincide with all AC, only AC 5 segments and only AC6 segments, show, with a 95 percent confidence, that a raised median decreases crashes after installation 100 percent of the time. Figure C-10 through Figure C-12 show the CMF plots for each AC.

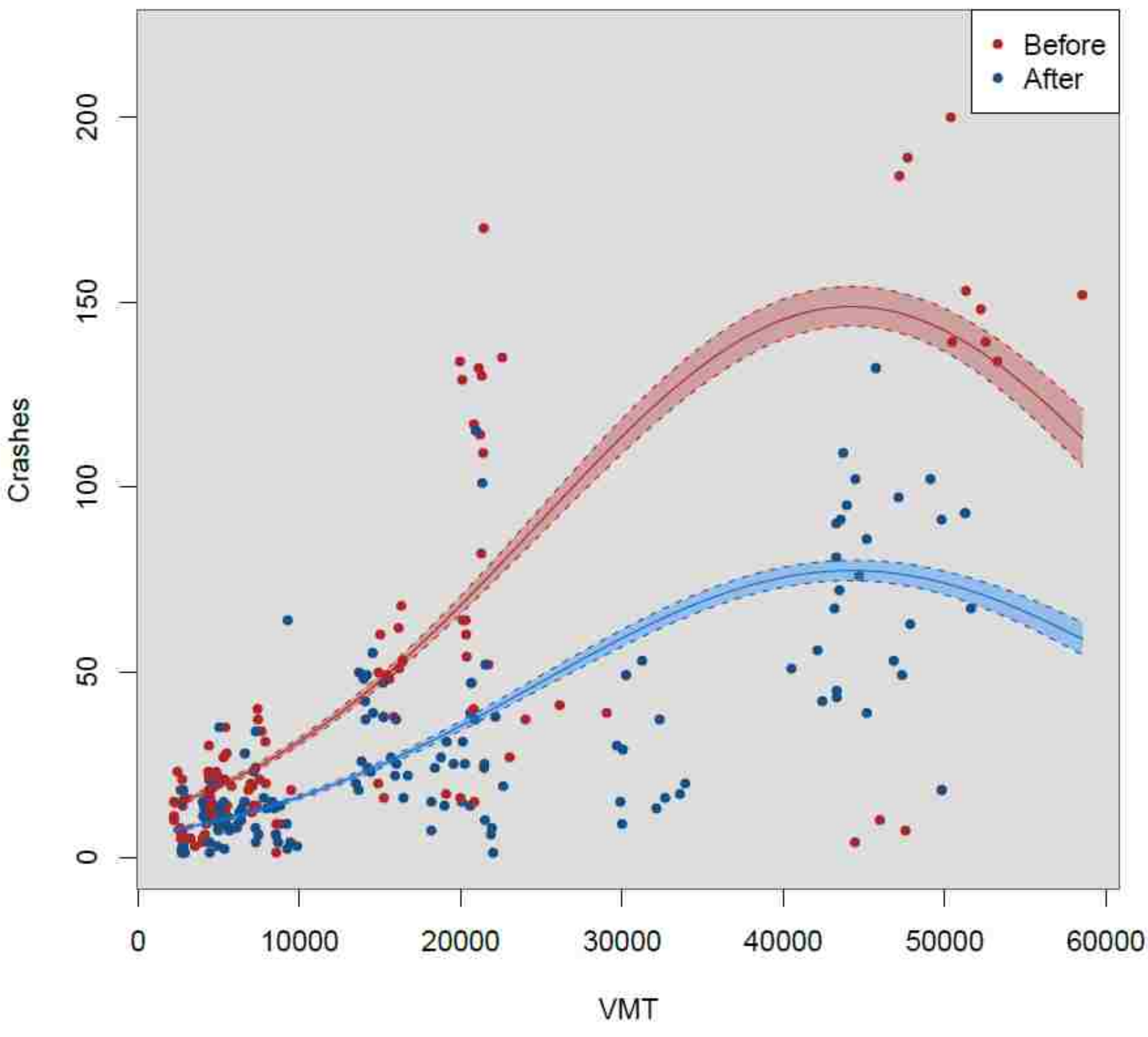

Figure C-7: Regression plot for all AC only including crashes with severity 1 and 2.

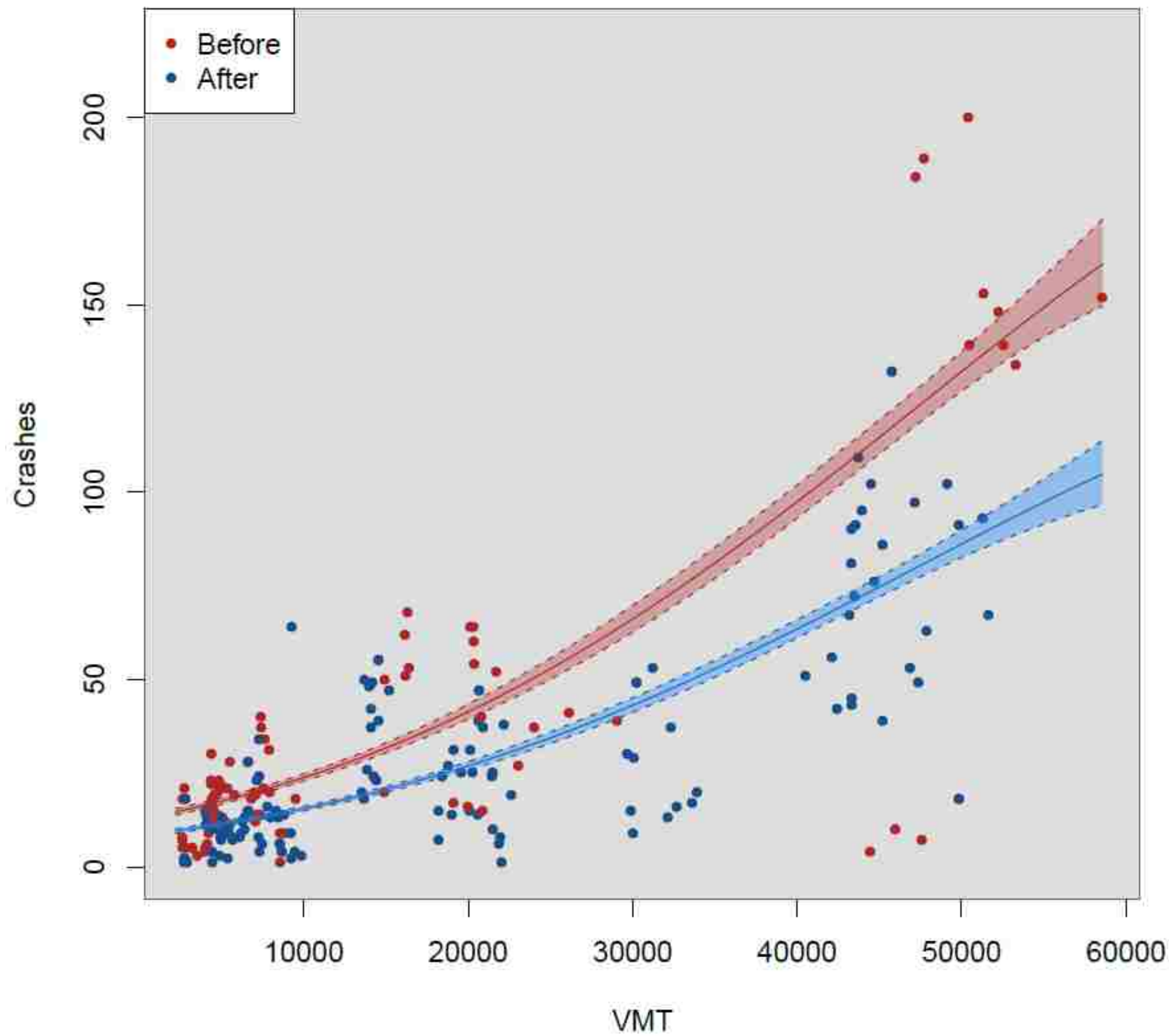

Figure C-8: Regression plot for AC 5 only including crashes with severity 1 and 2.

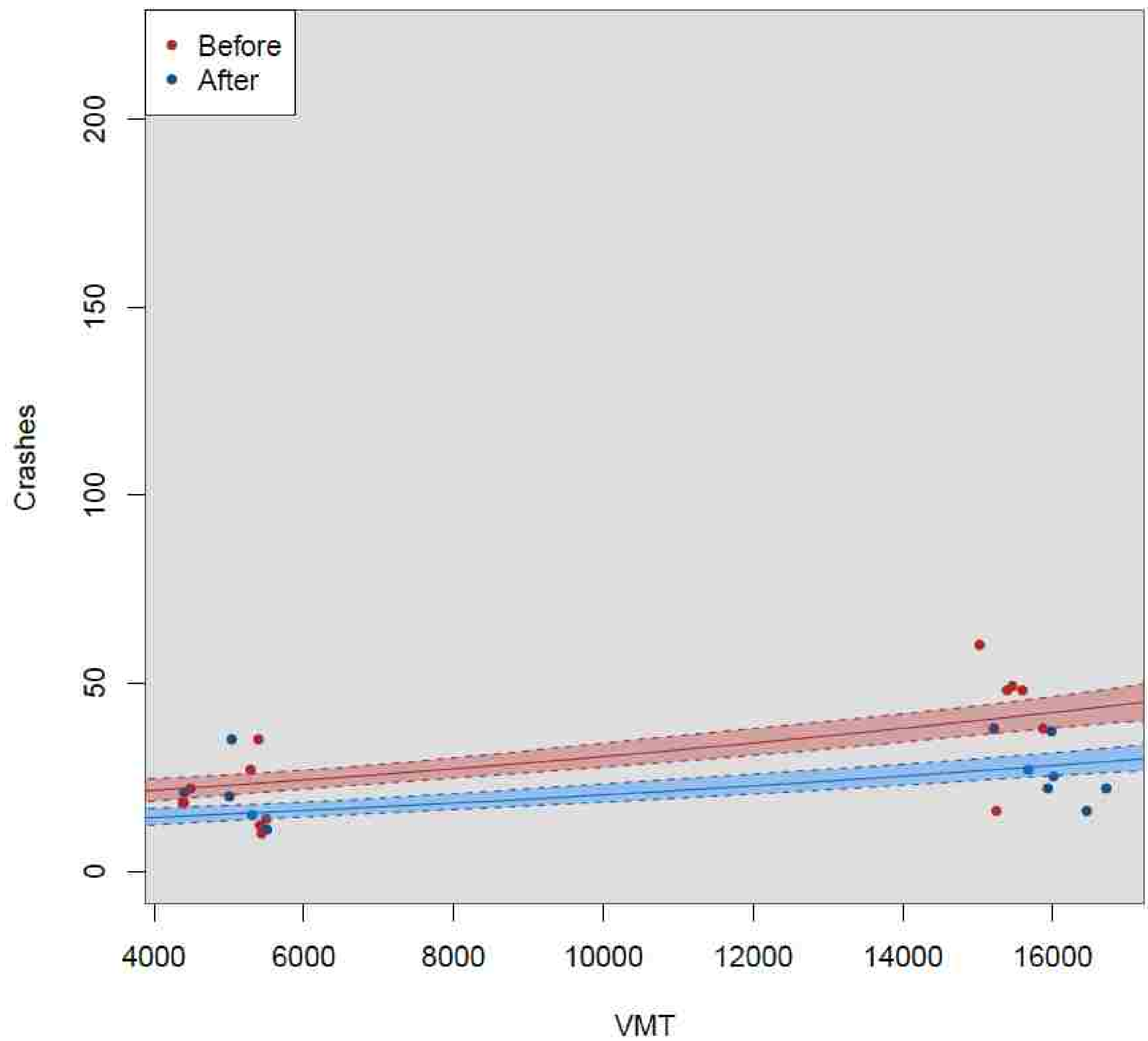

Figure C-9: Regression plot for AC 6 only including crashes with severity 1 and 2.

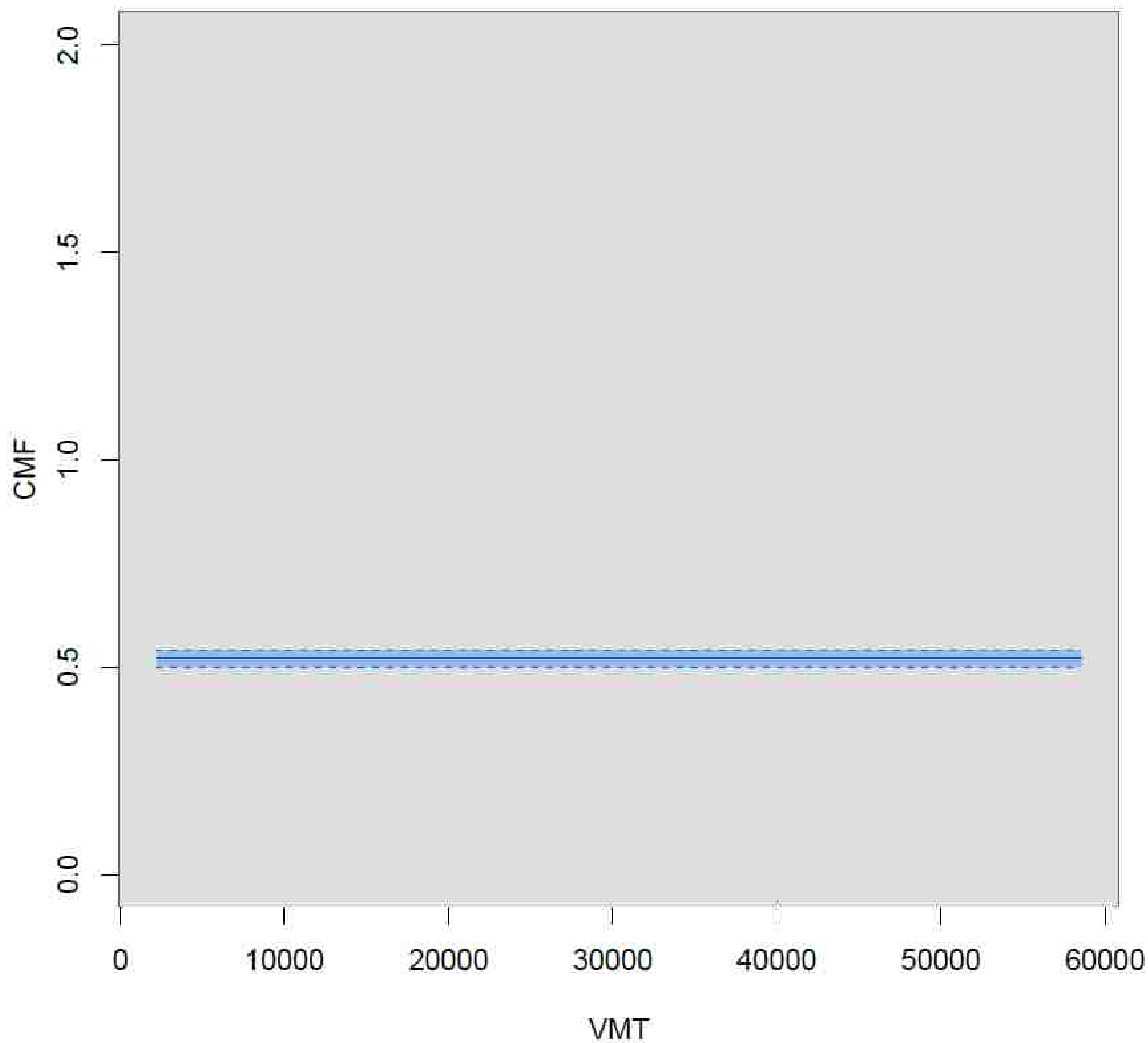

Figure C-10: Plot of CMF values for any given VMT for all AC, only including crashes with severity 1 and 2.

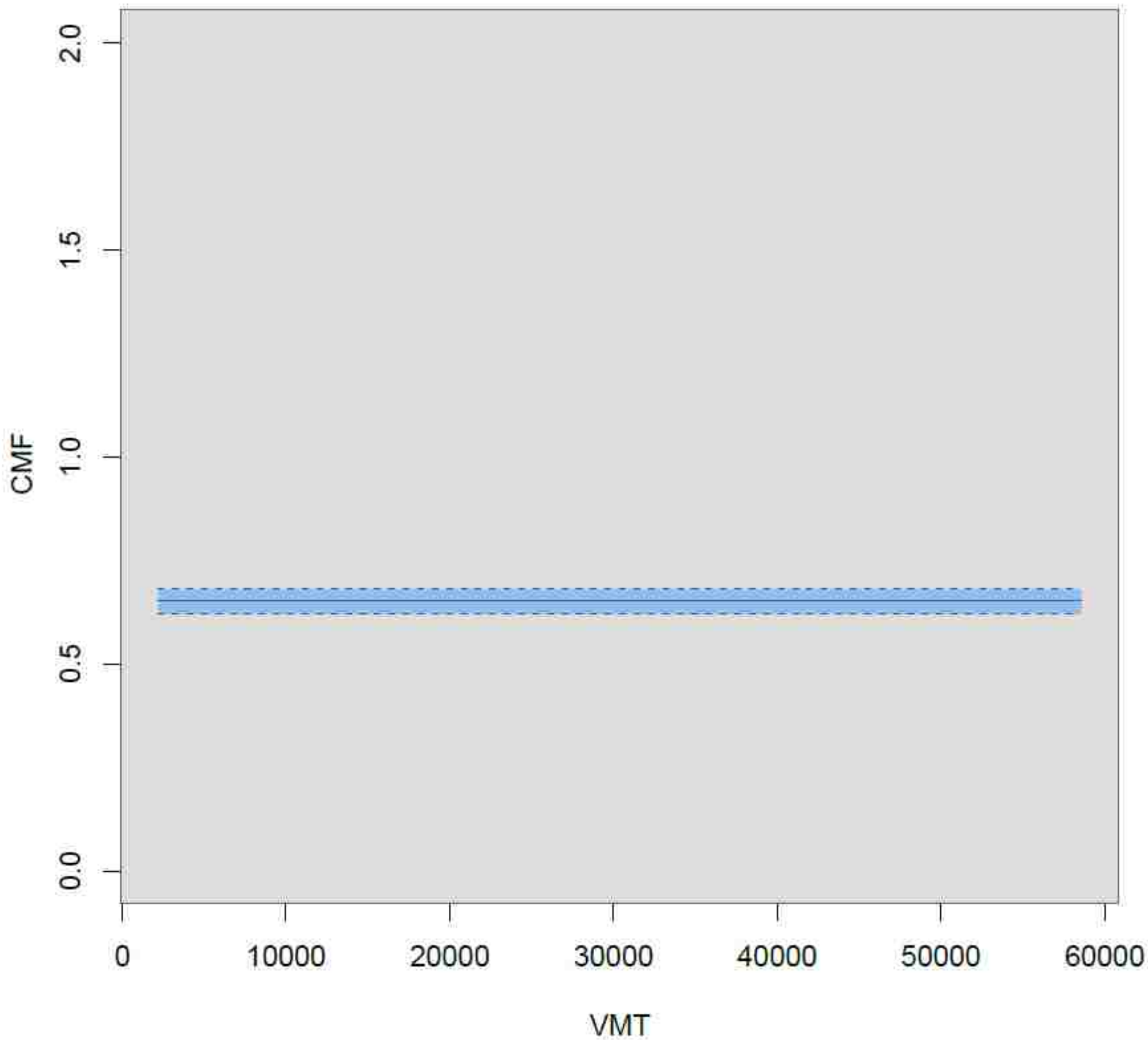

Figure C-11: Plot of CMF values for any given VMT for AC 5, only including crashes with severity 1 and 2.

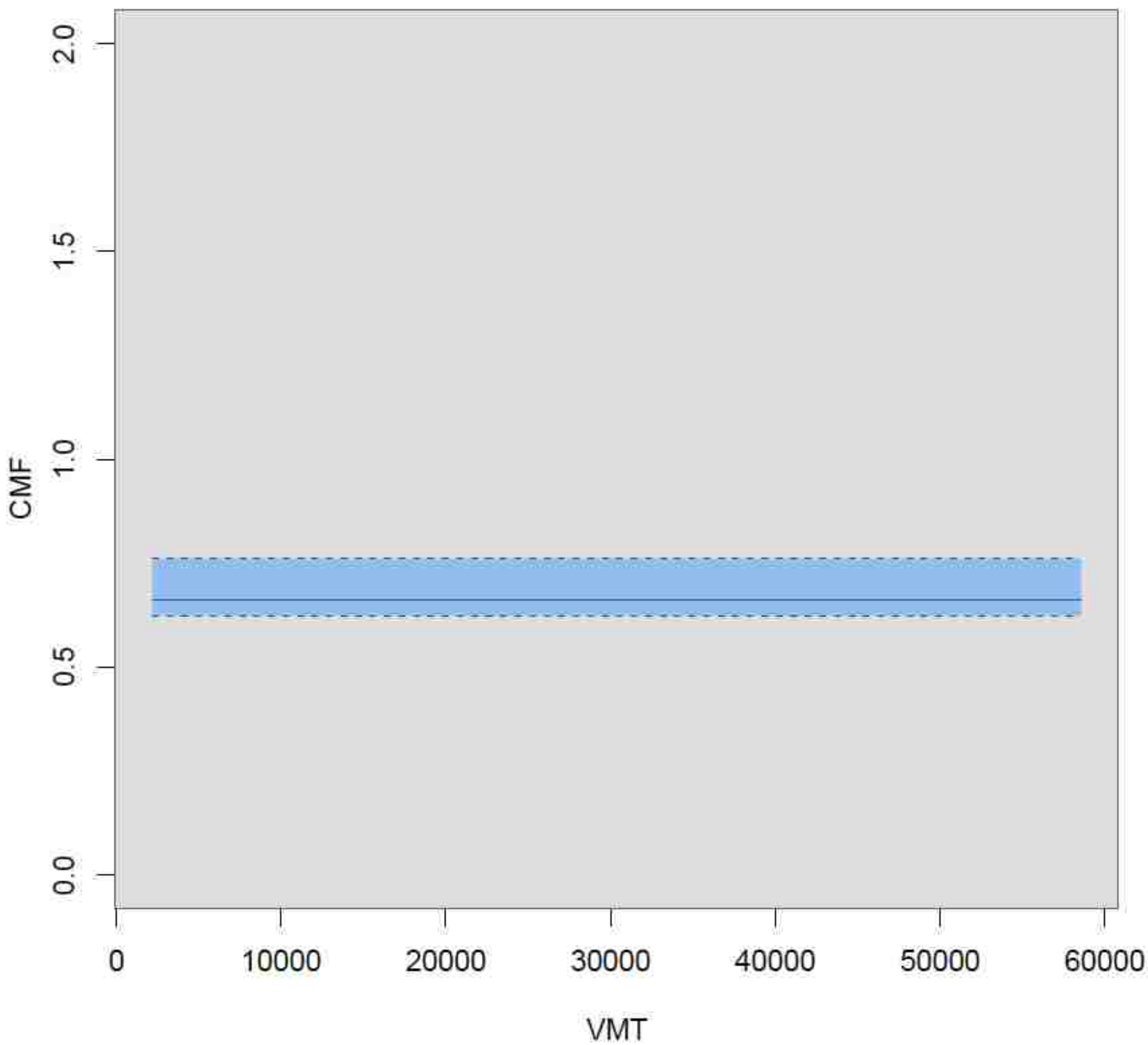

Figure C-12: Plot of CMF values for any given VMT for AC 6, only including crashes with severity 1 and 2.

C.2.2.2 Crash Severity 1, 2, and 3

Only crashes with a severity of 1, 2, and 3 were included in the before-after model. Figure C-13, Figure C-14, and Figure C-15, which coincide with all AC, only AC 5 segments, and only AC 6 segments, show, with a 95 percent confidence, that a raised median decreases crashes after installation 100 percent of the time. Figure C-16 through Figure C-18 show the CMF plots for each AC.

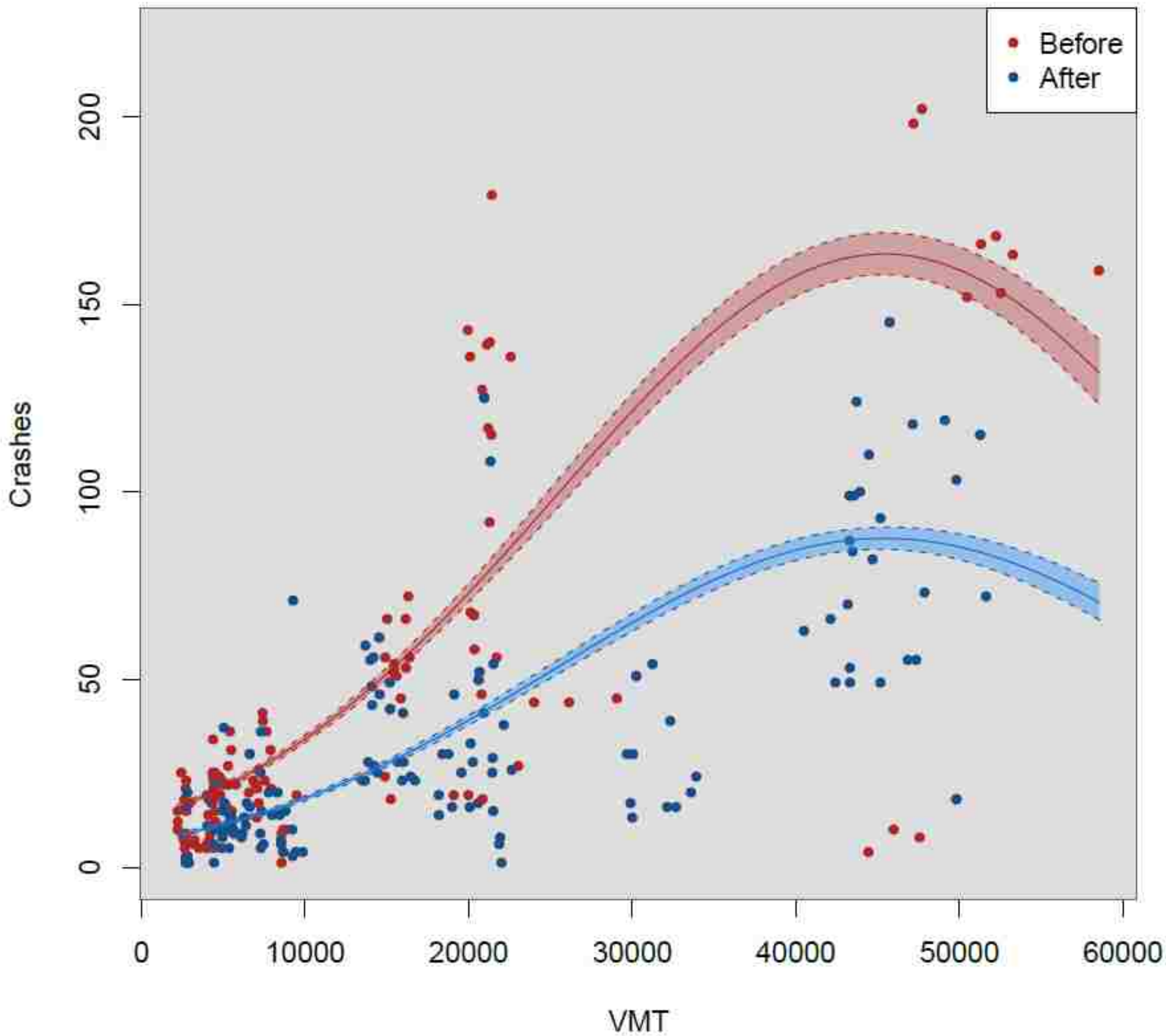

Figure C-13: Regression plot for all AC only including crashes with severity 1, 2, and 3.

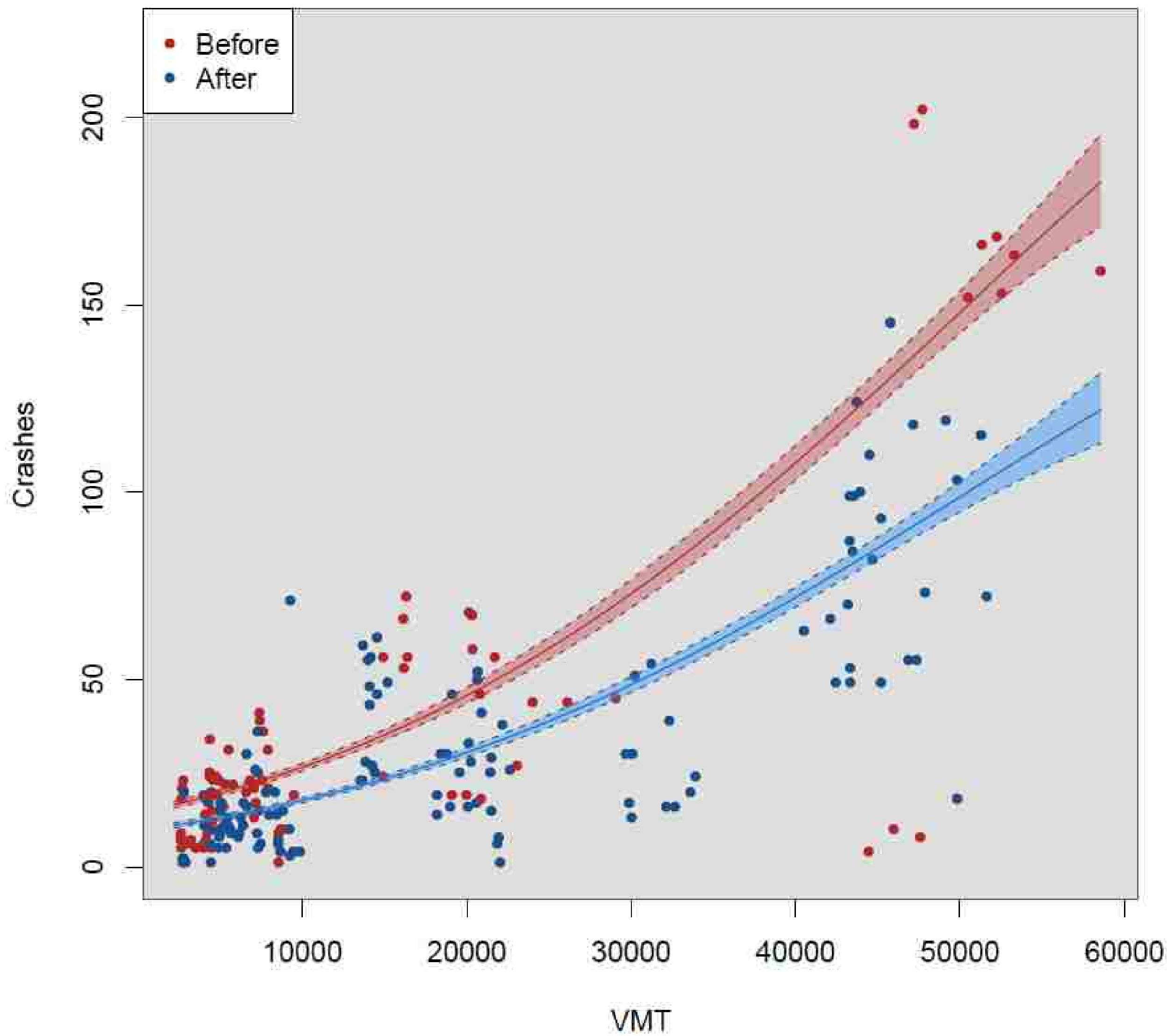

Figure C-14: Regression plot for AC 5 only including crashes with severity 1, 2, and 3.

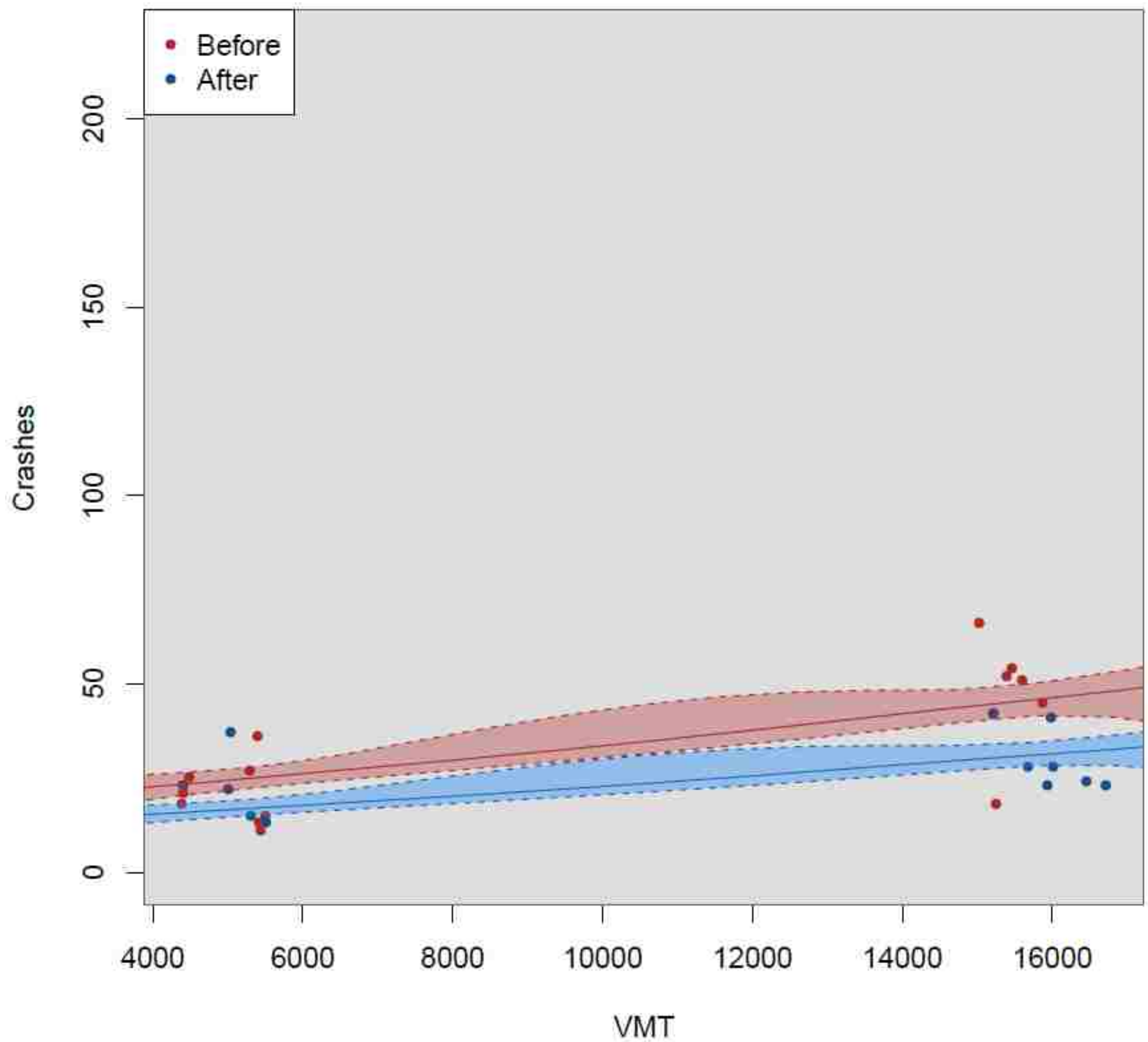

Figure C-15: Regression plot for AC 6 only including crashes with severity 1, 2, and 3.

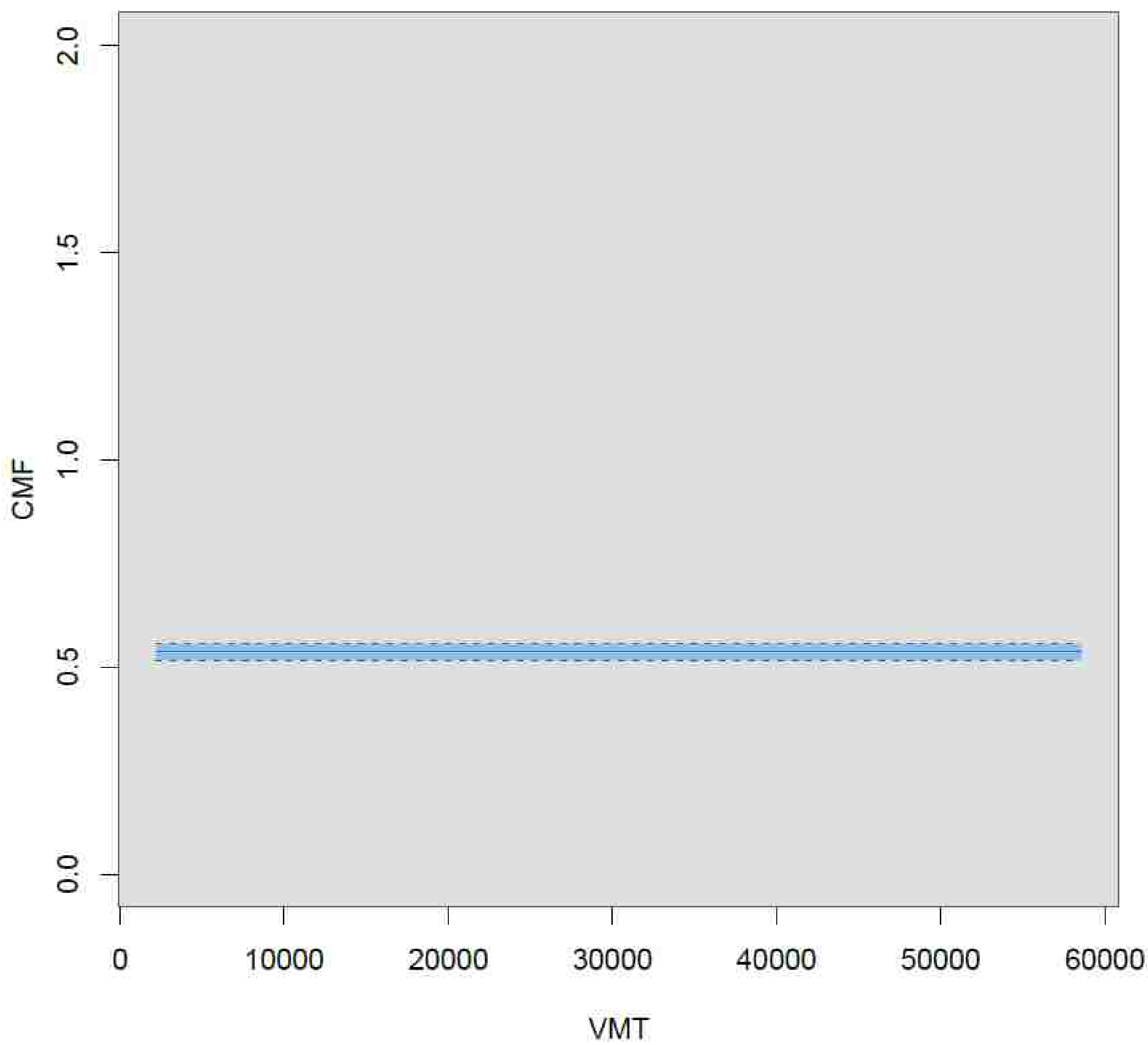

Figure C-16: Plot of CMF values for any given VMT for all AC, only including crashes with severity 1, 2, and 3.

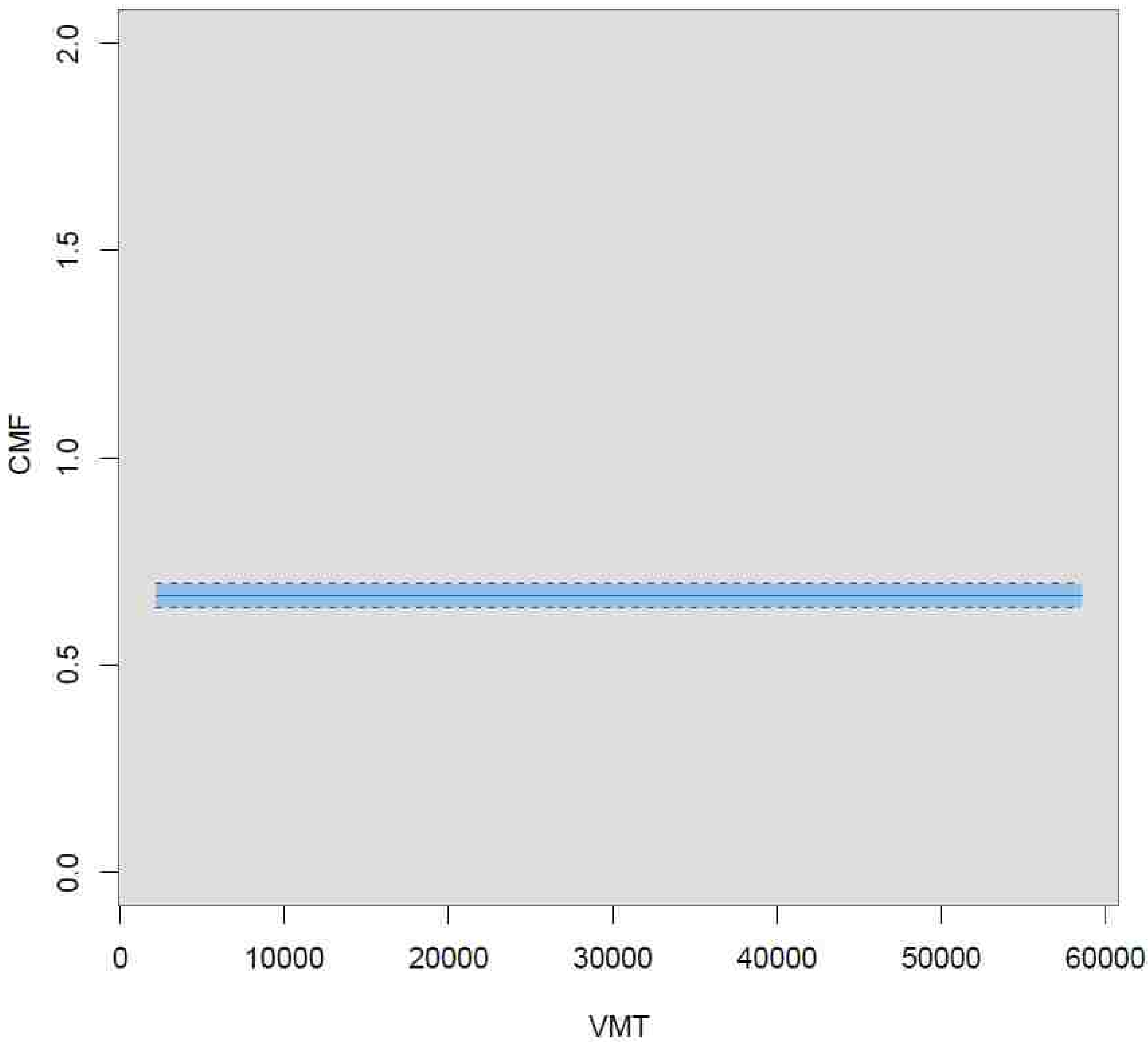

Figure C-17: Plot of CMF values for any given VMT for AC 5, only including crashes with severity 1, 2, and 3.

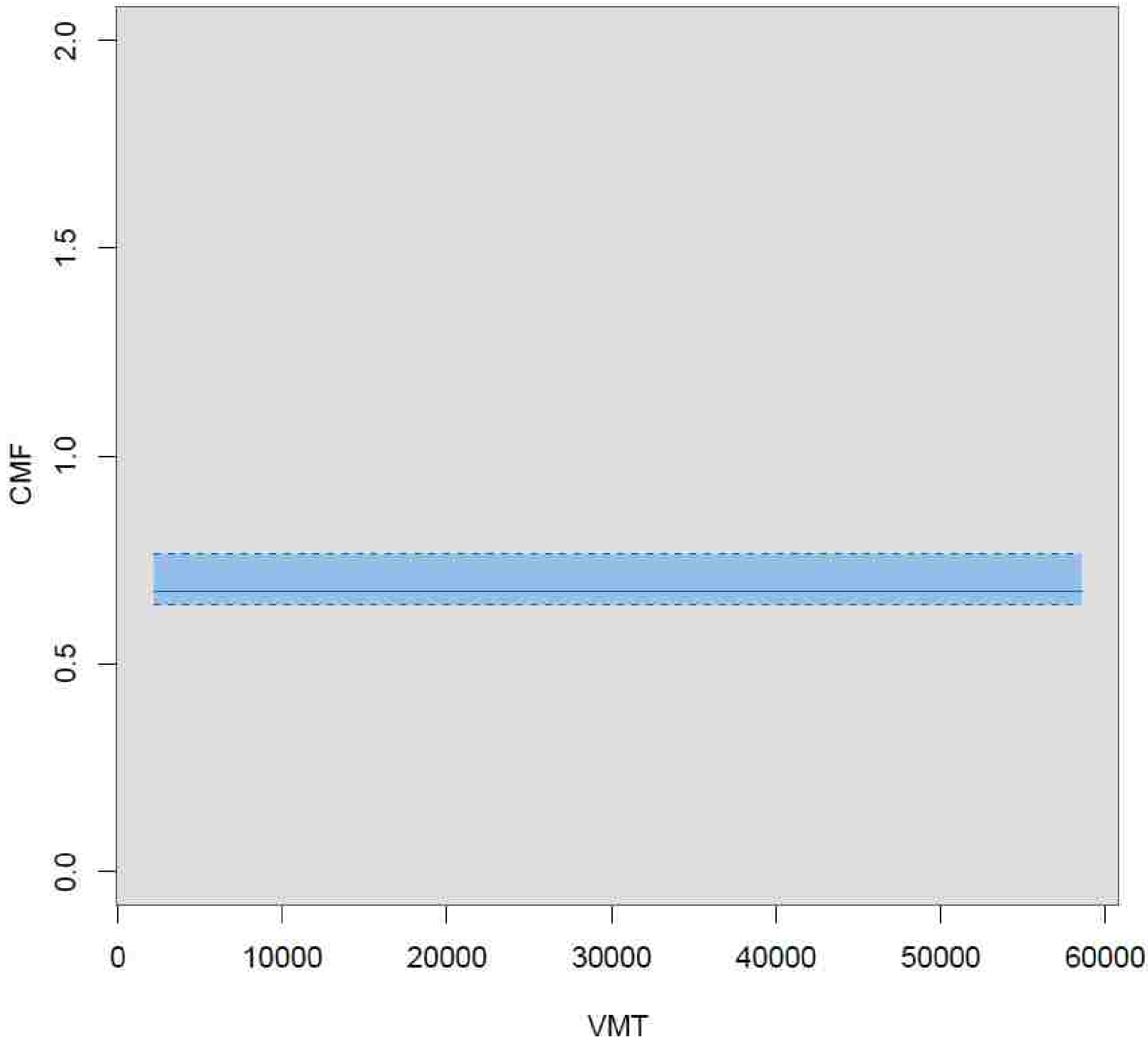

Figure C-18: Plot of CMF values for any given VMT for AC 6, only including crashes with severity 1, 2, and 3.

C.2.2.3 Crash Severity 3, 4, and 5

Only crashes with a severity of 3, 4, and 5 were included in the before-after model. Figure C-19 and Figure C-20, which coincide with all AC and only AC 5 segments, show, with a 95 percent confidence, that a raised median decreases crashes after installation 100 percent of the time. No conclusions can be drawn from the analyzing only the AC 6 segments since the 95 percent confidence intervals overlap for all VMT values. This regression plot is shown in Figure C-21. Figure C-22 through Figure C-24 show the CMF plots for each AC.

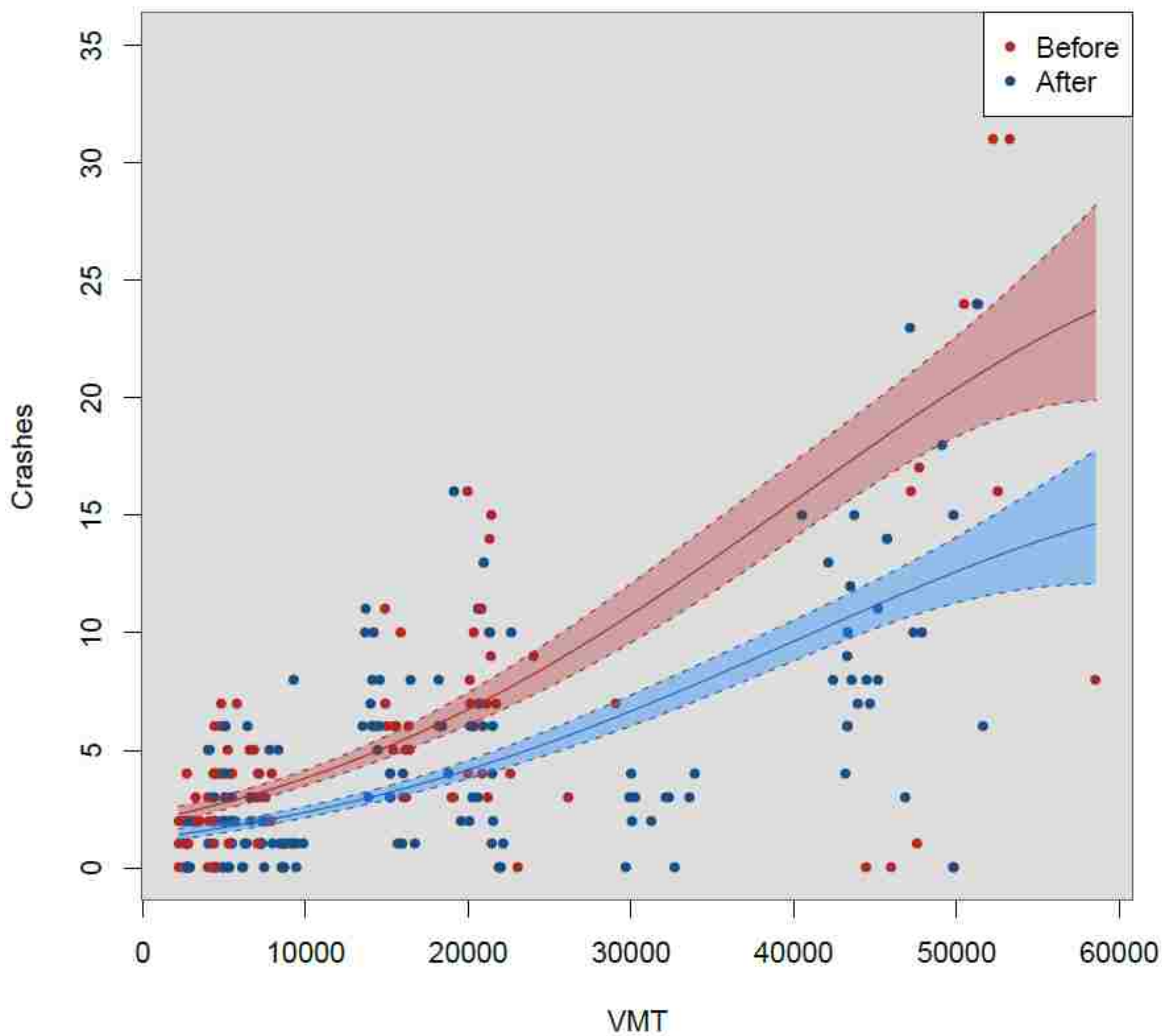

Figure C-19: Regression plot for all AC only including crashes with severity 3, 4, and 5.

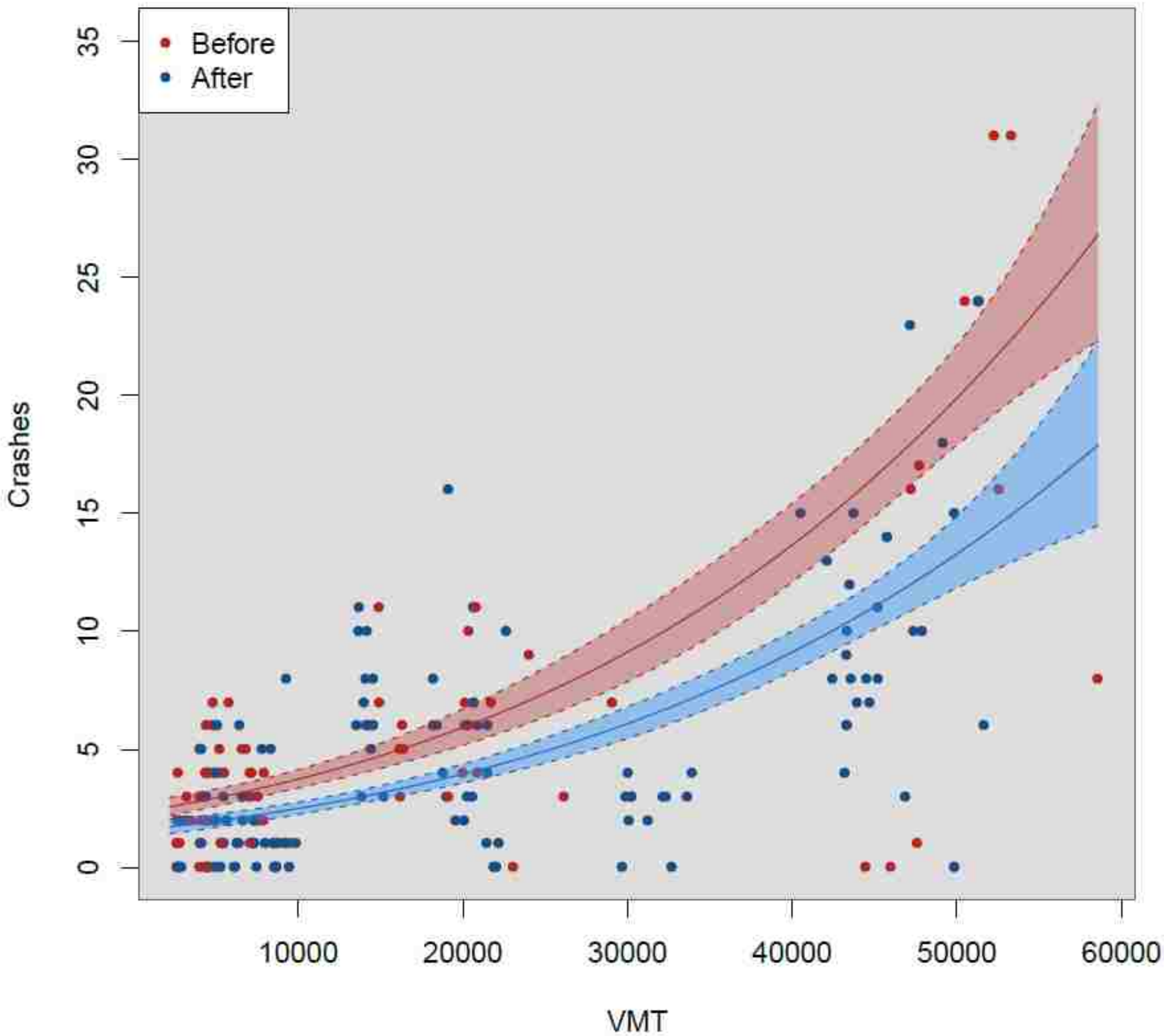

Figure C-20: Regression plot for AC 5 only including crashes with severity 3, 4, and 5.

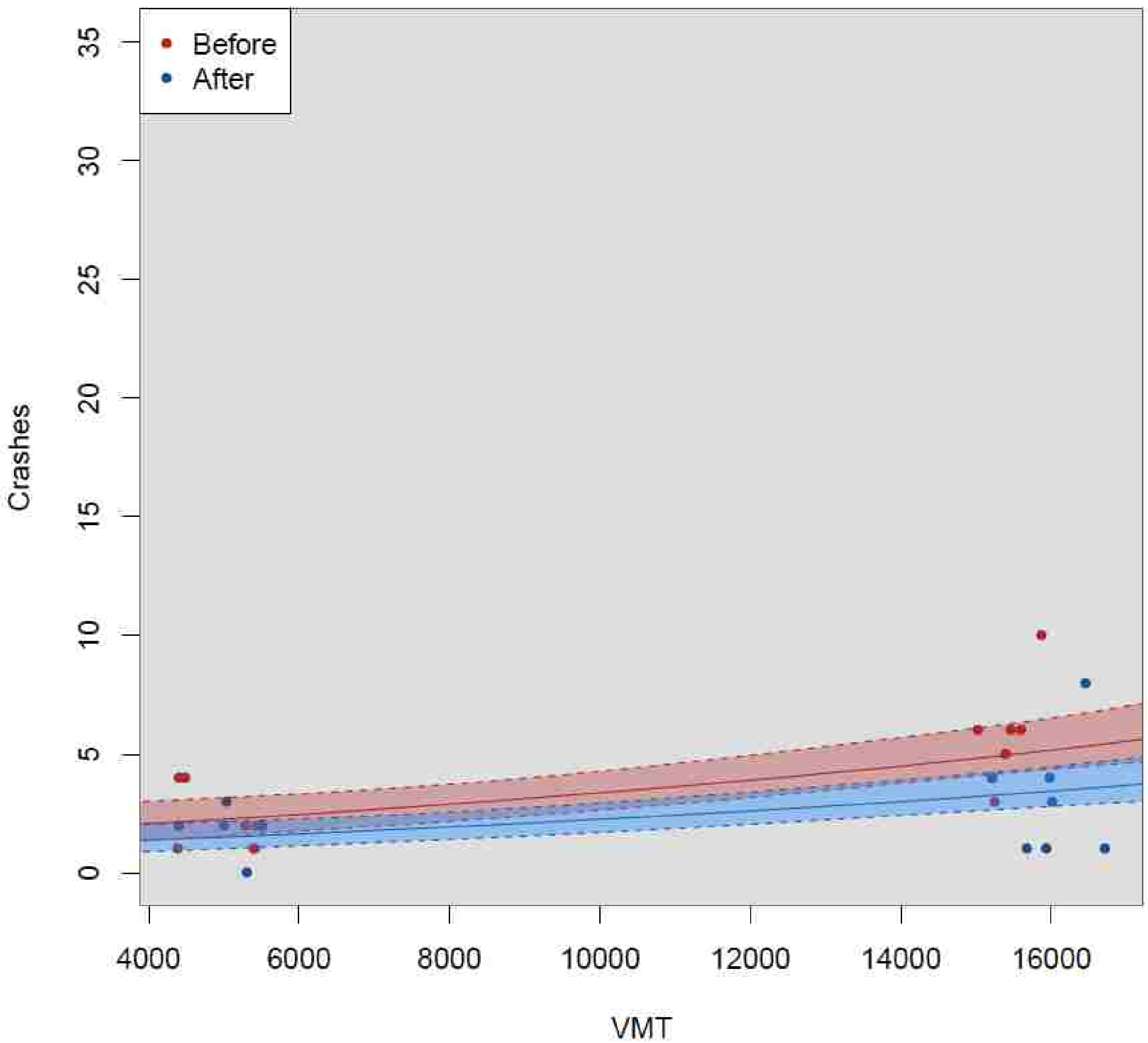

Figure C-21: Regression plot for AC 6 only including crashes with severity 3, 4, and 5.

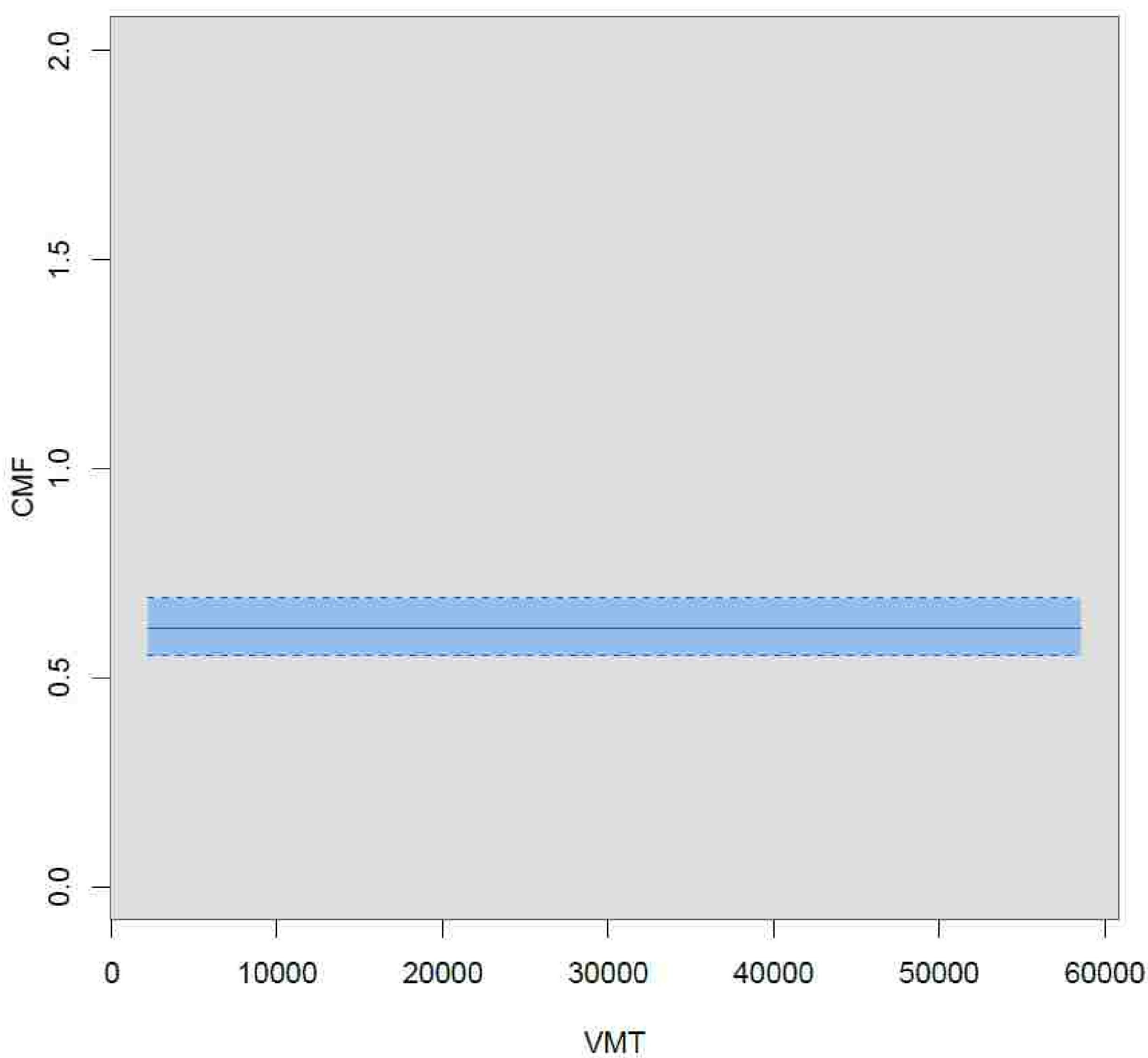

Figure C-22: Plot of CMF values for any given VMT for all AC, only including crashes with severity 3, 4, and 5.

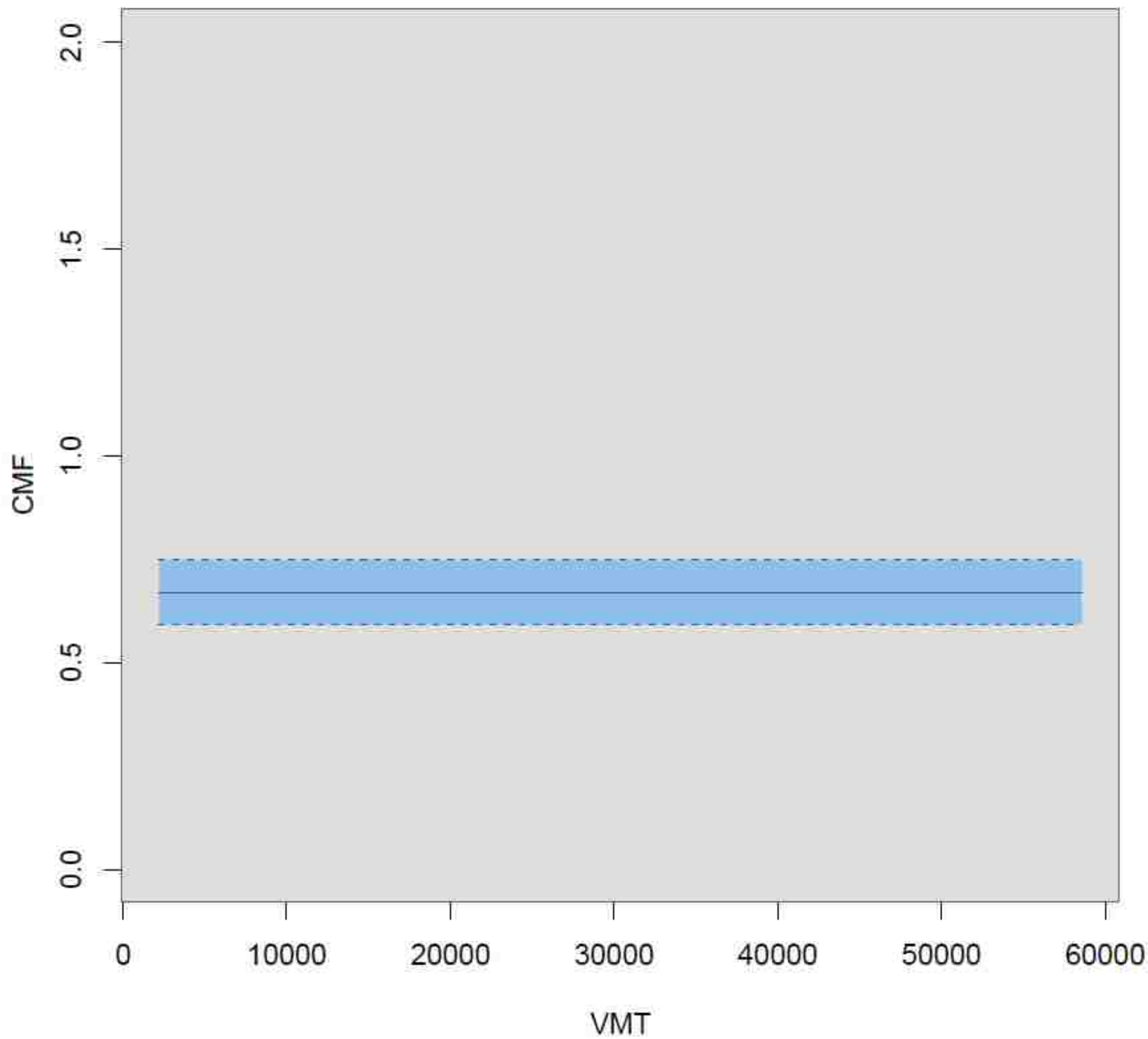

Figure C-23: Plot of CMF values for any given VMT for AC 5, only including crashes with severity 3, 4, and 5.

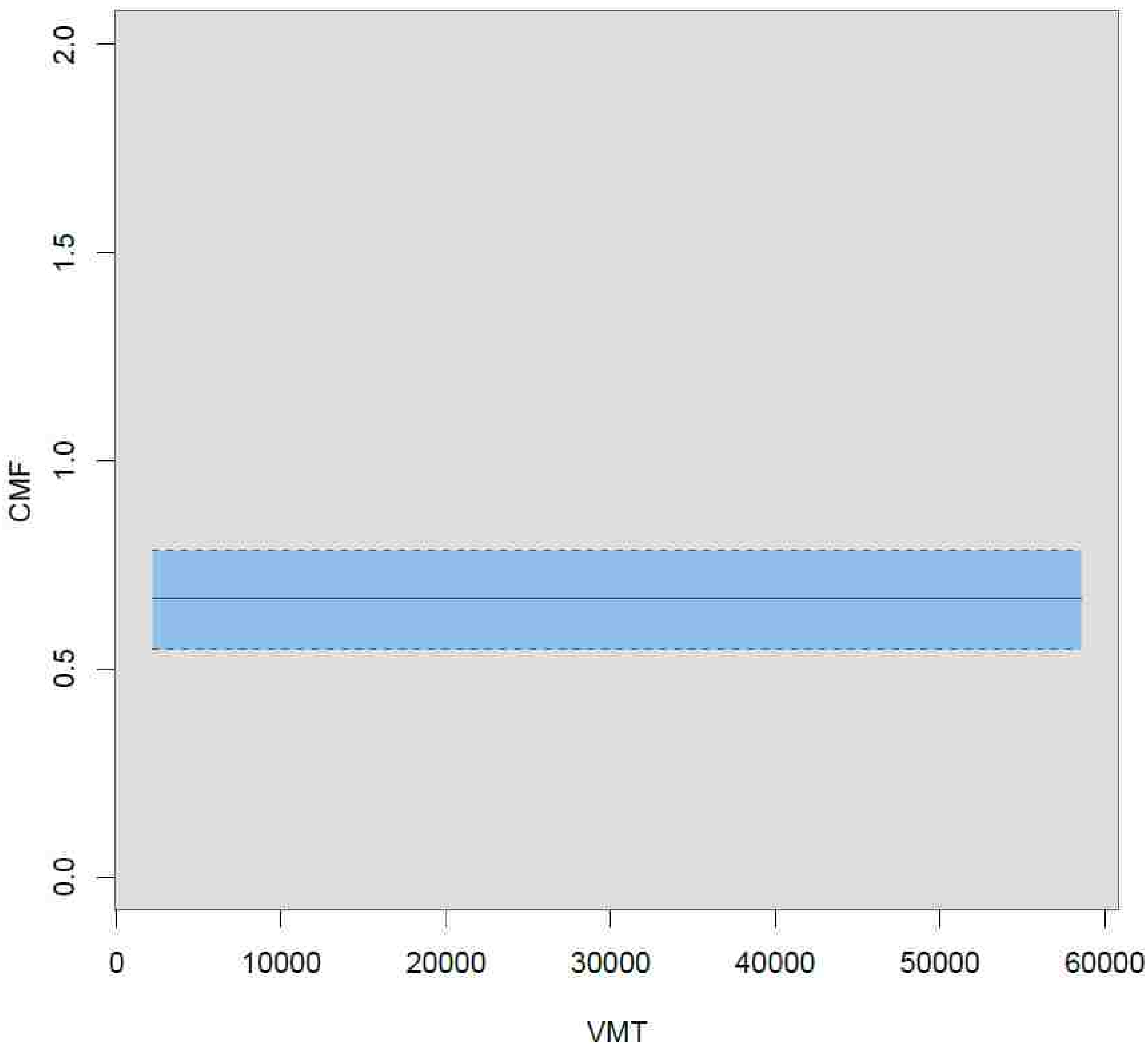

Figure C-24: Plot of CMF values for any given VMT for AC 6, only including crashes with severity 3, 4, and 5.

C.2.2.4 Crash Severity 4 and 5

Only crashes with a severity of 4 and 5 were included in the before-after model. Figure C-25 and Figure C-26, which coincide with all AC and only AC 5 segments, show, with a 95 percent confidence, that a raised median decreases crashes after installation 100 percent of the time. Conclusions can be drawn from the analyzing only the AC 6 segments since the 95 percent confidence intervals, from 8,000 and 18,000 VMT do not overlap. This regression plot is shown in Figure C-27. Figure C-28 through Figure C-30 show the CMF plots for each AC.

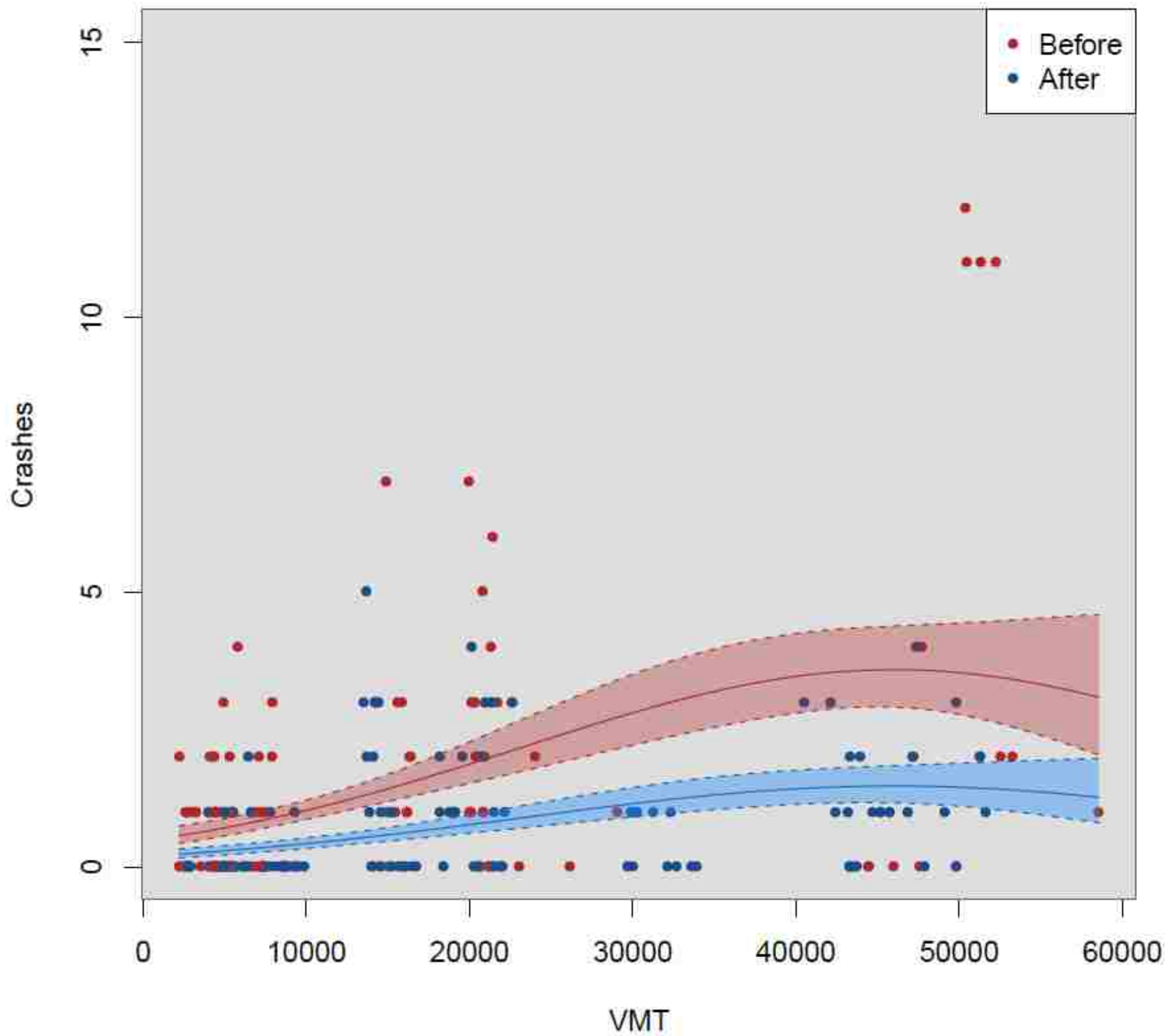

Figure C-25: Regression plot for all AC only including crashes with severity 4 and 5.

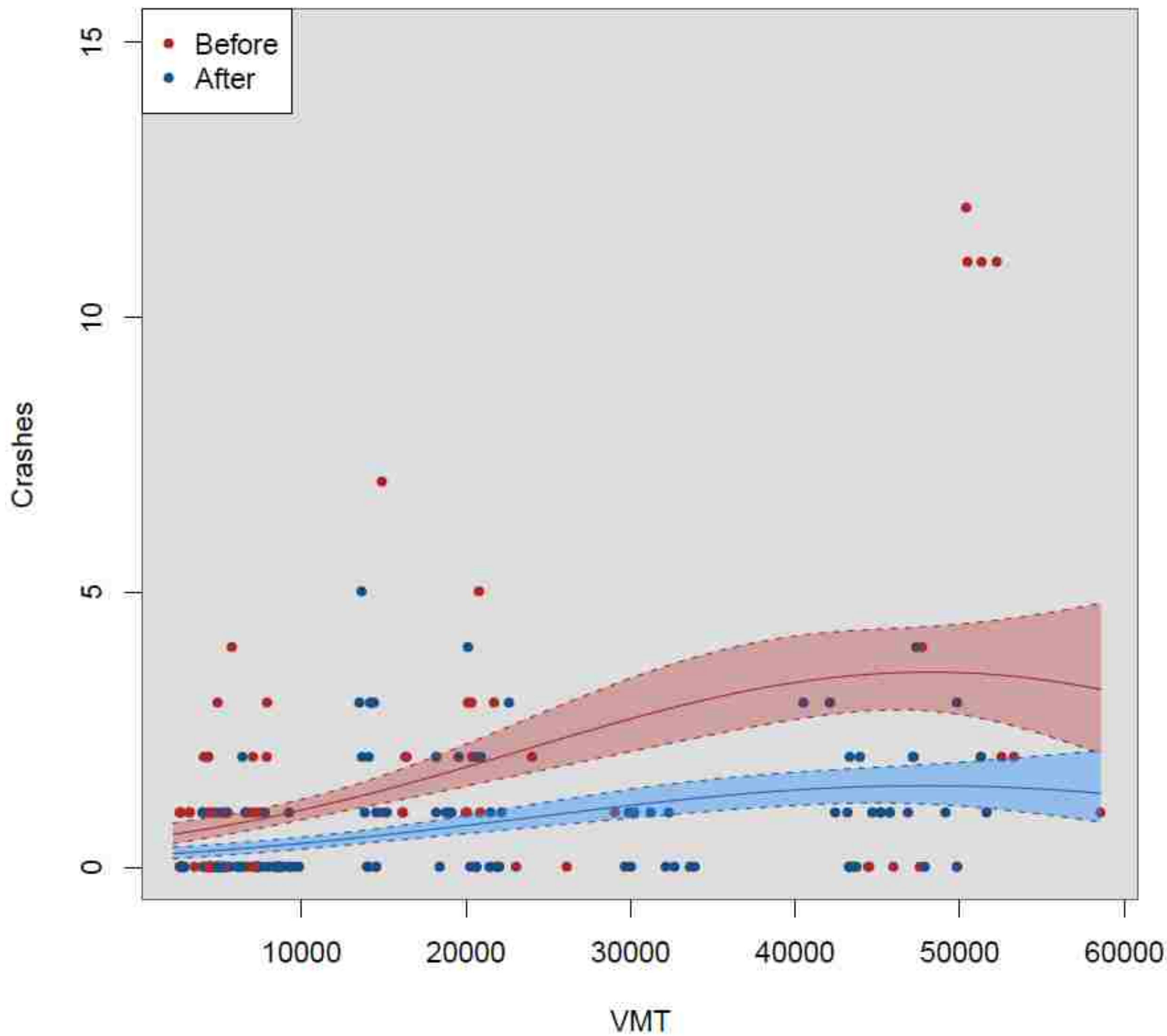

Figure C-26: Regression plot for AC 5 only including crashes with severity 4 and 5.

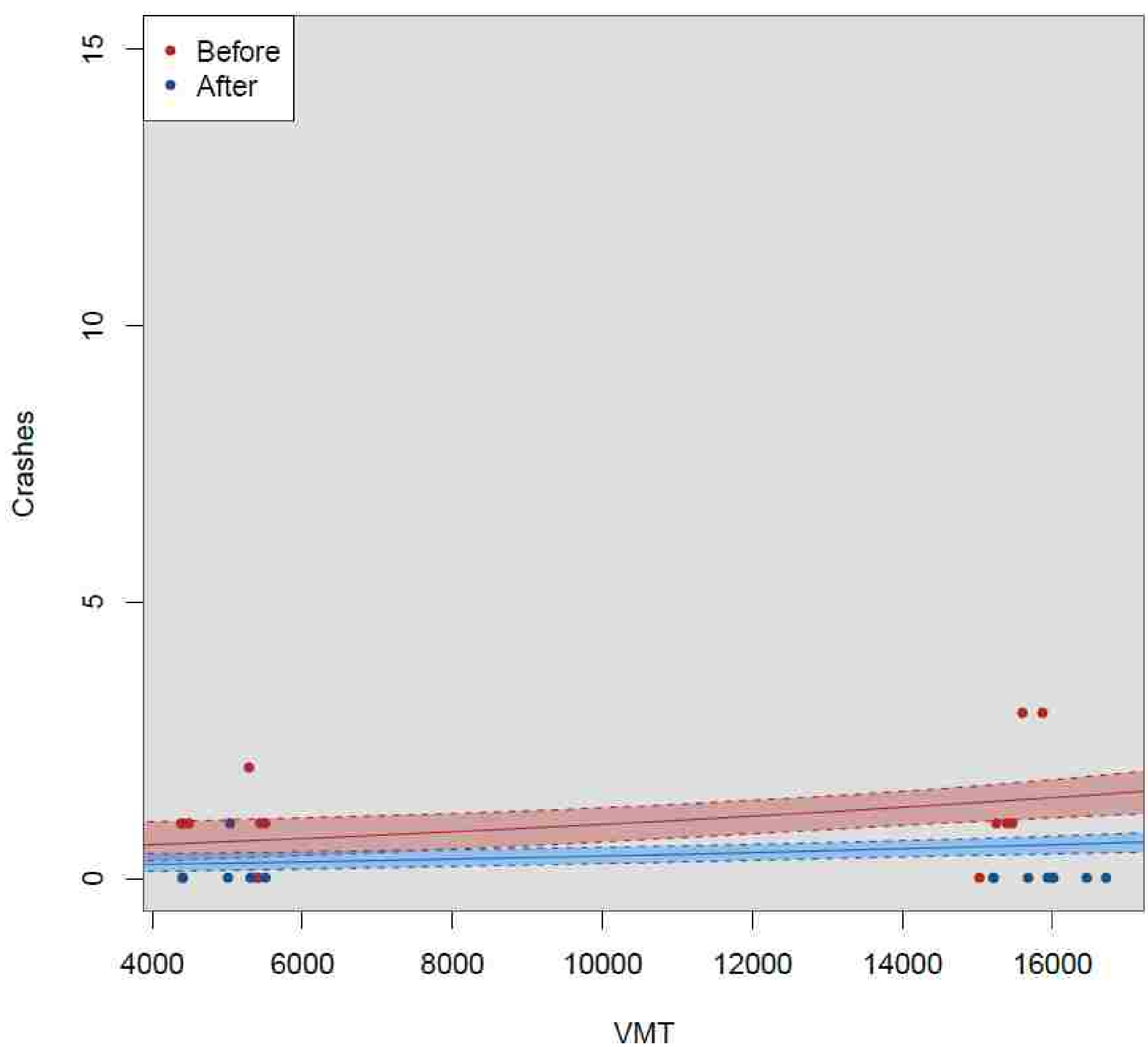

Figure C-27: Regression plot for AC 6 only including crashes with severity 4 and 5.

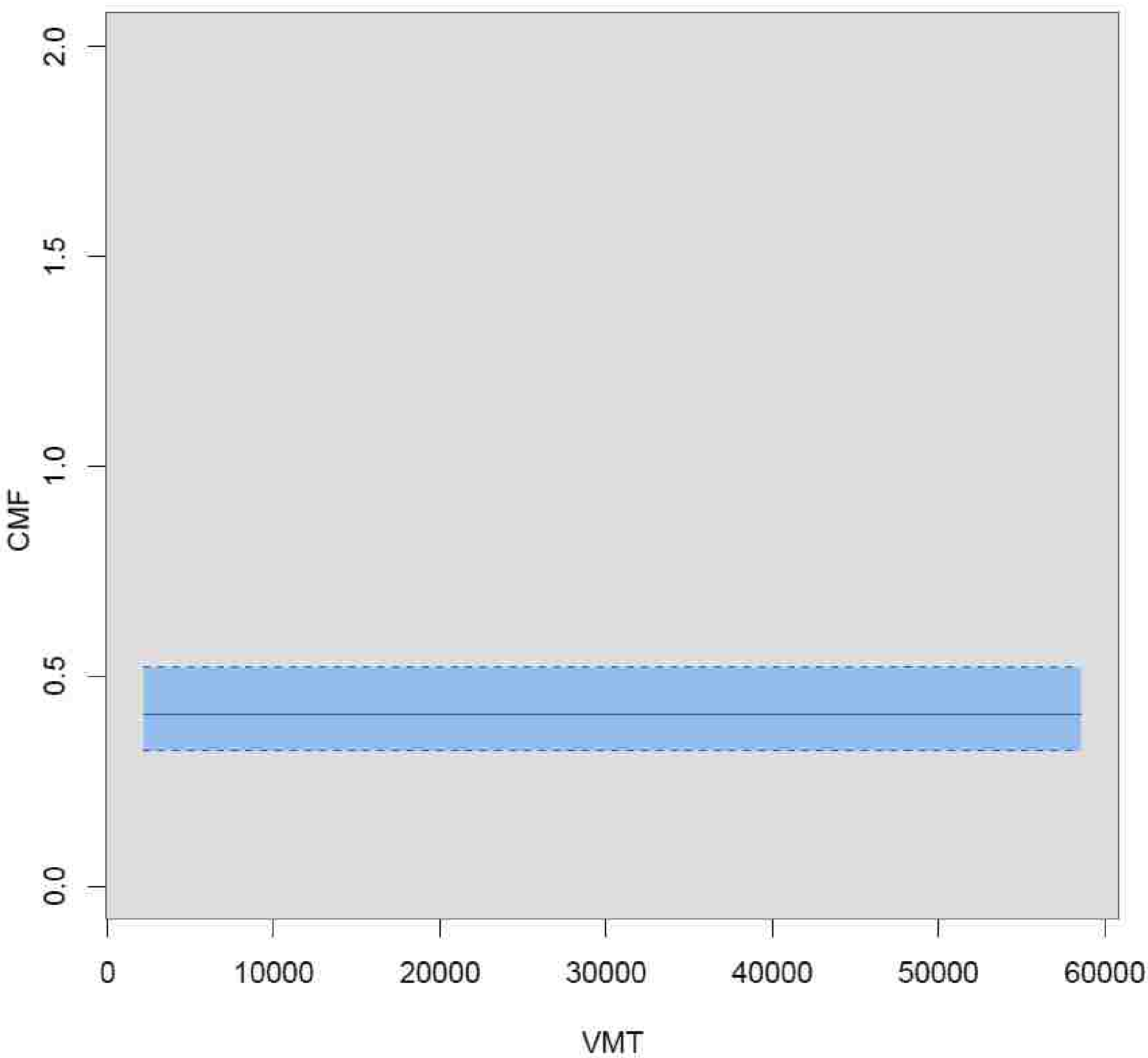

Figure C-28: Plot of CMF values for any given VMT for all AC, only including crashes with severity 4 and 5.

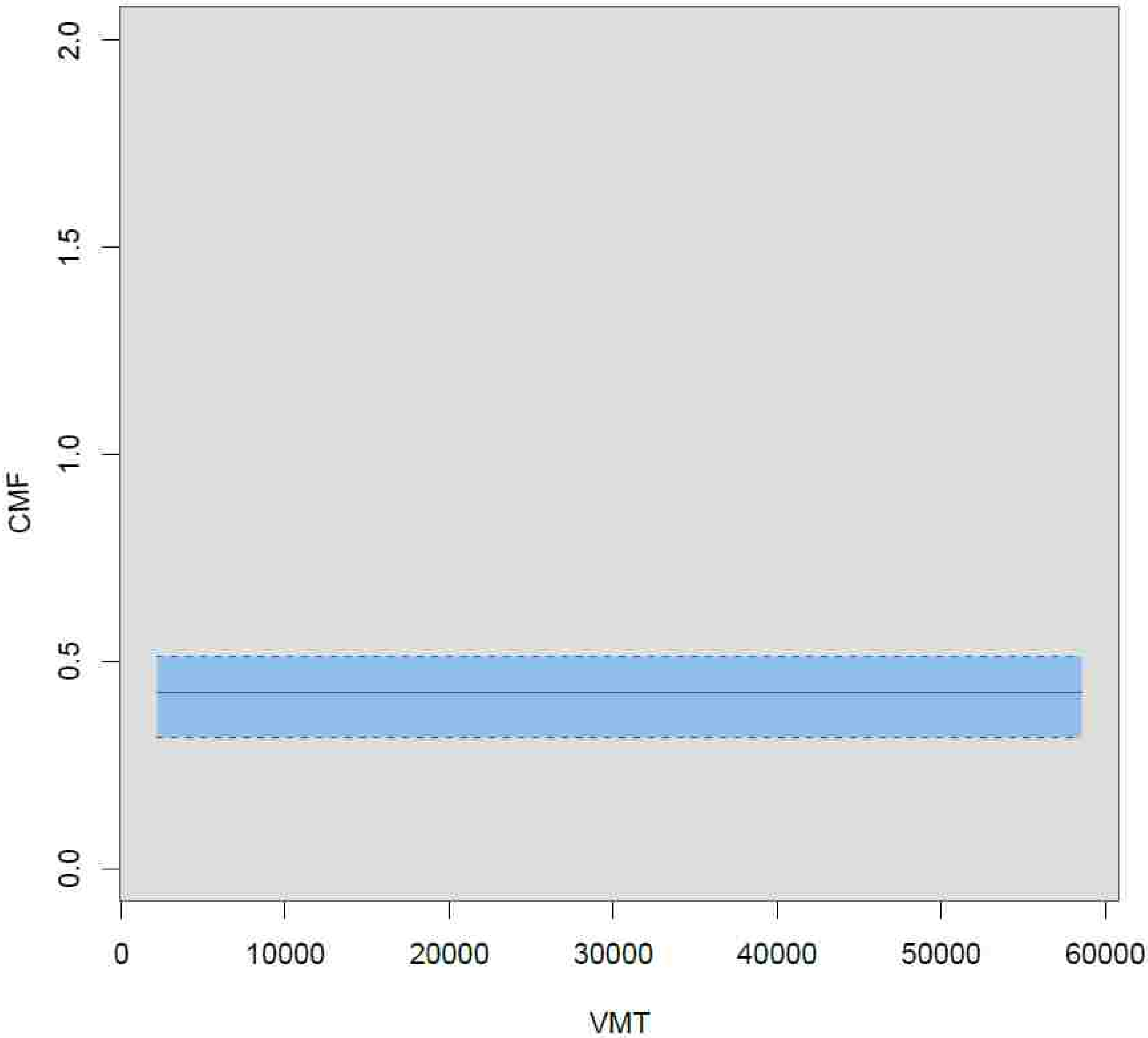

Figure C-29: Plot of CMF values for any given VMT for AC 5, only including crashes with severity 4 and 5.

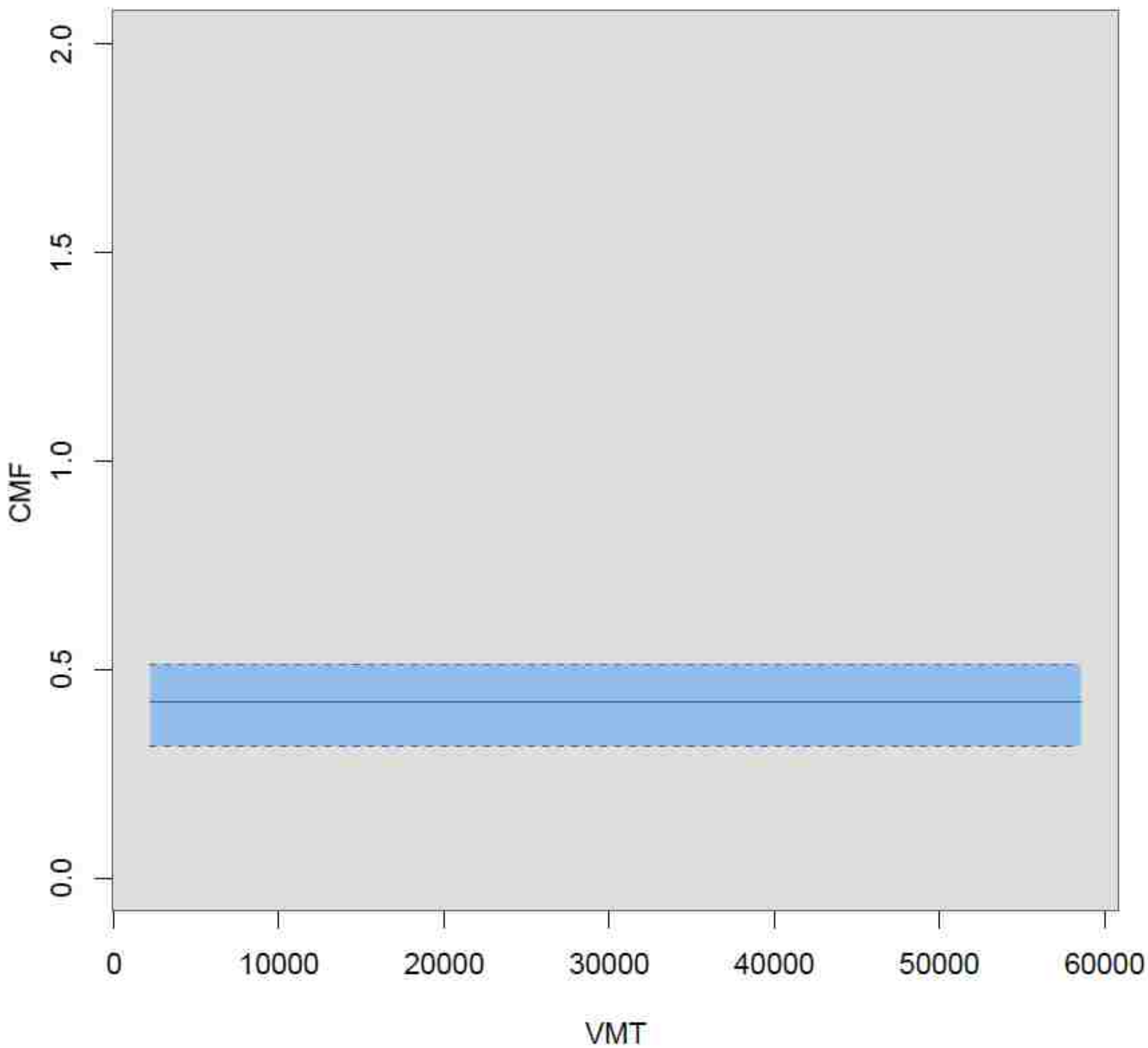

Figure C-30: Plot of CMF values for any given VMT for AC 6, only including crashes with severity 4 and 5.