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Examining the safety performance of urban/suburban arterials and freeway segments in consideration of roadway geometry and traffic control

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Examining the safety performance of urban/suburban arterials and freeway segments in consideration of roadway geometry and traffic control

by

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ABSTRACT

With the sprawling of major cities and creation of suburban areas, one problem that state agencies face is the increasing congestion in suburban arterials coupled with the safety risks posed by increasing traffic volumes at traditional intersections along arterials. In the early 1960s, a new intersection design was developed and installed in the state of Michigan, where left turns at intersections were replaced by median U-turn lanes (MUTs). This study focuses on the safety performance of corridors where median U-turns (MUTs) are present along urban and suburban boulevards. The analysis is performed in two stages; first models were developed separately for assessing the safety performance, through the examination of crash frequency and type, across individual MUTs, at intersections, and along segments on which MUTs are located. Subsequently, an aggregate-level analysis is conducted to assess the safety performance of specific intersections/MUT combinations. The second stage focused on developing models for examination of sites spanning each side of an intersection including upstream and downstream MUTs. These sites were compared to sample sites with allowed traditional left turn movements. Ultimately, the results provide guidance to agencies considering the installation of such alternative intersections.

Additionally, safety risks are present during work zone projects along freeways, which are essential facilities for providing mobility. The presence of a work zone generally results in both mobility and safety impacts to road users. Minimizing the adverse impacts associated with work zones has become a priority for road agencies. This study will estimate SPFs that consider freeway geometry and traffic conditions, as well as the effects of various temporary traffic control strategies such as lane shifts, shoulder closures, and lane closures. Crash modification factors were

developed for work zone duration and length. Additionally, the study results provide insight on the safety impacts associated with each of the four types of lane closures.

CHAPTER 1. INTRODUCTION

1.1 Statement of Problem

Although there had been a steady decline in traffic fatalities in the United States since 1996, the first half of last year saw the largest increase of about 10 percent in traffic fatalities in two decades (NHTSA, 2016). Extensive initiatives have been implemented at a national level, including mandates driven by recent transportation legislation. These efforts have led to agencies taking a more proactive approach to highway safety at all stages of transportation projects. States have implemented Highway Safety Improvement Programs (HSIPs) that are data-driven and aim toward continuing reductions in the frequency and severity of crashes. To this end, there has been extensive research focused on exploring those factors that affect the frequency and severity of crashes on various roadway facilities. Determining these relationships between various roadway, traffic, and behavioral factors with crash frequency and severity will allow transportation agencies to make more well-informed decisions in site prioritization and countermeasure selection, leading to more effective utilization of limited transportation funding.

Various research studies have helped to establish relationships between crashes and important explanatory variables such as traffic volumes, roadway geometry, and environmental characteristics. National guidance as to analysis methods that are appropriate for transportation safety are provided in the Highway Safety Manual (HSM), the first edition of which was published by the American Association of State Highway and Transportation Officials (AASHTO, 2010). Part C of the HSM presents a series of predictive models that can be utilized by state agencies to predict crash frequency for various roadway facilities, such as intersections and roadway segments, as a function of traffic volumes, roadway geometry, type of traffic control, and other factors. These crash prediction models, also known as safety performance functions (SPFs), can be utilized to estimate the safety impacts of site-specific design alternatives or to prioritize candidate locations for safety improvements on a network basis. As part of this process, these SPFs can also be integrated with decision support tools, such as *SafetyAnalyst* and the *Interactive Highway Safety Design Model* (*IHSDM*) (AASHTO, 2010).

The first edition of the *HSM* includes separate families of SPFs for three specific facility types: (1) Rural Two-Lane, Two-Way Roads (TWTL); (2) Rural Multilane Highways; and (3) Urban and Suburban Arterials. Chapters 10, 11, and 12 of the *HSM* provide full details of the SPFs for these respective facility types, which were developed based upon the results of empirical studies (Harwood et al. 2000; Vogt, 1999; Vogt and Bared, 1998; Lord et al. 2008; Harwood et al., 2007; Harwood et al., 2008). Subsequent research that will be integrated into the second edition of the *HSM* has analyzed other facility types, which include freeways and interchanges (Bonneson et al, 2012), as well as six-lane and one-way urban and suburban arterials (NCHRP 17-58, 2016).

While the SPFs presented in the *HSM* provide useful tools for road agencies, it is recommended that these functions are either calibrated for local conditions or re-estimated using local data to improve their accuracy and precision (AASHTO, 2010). A variety of states have conducted research that has shown the accuracy of the SPFs from the *HSM* to vary considerably from state to state as a result of differences in geography, design practices, driver behavior, differences in crash reporting requirements, and other factors. (Garber et al, 2010; Tegge et al, 2010; Dixon et al, 2012; Srinivasan and Carter, 2011; Brimley et al. 2012; Bornheimer et al. 2012; Lu et al. 2012; Lubliner and Schrock, 2012; Srinivasan et al. 2011; Alluri and Ogle, 2012). The variation in the performance of SPFs across jurisdictions creates the need for jurisdiction-specific SPFs, which allow transportation agencies to more efficiently invest available safety resources.

1.2 Research Objectives

Beyond providing analytical tools to assist transportation agencies in proactive decision-making, there remain a number of important safety-related issues related to design, operations, and maintenance that are under researched. Ultimately, the results of this research will provide important insights of practical value to transportation agencies and safety researchers based on the results of two studies, the objectives of which are briefly detailed here:

1. First, jurisdiction-specific SPFs are estimated to identify factors that are determinants of crash frequency and crash type for urban and suburban divided roadways using data from the state of Michigan. This study focuses on the safety performance of corridors where median U-turns (MUTs) are present along urban and suburban boulevards. Crash, traffic, and roadway geometry information were utilized to develop crash prediction models. First, separate models were estimated to examine how the presence of MUTs affects the safety performance: (a) across individual MUTs; (2) at intersections near the MUTs; and (3) along the overall segments on which the MUTs are located. This initial disaggregate-level analysis examines the frequency and type of crashes at each facility type. Subsequently, an aggregate-level analysis is conducted to assess the safety performance of specific intersections/MUT combinations. For this second analysis, the sites examined included the portions of individual road segments spanning each side of the associated intersection, including the upstream and downstream MUTs. A sample of sites with MUTs installed was compared to a sample of sites where traditional left-turn movements were allowed. Ultimately, the results provide guidance to agencies considering the installation of such alternative intersections.

2. The second study examines how crash frequency is affected by various lane closures that are commonly implemented in freeway work zones, again focusing on data from Michigan. The research examines temporary traffic control strategies in long-term freeway work zones. To this end, 790 work zone locations occurring on freeways between 2008 and 2013 were examined. These work zones were in place for a minimum duration of three days and cover a length of at least 0.4 miles. The types of work zones considered include shoulder closures, single-lane closures, multi-lane closures, and lane shifts. This study provides important information regarding the safety implications that each of these temporary traffic control strategies introduce.

1.3 Organization of Dissertation

This dissertation consists of five chapters. Having detailed the topics being investigated and outlined the research objectives in this chapter, the remaining chapters are focused on the following topics:

- Chapter 2 presents a summary of previous findings on operational and safety performance of Median U-Turns (MUTs), collection and processing of data from various sources, analysis framework, and finally discusses the results obtained related to the safety performance of MUTs on urban and suburban boulevard intersections and segments for the state of Michigan.
- Chapter 3 describes similar steps taken to assess the safety impacts of four types freeway work zones in the state of Michigan. The four types of work zones studied included shoulder closure, single lane closure, multi-lane closure, and lane shifts.

- Chapter 4 presents the major findings from each of the previous three chapters, lists any limitations of these studies, and provides an overview of potential future research avenues.

CHAPTER 2. SAFETY PERFORMANCE OF MEDIAN U-TURNS ON URBAN AND SUBURBAN ARTERIALS

The aim of this study is to develop a series of SPFs for urban and suburban 4-lane, 6-lane, and 8-lane divided arterials in Michigan. Urban arterials are generally designed to provide the highest level of service and speed. However, these roadways must also provide access to collector and local roads or directly to developments. This requires potential tradeoffs between mobility and safety. Consequently, it is imperative to be able to accurately predict the number of crashes that would be expected on such facilities. To this end, SPFs will be estimated to relate crashes to traffic volumes, roadway geometry and operational characteristics. In particular, the presence of median U-turns (MUTs) on urban and suburban divided roadways will be studied and its safety effects on both crash frequency and crash type will be examined.

As a part of this examination, this research also aims to provide guidance as to safety performance as it relates to a specific traffic control strategy that has been widely implemented throughout Michigan since the 1960s. This treatment, widely referred to as a “Michigan Left-Turn”, involves the prohibition of left turns, instead requiring drivers to utilize turning lanes downstream of the intersection for drivers to complete left-turn maneuvers. These turning lanes are also referred to as MUTs or crossovers. MUTs were installed to avoid interlocking left turn movements at intersections, thus improving operations and reducing delay (Reid et al, 2014). Despite having been installed as a solution for congestion problems, MUTs have also been studied for their safety effects, although these studies have been mostly at isolated intersections and/or for small samples of data. As state agencies are moving towards considering several design alternatives for improving congestion and safety problems in roadway system, there needs to be straightforward evidence of the potential benefits that these design alternatives have compared to more traditional intersections. This study will examine the impact of MUTs on crash frequency and type of urban and suburban trunklines as well as investigating the type of crashes and crash frequency in the vicinity of MUTs. The examination is done in two parts; the first part is performed at a disaggregate level, separately for the divided boulevard facilities of intersections, segments, and MUTs. This is done to account for the fact that a large part of these installed MUTs serve multiple intersections along the boulevard; e.g. a pair of MUTs will serve one major 4-leg intersection as well as additional 3-leg (most likely stop-controlled) intersections located along the boulevard. It is thus imperative to assess the performance of these MUTs for the boulevard segment crashes and intersection crashes. The second portion of the examination is performed at the aggregate level; this includes a comparison of sites that expand in length on each side of the intersection to the nearest MUT (including the MUT facility). Sites of similar length with MUTs and traditional left turns are compared in total crash frequency, as well as various crash types to assess the safety performance of MUTs in the area of the intersection and adjacent to it.

2.1 Literature Review

With the sprawling of major cities and creation of suburban areas, one problem that state agencies face is the increasing congestion in suburban arterials. Additionally, the increasing traffic volumes pose safety risks, especially at traditional intersections along these arterials. Since the early 1960s, with the first installation of a Median U-Turn (MUT) on the intersection of 8 Mile Rd and Livernois Avenue, in Wayne County, Michigan. (Reid et al, 2014), a greater number of alternative intersection designs have been implemented in various states. Some of these designs include MUTs and Restricted Crossing U-Turns (RCUT), among other alternatives.

The alternative intersection design of MUT prohibit direct left turns at the intersection. Instead, drivers are provided with a combination of right turns and U-Turns in order to complete the desired left turn. Figure 1 illustrates the movements a driver would have to make from the major road or the minor road to complete a left turn in the presence of an MUT. The installation of MUTs started in the state of Michigan, especially in the Detroit Metropolitan area, in the 1960s as a solution for reduced capacity in wide-median highways, caused by interlocking left turn movements at traditional intersections. Nowadays, more than 700 MUTs exist along urban corridors. According to the Michigan Department of Transportation (MDOT), the decision of where to install MUTs is made after studying crash history of major divided road intersections. They are mainly used in urban areas and not recommended for limited-access roadway facilities such as freeways (Reid et al, 2014).

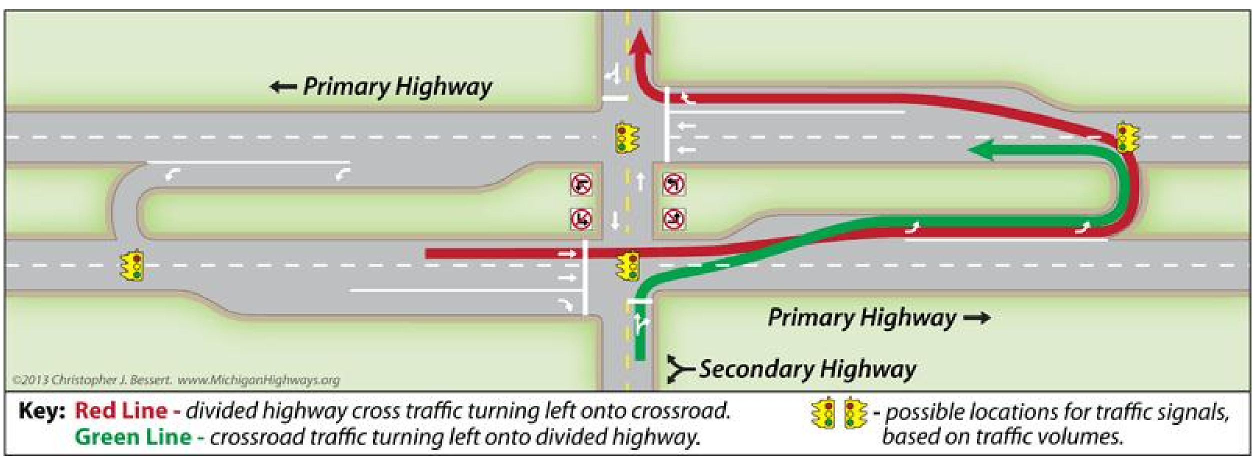

Figure 1. Schematic of the Michigan MUT (Bessert, 2017)

The other popular intersection design known as Restricted Crossing U-Turn or RCUT, was developed to solve the same problem of congestion in suburban arterials and was first by Richard Kramer and was also developed independently in Maryland and North Carolina. The Maryland State Highway Administration developed an unsignalized version of RCUT intersection design, called J-turns (Hummer et al, 2014). The J-Turn intersection design better serves an intersection with more major road left turns than minor road through movements (Mississippi DOT, 2010). The two intersection design alternatives are similar in that they restrict left turn movements from the minor road onto the major road, however, there are two main differences between the two designs: a) MUTs allow through movement for both the major and minor roads, whereas RCUTs only allow through movement for the major road, and b) MUTs prohibit left turn movements from both the major road and the minor road whereas RCUTs only prohibit left turns from the minor road. Substantial research has been conducted in assessing the operational performance and the safety performance of these alternative designs.

2.1.1 Operational Performance Research

Several studies have compared traffic operations between arterial corridors with Two-Way Left Turn Lanes (TWLTL) with corridors with MUTs. The main results reported were:

- MUTs demonstrated a 17 percent decrease in total travel time within the study area and a 25 percent increase in average traffic speeds. However, the number of stops along the corridor increased (Reid and Hummer, 1999).
- The corridor capacity experienced a 20 to 50 percent increase (Savage 1974, Maki 1992)
- The MUTs provided lower network travel times compared to the five-lane TWLTL design. When the left turn volume percentages were low, the left-turn total time and network total time were similar for directional medians with stop control and signalized directional medians.

In a comparison study of seven unconventional intersection designs, including the quadrant, MUT, superstreet, bowtie, jughandle, split intersection, and continuous flow intersections with traditional intersections, Reid and Hummer (2001) reached the following conclusions:

- MUTs produced significantly lower average total travel times
- The change in overall travel times for all movements through the intersection was −21 to +6 percent during peak conditions.
- The overall change in the number of stops was −2 to +30 percent during peak conditions.

Topp and Hummer (2005) compared MUTs on arterial highways with MUTs on the cross street with varying left turn and through volumes for the major and minor roads. The results showed that the MUT design located along the cross street performed better than the MUT design located on the major arterial in terms of reducing percent stops, total travel time, and delay for most of the volume combinations.

2.1.2 Safety Performance Research

Hummer and Reid (2000) compared the safety effectiveness of MUTs with two-way left turn lanes (TWLTL) and medians with conventional left turns on Michigan arterials. The results showed that collision rates were higher for TWLTL, slightly lower for unsignalized intersections with medians, and much lower for signalized MUTs.

Maki (1996) examined the safety benefits of replacing traditional signalized intersections with MUTs through a before and after study. The study segment was less than 0.5 miles long, located on Grand River Ave in Wayne County, Michigan, and 5 years of data (1990-1995) were utilized. Kach (1992) also compared the safety performance of conventional signalized intersections to MUTs locations in the State of Michigan, however, the comparison study sample consisted of only 15 MUTs and 30 conventional intersections.

Taylor et al (2001) conducted before-and-after analyses of replacement of bidirectional crossovers by directional crossovers. The former crossover allows turning movement in both directions while the latter only allows movements in one direction only. The results were comparable and showed reduction in total crashes as well as significant reduction in angle crashes. However, the study did not account for traffic volume changes, seasonal effects, or regression-to-the-mean. The difference in crash rate occurred in the presence of traffic signals, and as the traffic signal density increased, the crash rate was almost halved.

Studies were also performed to explore the safety effects of U-turns at signalized intersections. Carter et al. (2005) determined that signalized locations with double left-turn lanes, high left-turn, conflicting right-turn traffic volumes, and especially protected right-turn overlap, experience the greatest number of U-turn collisions. (Hughes et al. 2010) provided results which demonstrated the benefits of implementation of U-turns from conventional four-leg signalized intersections. U-turns reduced various type of crashes such as rear-end, angle, and sideswipe collisions by 17, 96, and 62 percent, respectively.

Castronovo et al. (1995) compared the safety benefits of MUTs with traditional intersections for 123 segments of boulevards. The results indicated lower MUT crash rates for higher signal density. On suburban segments with signal densities of one or more signals per mile, the crash rate for MUTs was 50 percent less than the crash rate of conventional intersections. In rural segments with signal densities of 1 or fewer per mile, the crash rate was reduced by 36 percent as compared to conventional intersections.

U-Turns have also been installed in high speed rural roadways. Tarko et al. (2012) used a multivariate probit model to simultaneously estimate crash frequency and severity for rural roads in Indiana as a function of traffic volumes and roadway characteristics. Median width and the presence of left and right acceleration lanes were shown to reduce crashes. The study included the examination of the effect of U-turns on crashes for 72 stop-controlled intersections in Michigan. The results showed that the presence of U-turns increased crashes, thus being counterintuitive. This could be due to endogeneity since these U-turns could have been installed to remedy underlying issues with traffic operation and safety. Therefore, the presence of U-turns does not represent a countermeasure but the presence of a safety problem. The transferability of model parameters between Indiana and Michigan was tested using the likelihood ratios test and was found inconclusive. This could be due to differences in data collection and certain aspects of data missing from the Michigan intersection datasets. Also, the sample size for Michigan intersections was much smaller than the sample size for Indiana, which can magnify irregularities and result in biased parameter estimates.

The study by Olarte et al. (2011) aimed to provide designers and decision-makers with a model which they can utilize to evaluate the feasibility and suitability of implementing unsignalized restricted crossing U-turns (RCUT) in rural intersections. An example of such an intersection geometry is illustrated in Figure 2. It can be seen that the left turn movements from the major road onto the minor road are permitted, however, separation is provided between the left turning lanes. The study identified the sites that were susceptible to bottlenecks and provided a regression model relating traffic density to traffic volumes. The second objective was to examine the relationship between traffic conflicts and traffic volumes through graphical means. Based on safety, the authors recommend that designers implement RCUTs by placing in speed-reduction signalization and also advisory signs that warn vehicles not to stop on the weaving or exit sections. RCUTs' design performance was examined by Inman and Haas (2012) for several locations in

Maryland. The before-and-after analysis showed a reduction in intersection crashes as well as adjacent segment crashes by 62% and 14%, respectively.

Figure 2. RCUT Example (Olarte et al. 2011)

In Missouri, an unsignalized version of RCUT, called J-turn, is used to substitute several two-way-stop controlled (TWSC) intersections in high speed rural expressways. The study by Edara et al. (2013) focused on evaluating 5 J-turn locations by employing a rigorous empirical Bayes before-and-after evaluation based on field studies, public survey, crash analysis, and traffic conflict analysis. J-turns were shown to reduce crash frequency for total crashes as well as disabling and minor injuries. Also, the right-angle crashes due to left turns were completely eliminated. The average time to collision was also higher at the J-turns compared to the TWSC sites, indicating greater safety at the J-turn sites. Time to collision is a conflict measure used to study intersection safety and it is defined as the time it takes for a collision between two vehicles to occur if the vehicles do not take an evasive action (MacCarley, 2011).

A study by Hummer et al (2010) studied the safety effects of superstreets in arterials in North Carolina by comparison group analysis and Empirical Bayes method. The study utilized HSM SPFs which were calibrated to reflect local conditions. A site is considered to be a full superstreet if it reroutes left and through movements from the side street to directional crossovers on both sides of the main intersection. The results showed that HSM SPFs underestimated crashes on North Carolina superstreets.

While the operational and safety benefits of U-turns have been explored and reported through different studies, their safety performance has not been assessed through crash prediction models, especially state-specific SPFs, for a statewide sample of urban and suburban arterial boulevards that have MUTs installed. This could be due to the fact that these treatments are not used in every state and also due to the variety of designs. For urban and suburban arterials, the SPFs provided in the HSM do not account for median width, presence of MUTs and the combined effects of these turnarounds with number of lanes, traffic control of the intersections, driveway/access point density, and other characteristics of the roadway segments. The variables used and not used in HSM safety predictions are included in Figure 3. This study aims to fill a gap in the assessment of these treatments at a corridor level for urban and suburban boulevards, intersections, and lastly at the MUT level. Additionally, aggregate models were estimated to compare the safety performance of MUTs at the intersection-to-MUT site level. These models would provide a more direct comparison for the portion of the roadway facility that extends from the intersections to the MUTs with sites of similar length that have traditional dual left turn lanes.

Variables	Chapter 10 Rural two-lane highways	Chapter 11 Rural multilane highways	Chapter 12 Urban and suburban arterials
Roadway Segments			
Area type (rural/suburban/urban)	X	X	X
Annual average daily traffic volume	X	X	X
Length of roadway segment	X	X	X
Number of through lanes	X	X	X
Lane width	X	X	
Shoulder width	X	X	
Shoulder type	X	X	
Presence of median (divided/undivided)		X	X
Median width		X	
Presence of concrete median barrier		X	
Presence of passing lane	X		
Presence of short four-lane section	X		
Presence of two-way left-turn lane	X		X
Driveway density	X		
Number of major commercial driveways			X
Number of minor commercial driveways			X
Number of major residential driveways			X
Number of minor residential driveways			X
Number of major industrial/institutional driveways			X
Number of minor industrial/institutional driveways			X
Number of other driveways			X
Horizontal curve length	X		
Horizontal curve radius	X		
Horizontal curve superelevation	X		
Presence of spiral transition	X		
Grade	X		
Roadside hazard rating	X		
Roadside slope		X	
Roadside fixed-object density			X
Roadside fixed-object offset			X
Percent of length with on-street parking			X
Type of on-street parking			X
Presence of lighting			X

Figure 3. Variables Used in HSM Safety Predictions (NCHRP, 2008)

2.1.3 Data Recommendations for SPF Development

The accuracy of an SPF depends mostly on the quality of the data from which it is developed. Some of the quality issues include inaccurate data, variation in crash reporting thresholds, and differences in crash reporting methods (AASHTO, 2010). One issue affecting the analysis of crash frequency and crash severity data is the underreporting of crashes, particularly those of lower severity levels (e.g., property damage only). In 2008, the Model Minimum Uniform Crash Criteria (MMUCC) guidelines were developed with funding provided by the National Highway Traffic Safety Administration (NHTSA) in collaboration with the Governor's Highway Safety Association (GHSA), Federal Highway Administration (FHWA), and Federal Motor Carrier Safety Administration (FMCSA), State DOTs, and law enforcement agencies, as well as other prominent traffic safety stakeholders. The MMUCC consists of a recommended minimum set of data elements for States to include in their crash forms and databases (NHTSA, 2015). This set includes 110 data elements, 77 of which are to be collected at the scene, 10 data elements to be derived from the collected data, and 23 data elements to be obtained after linkage to driver history, injury and roadway inventory data. These elements describe motor vehicle crashes and the vehicles, persons and environment involved.

As per MMUCC recommendations, all crashes involving death, injury, or property damage valued at $1,000 or greater should be reported. However, these are only recommendations that states are required to follow; most states have different dollar-value thresholds for crash reporting. This causes a portion of property damage only (PDO) crashes to not get reported, and thus not be included in models. Another issue arises from PDO crashes going unreported by drivers due to negative incidents on driving records and accompanying increased insurance rates. Given that the rate of underreporting is generally unknown, ignoring these effects may lead to biased parameter estimates (Kumara and Chin, 2005; Yamamoto et al. 2008; Ma, 2009). This often prompts models that include only crashes reported on a KABCO scale, which are often reported on a more consistent basis (Srinivasan et al. 2008). Differences in crash reporting methods exist on a local basis as well as statewide. The MMUCC has guidelines for crash reporting by law enforcement. Despite the level of detail required by so many data fields, law enforcement is ultimately responsible for the accuracy of the data (Brimley et al. 2012). Data inaccuracies include problems with inaccurately reported crash data based on location; this translates into excluding crashes from the model or including wrongly-located crashes. Both of these instances ultimately diminish the accuracy of the SPF models and result in erroneous crash predictions.

HSM and SafetyAnalyst have somewhat different data requirements due to their different purposes and different default SPFs. However, both require extensive data sets of crashes, traffic volumes, and roadway geometric characteristics. SafetyAnalyst requires a crash database to be comprehensive and include information on specific crash location, collision type, severity, relationship to junction, and types of maneuvers of the involved vehicles. Additionally, SafetyAnalyst requires that roadway data be split into three categories: segments, intersections, and ramps.

The HSM requires a sample between 30-50 sites with at least a total of 100 crashes (for the entire period of the study). The study period depends on the available data, however, to apply the EB method, at least 2 years of observed crash data are desirable (AASHTO, 2010). Hauer et al. (2002) outlines the procedures for EB estimation of crash frequency, both abridged and full EB. The abridged version of the method employs 2-3 years of crash counts and traffic volumes, while the full EB method utilizes a longer crash and traffic volume history. Roadway data is also important in safety analysis and includes all the physical features within a road's right-of-way. The HSM also requires roadway geometry data such as lane width, shoulder width and type, length, radius, and superelevation of horizontal curvature, grade, driveway density, and number of binary variables indicating presence of safety measures and turning lanes (AASHTO, 2010).

Several studies have particularly identified data availability and completeness as hurdles in meeting the input requirements of the *HSM* and *SafetyAnalyst* (Brimley et al. 2012; Hauer, 2002; Alluri et al, 2014; Lubliner et al. 2014). The results of the nationwide survey, summarized in the study by Alluri and Ogle (2012), demonstrated that most of the responding states reported issues with data collection, especially traffic volumes and roadway characteristics, and ability to spatially locate data. Particularly for intersections, traffic information and roadway geometry information might be cumbersome to obtain due to state practices which often result in minimal collection and maintenance of such data. Traffic data is usually available to higher classes of roadways, specifically interstates, highways, and state routes, with diminishing availability for local and low volume roads (Alluri and Ogle, 2012). The cumbersome process of obtaining data often results in a shorter study period, low sample mean and low sample size, and also omitted variables, all of which can affect the study results.

In order to include additional variables, a time and effort investment is required to collect data and merge datasets together. As a result, oftentimes researchers are constrained to exclude a portion of sample sites with missing data from the analysis. A study examining the state-specific SPFs for Georgia (Alluri and Ogle, 2012) demonstrated that data quality and availability greatly affects the statistical significance of SPFs; the significance of Georgia-specific SPFs was lower than the nationwide SafetyAnalyst SPF significance since data on traffic volume was collected only from 25% of the road segments. A Florida study identified meeting the data requirements of the HSM, and to a lesser extent *SafetyAnalyst*, as being challenging. In particular, many of the variables for deriving calibration factors presented in the *HSM* were not available in the state's Roadway Characteristics Inventory (Alluri et al. 2014). Additionally, *SafetyAnalyst* required a large effort be expended on local data conversion so that agency specific safety performance functions could be estimated. Researchers attempting to calibrate the *HSM* to Maryland noted that the purpose behind thresholds for sites (30-50) and crashes (100 per year) are not necessarily reflective of the goals of minimizing the error in calibration (Shin et al. 2014) while researchers in Kansas noted that the crash threshold, in conjunction with scarcity of intersection data, resulted in a sample that was small to the point that three- and four-leg rural stop-controlled intersections were considered together (Lubliner et al, 2014).

2.2 Data Sources and Collection for Disaggregate MUT Safety Performance

Ultimately, the preceding discussion was used to guide the development of the datasets that were leveraged for the purposes of this study. The data for assessing the safety impacts of MUTs on urban and suburban arterials, both at an aggregate and disaggregate level, were collected and assembled as part of two prior projects funded by MDOT, which saw the development of state-specific SPFs for urban/suburban trunklines (Savolainen et al. 2015, Savolainen et al. 2016). The data was collected and processed for urban and rural non-freeways, thus filtering was required in order to omit the rural segments from the dataset. Quality assurance was performed to assure that all the urban/suburban segments pertained to cities and towns with a threshold population of 50,000 according to HSM recommendations.

2.2.1 Intersection-Level Data

In order to develop a series of SPFs that will provide an accurate prediction of the safety performance of urban trunkline intersections, it was imperative to develop a robust high-quality database, which includes traffic crash information, traffic volumes, and roadway geometry. These data were obtained from the following sources:

- Michigan State Police Statewide Crash Database;
- MDOT SafetyAnalyst Calibration File;
- Michigan Geographic Data Library (MiGDL) All Roads File;
- MDOT SafetyAnalyst Annual Average Daily Traffic File; and
- MDOT Sufficiency File:

In addition to the intersection location, traffic volume, and crash data obtained from these sources, extensive data collection was conducted in order to obtain additional information about the geometric characteristics of each intersection, including:

- Number of intersection legs
- Type of traffic control
- AADT for major and minor road
- Number of approaches with left-turn lanes
- Number of approaches with right-turn lanes
- Presence of lighting
- One-way or two-way traffic
- Intersection sight distance
- Intersection skew angle
- Presence/type of left-turn phasing
- Pedestrian volumes
- Presence of bus stops
- Presence of on-street parking
- Presence of MUTs
- Distance of MUTs from intersections

Due to the cumbersome process of manual data collection, the above attributes were collected for a random sample of 350 intersections for each intersection type. The random sample was selected such that each of the seven regions was represented in the sample in order to account for regional differences and unique attributes during the development of SPFs. These data were aggregated to develop a comprehensive database of intersections over the five-year study period from 2008 to 2012. The final sample was comprised of the following number of locations by site type:

- 353 three-legged stop-controlled (3ST) intersections;
- 350 four-legged stop-controlled (4ST) intersections;
- 210 three-legged signalized (3SG) intersections; and
- 349 four-legged signalized (4SG) intersections.

The aforementioned sample sizes included intersections that were located on undivided and divided facilities. However, given that MUTs only exist in divided roadways, the data was truncated to only included intersections along divided arterials. This limited the sample size of intersections to 128. Due to differences in the study periods of the two projects, the intersection data was collected for years 2008-2012 while the segment data was collected for years 2010-2014, the intersection crash data and other attributes were collected for years 2013-2014. The summary statistics for the various variables for all intersections and subsequently, for each intersection by type of traffic control and number of legs, are described in Table 1 through Table 5.

It is not surprising that almost 40 percent of the intersections on divided arterials are located in the Metro Region. The Grand Region is the second area where almost 35 percent of divided arterial intersections sample are located. 58 percent of all the intersections have an MUT present on the Major Road. These MUTs are installed as close as 41 ft and as far as 2599 ft from the center of the intersection. Traffic volumes also range from just under 5000 veh/day to almost 89,000 veh/day in the signalized intersections.

Table 2 through Table 5 illustrate the descriptive statistics for all the variables in Table 1, however, provide more disaggregate information on how the 4 types of intersections compare in traffic volume, roadway geometric characteristics, and the presence of MUTs. The signalized intersections have a similar percentage of MUT presence, whereas the stop controlled intersections vary; almost 75 percent of 3-leg stop controlled intersections sampled have MUTs, while that percentage drops to only 38 for 4-leg stop controlled intersections. The 4-leg stop controlled intersections are the smallest sample in the group. This is due to the fact that these types of intersections are mainly present on rural areas and undivided roadways.

Table 1. Descriptive Statistics for All Intersections (N = 128)

Parameter	Average	Std. Dev	Min	Max
Major Road Annual Average Daily Traffic	24894.27	17445.17	4841	88842
Minor Road Annual Average Daily Traffic	5840.38	9418.40	49.50	47464
Major Road Through Lanes	3.94	1.52	2	8
Major Road Left Turn Lane	0.73	0.82	0	2
Major Road Right Turn Lane	0.51	0.78	0	2
Minor Road Through Lanes	1.67	1.57	0	4
Minor Road Left Turn Lane	0.60	0.70	0	2
Minor Road Right Turn Lane	0.28	0.62	0	2
Major Road Posted Speed Limit	45.08	8.82	30	55
Skew Angle	10.75	14.14	0	64.08
Lighting Presence	0.74	0.44	0	1
Right Turn on Red Presence	0.50	0.50	0	1
Major Road Driveway Count	1.36	2.03	0	9
Minor Road Driveway Count	1.96	2.35	0	11
Major Road MUT Presence	0.58	0.49	0	1
Major Road Nearest MUT Distance	506.55	264.29	41	1864
Major Road Farthest MUT Distance	751.54	408.23	279	2599
School Presence within 1/2 mile of Intersection	0.16	0.37	0	1
Superior Region	0.06	0.24	0	1
North Region	0.03	0.17	0	1
Grand Region	0.34	0.47	0	1
Bay Region	0.03	0.17	0	1
Southwest Region	0.08	0.27	0	1
University Region	0.08	0.27	0	1
Metro Region	0.38	0.48	0	1
Total Crash Frequency	7.49	13.63	0	104
Angle Crash Frequency	1.41	2.92	0	26
Head-on Crash Frequency	0.14	0.47	0	4

Table 2. Descriptive Statistics for 3SG Intersections (N = 27)

Parameter	Average	Std. Dev	Min	Max
Major Road Annual Average Daily Traffic	26300.52	16075.48	5998	62094
Minor Road Annual Average Daily Traffic	4534.37	7900.59	49.50	42828
Major Road Through Lanes	3.81	0.77	3	6
Major Road Left Turn Lane	0.70	0.60	0	2
Major Road Right Turn Lane	0.48	0.69	0	2
Minor Road Through Lanes	0.37	0.55	0	2
Minor Road Left Turn Lane	0.85	0.59	0	2
Minor Road Right Turn Lane	0.44	0.63	0	2
Major Road Posted Speed Limit	42.41	7.74	35	55
Skew Angle	7.81	13.04	0	64.08
Lighting Presence	0.78	0.42	0	1
Right Turn on Red Presence	0.96	0.19	0	1
Major Road Driveway Count	1.30	1.63	0	7
Minor Road Driveway Count	1.30	1.65	0	6
Major Road MTA Presence	0.48	0.50	0	1
Major Road Nearest MTA Distance	496.77	144.64	217	740
Major Road Farthest MTA Distance	737.38	264.35	308	1267
School Presence within 1/2 mile of Intersection	0.19	0.39	0	1
Superior Region	0.04	0.19	0	1
North Region	0.15	0.36	0	1
Grand Region	0.15	0.36	0	1
Bay Region	0.00	0.00	0	0
Southwest Region	0.07	0.26	0	1
University Region	0.07	0.26	0	1
Metro Region	0.52	0.50	0	1
Total Crash Frequency	5.20	5.79	0	30
Angle Crash Frequency	0.47	0.82	0	4
Head-on Crash Frequency	0.19	0.60	0	4

Table 3. Descriptive Statistics for 4SG Intersections (N = 42)

Parameter	Average	Std. Dev	Min	Max
Major Road Annual Average Daily Traffic	33499.45	22093.28	7790	88842
Minor Road Annual Average Daily Traffic	13859.13	11248.58	892	47464
Major Road Through Lanes	4.88	1.78	2	8
Major Road Left Turn Lane	1.29	0.91	0	2
Major Road Right Turn Lane	0.76	0.89	0	2
Minor Road Through Lanes	3.36	1.52	2	4
Minor Road Left Turn Lane	0.95	0.79	0	2
Minor Road Right Turn Lane	0.52	0.85	0	2
Major Road Posted Speed Limit	44.05	8.61	30	55
Skew Angle	13.35	15.39	0	52.7
Lighting Presence	0.90	0.29	0	1
Right Turn on Red Presence	0.88	0.32	0	1
Major Road Driveway Count	2.24	2.71	0	9
Minor Road Driveway Count	3.14	2.99	0	11
Major Road MTA Presence	0.55	0.50	0	1
Major Road Nearest MTA Distance	560.26	90.26	357	725
Major Road Farthest MTA Distance	652.09	132.33	483	1084
School Presence within 1/2 mile of Intersection	0.19	0.39	0	1
Superior Region	0.07	0.26	0	1
North Region	0	0	0	0
Grand Region	0.48	0.50	0	1
Bay Region	0.05	0.21	0	1
Southwest Region	0.05	0.21	0	1
University Region	0.05	0.21	0	1
Metro Region	0.31	0.46	0	1
Total Crash Frequency	17.33	19.64	0	104
Angle Crash Frequency	3.63	4.18	0	26
Head-on Crash Frequency	0.27	0.62	0	4

Table 4. Descriptive Statistics for 3ST Intersections (N = 43)

Parameter	Average	Std. Dev	Min	Max
Major Road Annual Average Daily Traffic	18621.40	9120.49	4841	43301
Minor Road Annual Average Daily Traffic	401.42	312.13	49.50	1384.5
Major Road Through Lanes	3.12	1.26	2	8
Major Road Left Turn Lane	0.28	0.45	0	1
Major Road Right Turn Lane	0.12	0.39	0	2
Minor Road Through Lanes	0.81	0.44	0	2
Minor Road Left Turn Lane	0.28	0.45	0	1
Minor Road Right Turn Lane	0.02	0.15	0	1
Major Road Posted Speed Limit	46.16	8.75	30	55
Skew Angle	7.78	11.59	0.01	52.29
Lighting Presence	0.70	0.46	0	1
Right Turn on Red Presence	0.00	0.00	0	0
Major Road Driveway Count	0.91	1.31	0	4
Minor Road Driveway Count	1.51	1.77	0	8
Major Road MTA Presence	0.74	0.44	0	1
Major Road Nearest MTA Distance	465.81	375.68	41	1864
Major Road Farthest MTA Distance	861.53	564.02	279	2599
School Presence within 1/2 mile of Intersection	0.16	0.37	0	1
Superior Region	0.00	0.00	0	0
North Region	0.00	0.00	0	0
Grand Region	0.37	0.48	0	1
Bay Region	0.02	0.15	0	1
Southwest Region	0.05	0.21	0	1
University Region	0.07	0.25	0	1
Metro Region	0.49	0.50	0	1
Total Crash Frequency	1.44	2.78	0	20
Angle Crash Frequency	0.15	0.49	0	4
Head-on Crash Frequency	0.02	0.14	0	1

Table 5. Descriptive Statistics for 4ST Intersections (N = 16)

Parameter	Average	Std. Dev	Min	Max
Major Road Annual Average Daily Traffic	16791.00	11162.60	6929	50132
Minor Road Annual Average Daily Traffic	1612.22	1693.32	123.50	6741
Major Road Through Lanes	3.88	0.86	2	6
Major Road Left Turn Lane	0.50	0.79	0	2
Major Road Right Turn Lane	0.94	0.90	0	2
Minor Road Through Lanes	1.75	0.43	1	2
Minor Road Left Turn Lane	0.13	0.48	0	2
Minor Road Right Turn Lane	0.06	0.24	0	1
Major Road Posted Speed Limit	49.38	9.16	30	55
Skew Angle	16.89	15.35	0	51
Lighting Presence	0.38	0.48	0	1
Right Turn on Red Presence	0.06	0.24	0	1
Major Road Driveway Count	0.38	1.05	0	4
Minor Road Driveway Count	1.19	1.42	0	5
Major Road MTA Presence	0.38	0.48	0	1
Major Road Nearest MTA Distance	539.17	121.96	300	675
Major Road Farthest MTA Distance	576.83	123.46	330	690
School Presence within 1/2 mile of Intersection	0.06	0.24	0	1
Superior Region	0.25	0.43	0	1
North Region	0.00	0.00	0	0
Grand Region	0.25	0.43	0	1
Bay Region	0.06	0.24	0	1
Southwest Region	0.25	0.43	0	1
University Region	0.19	0.39	0	1
Metro Region	0.00	0.00	0	0
Total Crash Frequency	1.79	1.66	0	7
Angle Crash Frequency	0.50	0.84	0	3
Head-on Crash Frequency	0.01	0.11	0	1

As it can be seen in Table 6, intersections are for the most part located on 4-lane divided roadways. The stop controlled intersections also experience a much lesser daily traffic volume as it can be seen from the descriptive statistics.

Table 6. Sample Size for Each Intersection Type

Type	Observations	Sites	4D	6D	8D
3SG	135	27	14	7	6
4SG	210	42	28	8	6
3ST	215	43	24	11	8
4ST	80	16	15	1	0

For more details regarding the data sources and the manual data collection for intersections, the readers can access the full project report (Savolainen et al. 2015). A comprehensive inventory of MUTs was also developed during the efforts for a companion project focused on urban and suburban arterial segments (Savolainen et al. 2016). Details for the data collection and processing for the MUTs are detailed in the following section.

2.2.2 Segment-Level Data

The dataset was assembled from individual data from a number of sources which are either publicly available or obtained through the Michigan Department of Transportation (MDOT). Michigan Geographic Data Library (MiGDL) All Roads File was used to obtain the framework for mapping data from Sufficiency File through linear referencing based on Physical Reference and Mile Point information. In order to facilitate the use of GIS software for this project, a GIS shapefile, called allroads_miv13a.shp, was obtained from the Michigan Geographic Data Library from the Michigan Center for Geographic Information (MCGI) website. The file consists of all the road segments found statewide. Although the file has a total of 36 attribute fields, the information utilized involved the Physical Road ID number (PR) and Beginning and End PR mile point for linear referencing system (BMP and EMP).

The Sufficiency database is maintained by MDOT and contains roadway data collected and maintained at a segment level, where each segment has homogeneous traffic and geometric characteristics. If one or more of these characteristics change, a new homogeneous segment is introduced in the database. MDOT Sufficiency File provides information with regards to:

- County and MDOT Region
- Route designation and number
- Lane width and number of lanes
- Shoulder type and width
- Median type and width
- Annual Average Daily Traffic (AADT)
- Predominant Posted Speed Limit
- Presence of passing lane or signalized intersection within the segment
- Length of no-passing zone within the segment

Traffic crash information from the Michigan State Police crash database, containing crash information regarding type and location.

In order to obtain driveway counts and densities, the MDOT database of geocoded driveway/access points was utilized to map these points on the roadway segments and compute the desired variables.

Lastly, an extensive manual collection of MUT points along 4D, 6D, and 8D segments was completed. The information collected included: U-Turns' physical road and mile point, traffic control type, and whether the U-Turn was merging or diverging from the segment on which it was recorded. Information on MUT specific data collection is provided in the following subsection.

Divided roadways in Michigan have different PR numbers for the opposing directions of travel. Due to the segmentation of the urban and suburban arterials it was determined that the divided arterials would be analyzed directionally. This means that for each direction of travel of the divided road, there are 5 years of observations and data. The decision was made due to two constraints; the first limitation was encountered due to the segmentation of arterials in a manner that did not often guarantee the same beginning and end mile point for the opposing direction of travel segments, and thus hindering the linking of the two segments. Additionally, certain matching segments might not have been included in the final dataset due to lack of available data for 5 consecutive years or due to presence of construction during one or more of the five years of data. Previous research (Hauer, 2004) recommends that due to differences in important geometric features such as grade, number of access points, or curvature, modeling for multilane divided roadways should be done by direction.

Extensive data review was conducted to ensure that the final datasets included only urban and suburban segments categorized into their facilities based number of lanes and whether the two directions of roadway were separated by a painted or physical median. Additional quality assurance was performed utilizing the historical aerial imagery in Google Earth based on which, segments that experienced construction during any of the 5 years between 2010 and 2014 were identified and removed from the dataset.

Table 7 through Table 10 provide summary statistics for all relevant variables among the divided segment types considered for modeling. Each table presents the minimum, maximum, mean value, and standard deviation for each variable of interest. As the descriptive statistics show, the more lanes a facility has, the higher the daily traffic volume. Lane width was fairly consistent among facility types, ranging from 10 ft to 12 ft with an average width of 11.75 ft. Shoulder widths are wider for 4-lane divided arterials, averaging 7.6 ft and 5 ft for the right and left shoulder, respectively. However, shoulder space tends to be limited for 6-lane and 8-lane divided arterials due to their location being mainly in highly urban areas where space (right-of-way) is limited. On average, median width follows the opposite trend; the wider facilities have more room allocated to separating the directions of travel. Driveway density also is much higher for wider facilities, which speaks to their urban nature. Over three quarters of the 6-lane divided arterials and 96 percent of the 8-lane divided arterials are located in the Metro Region. On average, the various types of intersection densities are lowest for 3-leg signalized and 4-leg stop controlled intersections, whereas 4-leg signalized and 3-leg stop controlled intersections are more frequent, especially in 6-lane divided facilities. Lastly, 4-lane divided arterials have high density of uncontrolled, yield-controlled, and stop-controlled MUTs. The other two facility types, 6-lane and 8-lane divided arterials mainly experience stop-controlled and signalized MUTs. Emergency MUTs are mainly present on 4-lane divided arterials.

Table 7. Descriptive Statistics for All Divided Segments (N = 281)

Parameter	Average	Std. Dev.	Min	Max
AADT	16347.66	10351.79	2752	51337
Segment Length	1.08	0.78	0.12	4.41
Lane Width	11.76	0.48	10	12
Right Shoulder Width	5.41	4.83	0	12
Left Shoulder Width	3.40	3.53	0	10
Median Width	52.58	44.92	2	550
Speed Limit	47.76	7.62	30	55
Driveway Count	11.89	17.59	0	92
Driveway Density	10.27	11.54	0	52.63
School Count	0.49	0.84	0	4
Commercial Vehicle %	4.18	2.78	0.40	13.40
Superior Region	0.09	0.29	0	1
North Region	0.02	0.14	0	1
Grand Region	0.30	0.46	0	1
Bay Region	0.01	0.08	0	1
Southwest Region	0.09	0.29	0	1
University Region	0.10	0.29	0	1
Metro Region	0.39	0.49	0	1
3-leg SG Intersection Density	0.05	0.19	0.00	1.72
4-leg SG Intersection Density	0.15	0.37	0.00	2.87
3-leg ST Intersection Density	0.32	1.20	0.00	11.47
4-leg ST Intersection Density	0.08	0.29	0.00	2.29
No Traffic Control MUT Density	0.32	1.44	0	13.07
Yield Controlled MUT Density	0.58	1.46	0	9.88
Stop Controlled MUT Density	1.65	2.11	0	9.43
Signalized MUT Density	0.49	0.85	0	4.81
Emergency MUT Density	0.11	0.53	0	4.81
Total Crash Frequency	6.59	11.90	0	105.00
Sideswipe Crash Frequency	1.08	2.17	0	21.00
Rear End Crash Frequency	3.37	8.04	0	72.00

Table 8. Descriptive Statistics for 4-lane Divided Segments (N = 169)

Parameter	Average	Std. Dev.	Min	Max
AADT	11138.86	6264.38	2752	32432
Segment Length	1.09	0.80	0.12	4.41
Lane Width	11.79	0.41	11	12
Right Shoulder Width	7.64	3.77	0	12
Left Shoulder Width	5.02	3.19	0	8
Median Width	44.78	45.44	2	550
Speed Limit	50.33	7.37	30	55
Driveway Count	5.95	9.89	0	46
Driveway Density	5.31	7.58	0	52.63
School Count	0.41	0.78	0	3
Commercial Vehicle %	5.06	3.01	0.90	13.40
Superior Region	0.15	0.36	0	1
North Region	0.04	0.19	0	1
Grand Region	0.47	0.50	0	1
Bay Region	0.01	0.11	0	1
Southwest Region	0.14	0.35	0	1
University Region	0.11	0.32	0	1
Metro Region	0.08	0.27	0	1
3-leg SG Intersection Density	0.06	0.21	0.00	1.72
4-leg SG Intersection Density	0.15	0.36	0.00	1.72
3-leg ST Intersection Density	0.13	0.48	0.00	3.44
4-leg ST Intersection Density	0.07	0.28	0.00	2.29
No Traffic Control MUT Density	0.49	1.79	0	13.07
Yield Controlled MUT Density	0.96	1.78	0	9.88
Stop Controlled MUT Density	0.80	1.67	0	9.43
Signalized MUT Density	0.26	0.70	0	4.81
Emergency MUT Density	0.16	0.67	0	4.81
Total Crash Frequency	4.55	7.49	0	90.00
Sideswipe Crash Frequency	0.59	1.30	0	13.00
Rear End Crash Frequency	1.98	4.72	0	63.00

Table 9. Descriptive Statistics for 6-lane Divided Segments (N = 59)

Parameter	Average	Std. Dev.	Min	Max
AADT	21709.89	9476.64	3499	45081
Segment Length	0.98	0.68	0.25	3.01
Lane Width	11.75	0.63	10	12
Right Shoulder Width	2.86	4.74	0	12
Left Shoulder Width	1.36	2.90	0	10
Median Width	61.71	43.51	6	183
Speed Limit	43.12	7.28	30	55
Driveway Count	17.36	20.56	0	87
Driveway Density	15.07	13.14	0	51.87
School Count	0.76	0.98	0	4
Commercial Vehicle %	3.08	2.03	0.40	13.00
Superior Region	0.00	0.00	0	0
North Region	0.00	0.00	0	0
Grand Region	0.07	0.25	0	1
Bay Region	0.00	0.00	0	0
Southwest Region	0.03	0.18	0	1
University Region	0.14	0.34	0	1
Metro Region	0.76	0.43	0	1
3-leg SG Intersection Density	0.06	0.20	0.00	1.15
4-leg SG Intersection Density	0.21	0.46	0.00	2.87
3-leg ST Intersection Density	0.83	2.16	0.00	11.47
4-leg ST Intersection Density	0.14	0.40	0.00	2.29
No Traffic Control MUT Density	0.13	0.74	0	5.13
Yield Controlled MUT Density	0.02	0.15	0	1.17
Stop Controlled MUT Density	2.63	2.13	0	8.30
Signalized MUT Density	0.62	0.78	0	2.72
Emergency MUT Density	0.00	0.00	0	0.00
Total Crash Frequency	7.55	9.60	0	59.00
Sideswipe Crash Frequency	1.40	1.99	0	11.00
Rear End Crash Frequency	4.16	6.09	0	36.00

Table 10. Descriptive Statistics for 8-lane Divided Segments (N = 53)

Parameter	Average	Std. Dev.	Min	Max
AADT	26987.56	10574.33	8165	51337
Segment Length	1.13	0.83	0.20	4.02
Lane Width	11.71	0.49	10	12
Right Shoulder Width	1.13	3.51	0	12
Left Shoulder Width	0.48	1.65	0	8
Median Width	67.29	38.94	30	183
Speed Limit	44.75	4.65	35	55
Driveway Count	24.74	23.47	0	92
Driveway Density	20.75	10.83	0	49.19
School Count	0.45	0.79	0	4
Commercial Vehicle %	2.60	1.13	1.00	6.37
Superior Region	0.00	0.00	0	0
North Region	0.00	0.00	0	0
Grand Region	0.04	0.19	0	1
Bay Region	0.00	0.00	0	0
Southwest Region	0.00	0.00	0	0
University Region	0.00	0.00	0	0
Metro Region	0.96	0.19	0	1
3-leg SG Intersection Density	0.02	0.11	0.00	0.57
4-leg SG Intersection Density	0.10	0.24	0.00	1.15
3-leg ST Intersection Density	0.38	1.17	0.00	6.88
4-leg ST Intersection Density	0.02	0.11	0.00	0.57
No Traffic Control MUT Density	0.00	0.00	0	0.00
Yield Controlled MUT Density	0.00	0.00	0	0.00
Stop Controlled MUT Density	3.24	1.95	0	7.18
Signalized MUT Density	1.06	1.03	0	4.37
Emergency MUT Density	0.05	0.23	0	1.24
Total Crash Frequency	12.05	20.66	0	105.00
Sideswipe Crash Frequency	2.30	3.57	0	21.00
Rear End Crash Frequency	6.91	14.55	0	72.00

2.2.3 MUT-Level Data

This section details the collection of additional information pertinent to each median U-turn (MUT). As described previously, MUTs are channelized lanes that divert traffic from one direction of the roadway to the opposite direction, and they can be uncontrolled, yield controlled, stop controlled, or signalized. As a comprehensive database to classify MUTs did not exist, an extensive review of the divided roadway facilities was conducted as part of the project during which urban and suburban arterial segment SPFs were developed. Utilizing MDOT PR Finder to identify the segments and Google Earth to collect aerial and street view information, for each urban and suburban segment represented by a PR, BMP, and EMP, the mile point information of each MUT was collected as illustrated in Figure 4.

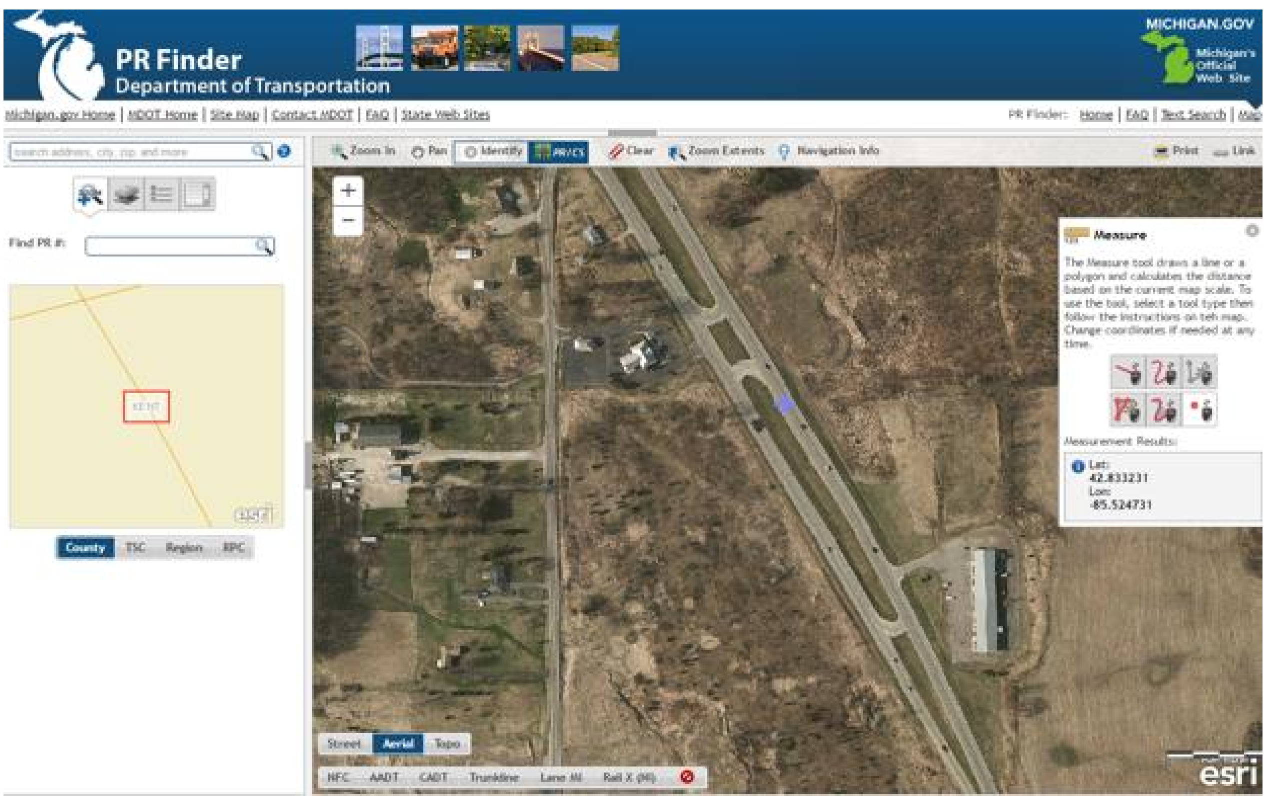

Figure 4. Screenshot of MDOT PR Finder

Additionally, MUTs were classified based on whether they diverged or merged traffic from/into the segment of interest, traffic control type, and whether the MUT merged traffic simply into the opposite direction of the roadway, a driveway, or another roadway, intersecting the segment of interest. Figure 5 illustrates diverging and merging MUTs:

Figure 5. Screenshot of an MUT on a 4D Segment

Emergency MUTs were also recorded when they were identified; these were somewhat difficult to identify when signs were not present indicating the MUT was for use by authorized vehicles only. Figure 6 provides an example of emergency MUTs while Table 11 provides a key outlining the classification of MUTs based on these characteristics.

Figure 6. Emergency MUT Example on a 4D Segment

Table 11. Classification of MUTs

Code	Description of MUT Type and Traffic Control
O	No traffic control; merging traffic only in the opposite direction of roadway
Y	Yield control; merging traffic only in the opposite direction of roadway
0	Stop control; merging traffic only in the opposite direction of roadway
1	Traffic signal; merging traffic only in the opposite direction of roadway
9	Diverging (from the segment of interest)
E	Emergency

One of the primary objectives of this study was to develop an MUT-specific crash frequency model aside from the intersection and segment crash frequency and crash type models. Therefore, data was collected for MUTs, such as AADT specific to the MUT segment, segment type and AADT on which the MUT was located, traffic control of the MUT, and whether the MUT was directional or bidirectional. The crashes for the MUT were selected via a field on the crash data which specifies intersection crashes and within a radius of 0.04 miles from the MUT center.

Table 12. Descriptive Statistics for MUTs (N = 637)

Parameter	Average	Std. Dev	Min	Max
Segment Annual Average Daily Traffic	45267.878	22155.803	7036	190838
MUT Annual Average Daily Traffic	1173.553	2738.023	90	28027
Signalized MUT	0.328	0.470	0	1
Stop Controlled MUT	0.527	0.499	0	1
Yield Controlled MUT	0.141	0.348	0	1
Uncontrolled MUT	0.003	0.056	0	1
Two-way MUT	0.020	0.141	0	1
One-way MUT	0.980	0.141	0	1
4-lane Divided Segment	0.292	0.455	0	1
6-lane Divided Segment	0.237	0.425	0	1
8-lane Divided Segment	0.471	0.499	0	1
Crash Frequency	3.85	4.603	0	37

Table 12 provides detailed descriptive statistics for MUT variables. On average, the MUT-specific traffic volumes were just under 1200 veh/day, with higher volumes on those MUTs located on 6-lane and 8-lane divided arterials. The majority of the MUTs were directional; over half of them were stop controlled, one-third of MUTs were signalized, and 14 percent were yield-controlled.

2.3 Data Sources and Data Collection for Aggregate-Level MUT Analysis

In order to assess the safety performance at a more aggregate level (i.e. at the portion of the roadway facility directly adjacent to the intersection including the MUTs), additional data was collected and processed.

Throughout the urban areas, these MUTs have been installed not only at signalized intersections, but also along boulevards and they often serve more than one intersection. This means the same MUT could serve one signalized and many stop-controlled (3-leg stop controlled) intersections which are widespread along urban boulevards.

Figure 7. MUT Installations Along a Boulevard

Figure 7 illustrates MUT installations along a boulevard. It can be seen that several of these MUTs do not serve a specific intersection, rather the various developments located along the boulevard.

First, a representative sample size of traditional and MUT-equipped intersections was chosen from the intersection data described in subsection 2.2.1. The selection of these sites was done randomly as well as to assure that these sites represent the traditional installation of MUTs and the sample size included 32 sites.

As mentioned previously, a site would include an intersection along with the portion of segment extending from the intersection to the MUTs that serve that intersection, including the MUT lanes. The data was processed in ArcGIS, which allowed for the visualization of the data as well as the spatial selection of crash data for all the sites. Once the sites were randomly selected, boxes were drawn to incorporate the intersection and the portion of the segment extending to the MUTs. The lengths of the boxes were measured and recorded and an average value computed. For a direct comparison between sites that are served by MUTs and similar traditional (i.e., non-MUT) sites, the average length of MUT-equipped sites/boxes was used to draw boxes around the traditional sites. Figure 8 and Figure 9 illustrate through aerial imagery examples of site types.

Figure 8. Aerial Image of an MUT-Equipped Site

Figure 9. Aerial Image of a Left-Turn Site

The final dataset included an entry for each site characteristics for each year of study (2010-2014). The intersection information was already available and was not processed any further. The descriptive statistics of the sampled intersections are illustrated in Table 13 for MUT-equipped intersections and Table 14 for traditional left turn intersections.

Table 13. Descriptive Statistics for Intersections with MUTs (N=23)

Parameter	Average	St. Dev	Min	Max
Length (ft)	1980.4	361.4	1305.3	2817.5
Length (mi)	0.375	0.068	0.247	0.534
Major Road Annual Average Daily Traffic	39736.5	22188.1	9682	88842
Minor Road Annual Average Daily Traffic	10595.6	11128.4	446	38542
Skew Angle	10.091	11.742	0	38.18
Presence of Lighting	0.783	0.414	0	1
Presence of Right Turn on Red	0.87	0.338	0	1
Major Road Posted Speed Limit	48.043	7.366	30	55
3-Leg Signalized Intersection	0.217	0.414	0	1
4-Leg Signalized Intersection	0.696	0.462	0	1
4-Leg Stop Controlled Intersection	0.087	0.283	0	1
Head-on Crash Frequency	0.122	0.378	0	2
Angle Crash Frequency	3.609	5.143	0	26
Rear End Crash Frequency	10.296	13.365	0	60
Sideswipe Same Side Crash Frequency	2.843	5.396	0	28
Total Vehicular Crash Frequency	18.174	23.419	0	104

Table 14. Descriptive Statistics for Control Intersections without MUTs (N=9)

Parameter	Average	St. Dev	Min	Max
Length (ft)	1911.63	87.32	1752.5	1990.8
Length (mi)	0.362	0.017	0.332	0.377
Major Road Annual Average Daily Traffic	18587.89	8061.6	7961	31402
Minor Road Annual Average Daily Traffic	6120.11	3956.83	726	10879
Skew Angle	13.7	14.97	0.01	44.24
Presence of Lighting	0.67	0.48	0	1
Presence of Right Turn on Red	0.78	0.42	0	1
Major Road Posted Speed Limit	49.44	8.06	35	55
3-Leg Signalized Intersection	0.222	0.42	0	1
4-Leg Signalized Intersection	0.444	0.503	0	1
4-Leg Stop Controlled Intersection	0.333	0.477	0	1
Head-on Crash Frequency	0.489	0.895	0	4
Angle Crash Frequency	2.244	2.356	0	9
Rear End Crash Frequency	5.578	6.576	0	23
Sideswipe Same Side Crash Frequency	0.644	0.933	0	3
Total Vehicular Crash Frequency	10.000	9.038	0	30

As seen on Table 13 and Table 14, the average traffic for both major and minor roads was higher on sites with MUTs than similar sites where left-turning vehicles are served directly at the primary intersection. This is reflective of the small sample size of the traditional left turn sites stemming from the 128 intersections with detailed information available on divided arterials. The skew angle, presence of lighting, and presence of right turn on red are comparable among the MUT sites and the traditional sites.

There is an adequate distribution of sites for signalized intersections, however, there are very few 4ST sites that have MUTs present. This was discussed in the first part of the paper as being one of the limitations of this study; 4ST intersections are not very common in urban and suburban areas, especially on divided arterials.

In terms of various crash type frequencies, as expected, the MUT sites exhibit less head-on/head-on left turn crashes and significantly more sideswipe and rear end crashes. The slightly higher angle crash frequency on MUT sites could be attributed to the higher traffic volumes for these sites. All crash types and total vehicular crashes exhibit overdispersion, as evident in the descriptive statistics present in Table 13 and Table 14.

The segment information, on the other hand, demanded some processing due to the fact that the first part of the study examined divided arterials directionally to assess the safety performance of MUTs. For the second part of the study, the segment portion of each site was represented for the entire arterial by combining direction characteristics. For most of the sites, there were only two segments with homogeneous characteristics included inside each box, one segment per direction of travel. However, other sites included more than two segments, therefore, data aggregation through averaging of variables was first performed. Afterwards, the two directions of travel were combined by adding the directional traffic volumes, number of lanes, access points along each site, and averaging other variables such as shoulder widths.

Table 15 display the descriptive statistics for the short segments that run from immediately upstream to immediately downstream of each intersection, inclusive of the adjacent MUTs. Table 16 provides similar data for control sites with traditional left-turn treatments. Collectively, these tables show that all of the traditional (i.e., control) sites and more than half of the MUT sites are located on 4-lane divided arterials. This speaks to the nature of MUT installations on 6-lane divided and 8-lane divided arterials; as previously mentioned, in the most developed urban areas, these MUTs are not installed to serve specifically one intersections, but rather at a boulevard level, serving multiple intersections and driveways. Since the selection of MUT sites was done to isolate mostly those sites where each MUT pair serves primarily one major intersection, it can be seen why the majority of MUT sites are located on 4-lane divided arterials.

The sites have comparable lane and shoulder widths, however, MUT sites have a wider range of median widths. This is reflective of the fact that MUTs were primarily installed in wide median boulevards. Similar statistics are also seen for commercial vehicle percentage and school presence along the sites. In terms of access points, the MUT sites exhibit larger counts for both residential and commercial driveways, potentially introducing more conflict points along a segment. This could also reflect the presence of MUTs to serve various developments along a boulevard or vice versa, that development has grown on boulevards that allow more access to businesses. This can also be reflective of the slightly higher angle crash frequency exhibited by the segment portion of MUT sites. Additionally, some of these MUTs are directly across from driveways or stop controlled intersections, which may introduce the potential for conflict points and thus certain types of crashes.

Table 15. Descriptive Statistics for Segments with MUTs (N=23)

Parameter	Average	St. Dev	Min	Max
4-lanes Divided Segments	0.522	0.502	0	1
6-lanes Divided Segments	0.261	0.441	0	1
8-lanes Divided Segments	0.174	0.381	0	1
Lane Width	11.739	0.488	10	12
Median Width	76.087	53.388	26	183
Right Shoulder Width	6.826	4.726	0	12
Left Shoulder Width	2.652	3.157	0	8
School Presence	0.304	0.462	0	1
Commercial Vehicle Percent	3.95	2.683	1.213	11.766
Count of Residential Driveways	2.522	5.9	0	24
Count of Commercial Driveways	8.783	12.548	0	42
Head-on Crash Frequency	0.035	0.184	0	1
Angle Crash Frequency	0.357	0.797	0	5
Rear End Crash Frequency	3.313	5.983	0	34
Sideswipe Same Side Crash Frequency	1.009	1.871	0	11
Total Vehicular Crash Frequency	5.687	8.515	0	47

Table 16. Descriptive Statistics for Control Segments without MUTs (N=9)

Parameter	Average	St. Dev	Min	Max
4-lanes Divided Segments	0.956	0.208	0	1
6-lanes Divided Segments	0	0	0	0
8-lanes Divided Segments	0	0	0	0
Lane Width	11.611	0.463	11	12
Median Width	25.333	8.752	13	36
Right Shoulder Width	7.333	4.045	0	10
Left Shoulder Width	5.667	3.438	0	8
School Presence	0.333	0.477	0	1
Commercial Vehicle Percent	6.408	3.299	1	12.555
Count of Residential Driveways	0	0	0	0
Count of Commercial Driveways	0.889	1.933	0	6
Head-on Crash Frequency	0	0	0	0
Angle Crash Frequency	0.289	0.757	0	4
Rear End Crash Frequency	2.222	3.704	0	19
Sideswipe Same Side Crash Frequency	0.867	1.854	0	10
Total Vehicular Crash Frequency	4.333	5.924	0	33

Some additional information was manually collected for MUTs, including number of lanes, the presence of truck loons, which provide additional turning space for large vehicles such as trucks, and the presence of a driveway or intersection across the road from the MUT opening. The summary of such information is included in Table 17. The majority of MUT pairs consisted of signalized, stop controlled, or yield controlled MUTs, with some mixed pairs in terms of traffic control. Almost three quarters of the MUTs were one lane each and 17 percent of MUTs had two lanes each. The majority of MUTs were across the road from a driveway or intersections, which was mentioned previously as a factor for introduction of potential conflict points at these locations. However, this is a challenging aspect of the sample selection given that these MUTs are, in fact, located in developed areas, where access is given to subdivisions and also businesses along the boulevards. Just over a quarter of these MUTs had truck loons present for each of the MUTs in the pair.

Table 17. Descriptive Statistics for Aggregated MUTs (N=23)

Parameters for MUT Pair	Average	St. Dev	Min	Max
Both Signalized	0.217	0.414	0	1
Both Stop Controlled	0.391	0.490	0	1
Both Yield Controlled	0.174	0.381	0	1
Signalized/Stop Controlled	0.130	0.338	0	1
Signalized/Yield Controlled	0.087	0.283	0	1
One Lane Each	0.739	0.441	0	1
Two Lane/One Lane	0.087	0.283	0	1
Two Lanes Each	0.174	0.381	0	1
Driveway Across from MUT Opening	0.652	0.701	0	1
Intersection Across from MUT Opening	0.174	0.381	0	1
Presence of Loons	0.261	0.441	0	1
Head-on Crash Frequency	0.009	0.093	0	1
Angle Crash Frequency	0.348	0.928	0	6
Rear End Crash Frequency	1.348	3.763	0	33
Sideswipe Same Side Crash Frequency	0.417	1.017	0	6
Total Vehicular Crash Frequency	2.452	5.694	0	42

2.4 Statistical Methods

Once the database was assembled, the safety performance functions were estimated at a facility level, for intersections, segments, and MUTs, and at the site level. Subsequently, the data was used to predict a series of regression models to examine how the annual number of crashes for a given intersection and segment, changes as a function of traffic volume, operational, and geometric characteristics of the roadway, and most importantly, the presence of MUTs or the density of MUTs. Several models were estimated for total vehicular crash frequency by crash type for head-on crash frequency, angle crash frequency, sideswipe crash frequency, and rear-end crash frequency.

One of the common frameworks for crash data modeling is the Poisson model. The probability of a segment or intersection i experiencing y_i crashes during a specific period, in the structural form shown in Equation 1.

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!} \quad \text{(Eq. 1)}$$

where λ_i is the Poisson parameter for segment i, which is equal to the segment's expected number of crashes during the analysis period, $E[y_i]$. Poisson regression models are estimated by specifying the Poisson parameter λ_i as a function of explanatory variables. The most common functional form for the Poisson parameter is shown in Equation 2.

$$\lambda_i = \text{EXP}(\beta X_i) \quad \text{(Eq. 2)}$$

where X_i is a vector of explanatory variables and β is a vector of estimable parameters. However, the crash data is often susceptible to dispersion, where the variance is larger or smaller than the sample mean. To accommodate for the overdispersion of crash data, a negative binomial regression model was initially utilized. The negative binomial model is derived by rewriting this Poisson parameter for each segment i as shown in Equation 3.

$\lambda_i = \text{EXP}(\beta X_i + \varepsilon_i)$ (Eq. 3)

where EXP(ε_i) is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as shown in Equation 4.

$\text{VAR}[y_i] = E[y_i] + \alpha E[y_i]^2$ (Eq. 4)

The α term is also known as the over-dispersion parameter, which is reflective of the additional variation in crash counts beyond the Poisson model (where α is assumed to equal zero).

For both intersections and segments, there is strong evidence of overdispersion which is reflected by the summary statistics in Table 1 through Table 5 for intersection crashes and Table 8 through Table 12 for MUT and segment crashes.

While the negative binomial framework accommodates overdispersion of crash data, another methodological issue that arises when using multiple years of data for the study sites is temporal correlation. To account for temporal correlation among the observations for each site, a random effects framework was utilized instead. This model allows for the constant term to vary across locations (study sites) as shown in Equation 5.

$\beta_i = \beta + \omega_i$ (Eq. 5)

where the *i* subscript indexes a specific road segment and ω_i is a random error term that is assumed to follow a specific distribution. The error term is assumed to follow a normal distribution, with a mean of zero and variance to be estimated as a model parameter, which is allowed to vary across intersections, road segments and MUTs.

2.5 Results and Discussion

2.5.1 Disaggregate-Level Analysis of MUTs

The data for this analysis was structured in three parts: an intersection crash frequency and type data set, a segment crash frequency and type data set, and an MUT-specific data set. These data sets were subsets of the data used for the Michigan SPF Intersection and Segment projects. In other words, only the divided roadway segments (4D, 6D, and 8D) were utilized considering MUTs only exist in divided roadways. This means that from the group of randomly selected intersections which were reviewed in detail as part of the Intersection SPF project, only the ones which were located on divided roadway segments were identified and utilized. Due to differences in the study periods of the two projects, the intersection data was collected for years 2008-2012 while the segment data was collected for years 2010-2014, the intersection crash data and other attributes were collected for years 2013-2014.

Each of the intersections was classified into one of four types based on number of legs and traffic control. Table 6 outlines the breakdown of the 128 intersections by type (number of legs and traffic control) and on which types of segments these intersections were located.

Table 18 describes the crash frequency and crash type (angle crashes and head-on/head-on left turn crashes) for each of these intersection types.

Table 18. Crash Type Counts and Total Vehicular Crashes by Intersection Type

Type	Observations	Sites	Angle Crash	Head-On Crash	Total Vehicle Crash
3SG	135	27	64	25	702
4SG	210	42	763	57	3640
3ST	215	43	33	4	310
4ST	80	16	40	1	143

As it can be observed on Table 18, the majority of angle crashes occur at signalized intersections, especially 4-leg intersections. Similarly, the head-on crash frequency is highest at these locations. The same trend can also be seen for total vehicular crashes. This could be explained by the fact that the urban and suburban signalized intersections carry a much larger traffic volume on a daily basis, as volume is one of the most critical exposure factors.

So far, a series of random effect models have been estimated examining the intersection total vehicular crash frequency, angle crash frequency, and head-on crash frequency. The random effects framework accommodates the temporal correlation caused by the repeated observations for each site over 5 study years by allowing the intercept term to vary across locations.

Table 19 provides the intersection model results of the total crash frequency. As expected, the major road and minor road traffic volumes play a significant role in crash frequency. The relationship of major road AADT and crash frequency is such that for every unit increase in traffic, one would expect 0.86 more crashes. 3-leg signalized intersections and stop-controlled intersections are associated with fewer crashes as compared to 4-leg signalized intersections. This can be attributed to less traffic for both intersection types, and less conflict points when comparing the 3SG with the 4SG intersections. The number of through lanes is associated with higher crash frequency, which seems intuitive given that the more lanes a facility has, the more traffic is usually generated. Interestingly, the presence of a right turn lane is also associated with higher crash frequency. This can be explained by the added conflict points when another movement is allowed at an intersection. Parking on the major road is associated with a lower crash frequency. This could be due to several reasons: primarily, parking is installed in the lower speed arterials, where traffic volumes are not as high, thus not impacting the flow of traffic. Additionally, the presence of parked vehicles could deter drivers from careless driving, especially given the lack of shoulder/recovery space is not available when parking is present, which in turn can reduce the room for recovery when drivers swerve. Lastly, the prohibition of the left turn movement at an intersection is associated with lower crash frequency, as is the presence of an MUT, albeit at a higher level.

Table 19. Intersection Total Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-8.7741	1.3688	-6.41	<0.0001
Log of Major Road Annual Average Daily Traffic	0.8675	0.1422	6.1	<0.0001
Log of Minor Road Annual Average Daily Traffic	0.2033	0.0662	3.07	0.0021
3-Leg Signalized Intersection	-0.5393	0.2297	-2.35	0.0189
Stop Controlled Intersection	-0.821	0.2824	-2.91	0.0036
Prohibited Left Turn	-0.4562	0.2451	-1.86	0.0627
Presence of MUT on Major Road	-0.7976	0.327	-2.44	0.0147
Major Road Through Lanes	0.1044	0.0605	1.73	0.0844
Major Road Right Turn Lane Presence	0.5239	0.1685	3.11	0.0019
Major Road Parking Presence	-1.3725	0.5948	-2.31	0.021
Interaction: Prohibited Left Turn & Presence of MUT	0.513	0.3903	1.31	0.1887

Table 20 provides the intersection model results of the angle crash frequency. The traffic volumes have a lesser effect on angle crashes as compared to total vehicular crashes. However, as it can be seen, the 3SG intersections are associated with much lower angle crash frequency. This is highly likely due to the only two possibilities for left turn movements at a 3SG facility as compared to the 4SG facility, which usually has left turn movements from both legs of each of the intersecting roadways, coupled with higher volumes. Both prohibition of left turns and the presence of MUTs are associated with fewer angle crashes, at a similar effect. Similar effects are seen for through lanes and presence of right turn lanes as in the model for total crash frequency. Additionally, regional indicators were added in this model to ascertain how angle crashes vary by region. It can be seen that as compared to the Metro Region, all the rest of the regions are associated with higher angle crash frequency.

Table 20. Intersection Angle Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-9.9855	1.8686	-5.34	<0.0001
Log of Major Road Annual Average Daily Traffic	0.6632	0.1818	3.65	0.00026
Log of Minor Road Annual Average Daily Traffic	0.3055	0.0814	3.75	0.00017
3-Leg Signalized Intersection	-1.4953	0.2842	-5.26	<0.0001
Stop Controlled Intersection	-0.8884	0.2973	-2.99	0.0028
Prohibited Left Turn	-0.628	0.2616	-2.4	0.01636
Presence of MUT on Major Road	-0.751	0.3073	-2.44	0.01453
Major Road Through Lanes	0.1807	0.0581	3.11	0.00189
Major Road Right Turn Lane Presence	0.4354	0.1854	2.35	0.01883
Superior Region	1.255	0.4151	3.02	0.0025
North Region	1.6018	0.4495	3.56	0.00037
Grand Region	0.486	0.2284	2.13	0.03338
Bay Region*	0.7678	0.533	1.44	0.14971
Southwest Region	1.1901	0.3788	3.14	0.00168
University Region	0.75	0.3631	2.07	0.03887
Interaction: Prohibited Left Turn & Presence of MUT	1.0381	0.3801	2.73	0.00632

*Not significant at the 95% confidence interval

Table 21 provides the intersection model results of the head-on crash frequency. Head on crash frequency is only affected by traffic volumes on the major road, the prohibition of left turns, and the presence of MUTs. The effects are similar to the previous two models, aside from the magnitude of the effects being much higher. Also, the fact that head-on crashes are not as frequent as angle crashes makes the model more difficult to specify.

Table 21. Intersection Head-On Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-10.35	2.243	-4.61	<0.0001
Log of Major Road Annual Average Daily Traffic	0.948	0.228	4.16	<0.0001
Prohibited Left Turn	-2.4	0.555	-4.33	<0.0001
Presence of MUT on Major Road	-1.342	0.497	-2.7	0.007
Interaction: Prohibited Left Turn & Presence of MUT	1.575	0.754	2.09	0.037

Due to the larger traffic volume they carry, the 6D and 8D roadways experience more rear-end and sideswipe crashes per observation (note that the sample size for these facilities is one-third of the sample size of 4D facilities). Similarly, this can also be observed for total vehicular crashes in Table 22.

Table 22. Crash Type Counts Total Vehicular Crashes by Segment Type

Type	Observations	Sites	Rear End Crash	Sideswipe Same Side Crash	Total Vehicle Crash
4D	845	169	1676	501	3842
6D	295	59	1228	413	2226
8D	265	53	1830	610	3194

As for the intersections, three models were estimated for the segment data, a total crash frequency model, a rear end crash frequency model, and a sideswipe/same side crash frequency model. The results have been presented in Table 23 through Table 25.

Table 23 provides the segment total crash frequency model results. Total crashes are positively associated with traffic volume, as expected. Posted speed limits also have a positive effect on crashes, however, posted speed limit is associated with functional class. The higher speed arterials are also the ones that carry more volume, thus one would expect more crashes to occur on these facilities. Commercial driveway density also is associated with higher crash frequency. Commercial development is usually denser in urban areas and can be the cause of higher access points along these routes. This in turn leads to higher volumes, and more conflict points. On the other hand, industrial driveways are located in less busy areas, away from commercial or residential development, thus being associated with less crashes. The higher densities of signalized intersections and MUTs is related to higher segment crashes as well. Lastly, the presence of schools on the segments has a decreasing effect on crashes. This could possibly be explained by lower speed limits or driver behavior.

Table 23. Segment Total Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-8.5488	0.75478	-11.33	<0.0001
Log of Annual Average Daily Traffic	0.89039	0.07058	12.61	<0.0001
Posted Speed Limit	0.02243	0.00611	3.67	0.00024
Commercial Driveway Density	0.01535	0.00839	1.83	0.06711
Industrial Driveway Density	-0.08598	0.02881	-2.98	0.00284
Signalized Intersection Density	0.07477	0.03282	2.28	0.0227
MUT Density	0.05056	0.01017	4.97	<0.0001
School Presence	-0.20237	0.09828	-2.06	0.03948

The model for same side sideswipe crash frequency, presented in Table 24, illustrates mostly the same relationships between these crashes and the variables of traffic volume, posted speed limit, signalized intersection density, MUT density, and school presence. Additionally, left shoulder width has a decreasing effect on crashes; as the shoulders get wider, drivers are provided with more room to maneuver and correct for driving mistakes. Similar effects were observed with the rear end crash frequency model in Table 25; additionally, some regional effects were found for the Superior, Southwest, and University regions, where all three exhibited a lower rear end crash frequency compared to the Metro region.

Table 24. Segment Sideswipe Same Side Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-11.8623	1.0996	-10.79	<0.0001
Log of Annual Average Daily Traffic	1.0648	0.1085	9.82	<0.0001
Left Shoulder Width	-0.0917	0.0241	-3.8	0.00015
Posted Speed Limit	0.0236	0.01	2.36	0.01829
Signalized Intersection Density	0.1002	0.0401	2.5	0.01253
MUT Density	0.0464	0.0136	3.41	0.00064
School Presence	-0.2353	0.1234	-1.91	0.05665

Table 25. Segment Rear End Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-12.0166	1.2512	-9.6	<0.0001
Log of Annual Average Daily Traffic	1.2701	0.1255	10.12	<0.0001
Left Shoulder Width	-0.0177	0.0208	-0.85	0.3934
MUT Density	0.0395	0.0151	2.61	0.009
Superior Region	-0.7633	0.3184	-2.4	0.0165
Southwest Region	-0.8943	0.305	-2.93	0.0034
University Region	-0.5025	0.262	-1.92	0.0551

The last model estimated was an MUT-specific model for total vehicular crash frequency illustrated in Table 26. This was done to examine the manner in which traffic volumes for both the MUT and the segment on which it is located, as well as MUT type of traffic control and the segment number of lanes, affect crash frequency at the MUT. As previously mentioned, the crashes were queried such that they were labeled as intersection crashes and within a 0.04-mile radius to ensure that segment crashes were not included and as such, over represented. Traffic volumes for the MUT display similar effects, in terms of exposure on the major and minor roads, as would be seen in the case of an intersection. This is not surprising given that MUTs act as a "hybrid" intersection where only turning movements are allowed, directional or bidirectional. Higher crashes can be expected at stop controlled and signalized MUTs, however, this is also reasonable given the higher traffic volumes these MUTs carry on a daily basis.

Table 26. MUT Total Vehicular Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-9.416	0.895	-10.520	<0.001
Log of Segment Annual Average Daily Traffic	0.714	0.088	8.140	<0.001
Log of MUT Annual Average Daily Traffic	0.261	0.026	10.180	<0.001
Signalized MUT	1.297	0.146	8.900	<0.001
Stop-controlled MUT	0.549	0.136	4.040	<0.001
Overdispersion Parameter	0.066	0.011		
Variance of Random Effects, σ^2	0.740			

2.5.2 Aggregate-Level Analysis of MUTs

Several models were estimated for total crash frequency and the four types of crash type frequencies; angle crashes, rear-end crashes, and sideswipe crashes. The significantly small sample size and sample mean of head-on crashes did not allow for the estimation of a head-on crash frequency model.

Table 27 presents the model results for total crash frequency for MUT-equipped sites and left-turn sites. As expected, there is a positive correlation between both major and minor street traffic volume and the frequency of traffic crashes.

Table 27. Total Vehicular Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-5.428	1.275	-4.260	0.004
Log of Major Road Annual Average Daily Traffic	0.627	0.131	4.800	<0.001
Log of Minor Road Annual Average Daily Traffic	0.346	0.058	5.930	<0.001
Presence of MUTs	-0.151	0.166	-0.910	0.360
Unsignalized Intersection	-0.254	0.239	-1.060	0.290
Overdispersion Parameter	0.141	0.027		
Variance of Random Effects, σ^2	0.087			

The presence of median U-turns was associated with lower crash frequency. However, this result was not statistically significant (p-value = 0.36). In spite of this fact, this initial evidence is important because it indicates a potential net-benefit to roadway safety, in addition to the operational advantages such as more efficient signal timing. Further analysis of this finding is examined in Table 28 in terms of a more detailed MUT-type model and type-specific crash frequency models.

Ideally, a larger sample would be utilized to facilitate the development of separate models for signalized and unsignalized intersections, however, that was not possible for this analysis. As one would expect, fewer crashes occur at unsignalized intersections in comparison to signalized intersections, due primarily to the fact that signals are utilized at locations with higher volumes and higher frequency of conflicting maneuvers. Due to the lower traffic volume, particularly of the minor street, associated with unsignalized intersections, there are fewer conflicts and ultimately, fewer crashes.

While the prior results suggest a potential safety benefit associated with median U-turns, it is important to acknowledge that not every median U-turn is similarly designed. In fact, locations where the median U-turns are signalized may be functioning as a series of intersection, with some of the intersection-related crashes being shifted toward the upstream or downstream MUT. Table 28 presents a model that allows for an investigation of such differences.

Table 28. Detailed Total Vehicular Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-3.292	1.437	-2.290	0.022
Log of Major Road Annual Average Daily Traffic	0.525	0.138	3.820	0.000
Log of Minor Road Annual Average Daily Traffic	0.221	0.062	3.570	0.000
Density of Three-leg Stop Controlled Intersections	-0.020	0.009	-2.270	0.024
Signalized Intersection w/ Signalized MUTs	0.150	0.213	0.700	0.482
Signalized Intersection w/ 1 Signalized MUT and 1 Unsignalized MUT	0.087	0.200	0.440	0.662
Signalized Intersection w/ Unsignalized MUTs	-0.279	0.176	-1.580	0.114
Unsignalized Intersection w/ Unsignalized MUTs	-0.718	0.315	-2.280	0.022
Unsignalized Intersection w/o MUTs	-0.538	0.271	-1.990	0.047
Eight Lanes	0.408	0.235	1.740	0.082
Overdispersion Parameter	0.141	0.027		
Variance of Random Effects, σ^2	0.052			

This model was estimated such that all combinations of intersection control and MUT presence are being compared to signalized intersections without MUTs. Locations where the primary intersection was signalized, and where one or both of the MUTs were also signalized, were associated with a higher crash frequency, though this effect was not statistically significant. It is possible that the increased crash frequency associated with signalized MUTs is due to the fact that these sites tended to experience higher volumes, particularly for left-turning traffic. As a consequence, it is somewhat challenging to identify comparable control (i.e., non-MUT) locations. It is also worth noting that this analysis utilized a relatively small sample size for this level of fidelity among the site types and that a larger sample could potentially have an impact on the observed safety effect. Additionally, the utilization of turning movement specific volume information could potentially provide additional insight into this observation.

For locations with unsignalized MUTs, a safety benefit was observed for both signalized and unsignalized intersections. Unsignalized MUTs are utilized at locations with lower turning volumes that signalized MUTs, so ultimately, it makes sense that they would have fewer crashes than signalized MUTs. This again brings up the potential usefulness of turning-movement specific volume information, particularly for the main intersection associated with each site.

Eight-lane divided roads were shown to be associated with higher crash frequency. This is again due to the number conflicting movements that likely occur at these locations due to lane change maneuvers.

Beyond simply investigating the effect of MUTs on total crashes, it is also important to consider their effect on specific crash types, as some crash types are inherently more severe than others. To this end, Table 29 presents a model that was estimated to examine the effect of MUTs on angle crashes.

Table 29. Angle Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	p-Value
Intercept	-6.219	1.588	-3.920	<0.001
Log of Major Road Annual Average Daily Traffic	0.490	0.179	2.740	0.006
Log of Minor Road Annual Average Daily Traffic	0.387	0.098	3.970	<0.001
Signalized Intersection with Unsignalized MUT	-0.521	0.240	-2.170	0.030
Overdispersion Parameter	0.002	0.000		
Variance of Random Effects, σ^2	0.236			

Overall, it was observed that the presence of MUTs was associated with lower angle crash frequency, however, this was only shown for unsignalized MUTs at signalized intersections. This result is intuitive, as angle crashes largely occur when left-turning vehicles enter the path of oncoming traffic, an event that's likelihood is reduced when left turns are prohibited due to the MUTs. It is quite likely that a larger sample would further highlight this finding. The other type of intersection-MUT traffic control combinations were not significant and thus were not included in the model.

Table 30 presents the results for sideswipe crash frequency model. The combination of signalized intersections with signalized MUTs is shown to be associated with higher sideswipe crash frequency. Additionally, the percentage of commercial vehicles is associated with less sideswipe crashes. This could reflect certain driver behavior of potentially maintaining lane position and less lane switching.

Table 30. Sideswipe Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-4.287	2.335	-1.840	0.066
Log of Major Road Annual Average Daily Traffic	0.437	0.217	2.010	0.044
Log of Minor Road Annual Average Daily Traffic	0.209	0.086	2.440	0.015
Signalized Intersection w/ 1 or more signalized MUTs	0.682	0.237	2.880	0.004
Commercial Vehicle Percent	-0.090	0.045	-1.990	0.047
Overdispersion Parameter	0.355	0.113		
Variance of Random Effects, σ^2	0.099			

Increased frequency of rear end collisions was associated with the presence of signalized MUTs at signalized intersections, in comparison to signalized and unsignalized intersections without MUTs as shown in Table 31. This result is somewhat counter-intuitive, as one might expect that by taking the left-turning vehicles out of the through traffic flow, these types of crashes would likely be reduced. This result is potentially attributable to additional stopping points for the through traffic. Additionally, since signalized MUTs are indicative of a large volume of would-be left turning vehicles, it is possible that the queue for the MUT may be spilling into the through lanes, resulting in more crashes.

Table 31. Rear-End Crash Frequency Model Results

Parameter	Estimate	Std. Error	z-Value	Significance
Intercept	-6.883	1.799	-3.830	<0.001
Log of Major Road Annual Average Daily Traffic	0.663	0.176	3.780	<0.001
Log of Minor Road Annual Average Daily Traffic	0.201	0.087	2.300	0.021
Signalized Intersection, 1 or More Signalized MUT	0.640	0.239	2.680	0.007
Unsignalized Intersection with MUTs	-0.712	0.621	-1.150	0.251
Overdispersion Parameter	0.370	0.116		
Variance of Random Effects, σ^2	0.104			

Conversely, unsignalized intersections with MUTs were associated with lower frequency of rear-end collisions. It is likely that operational efficiency of these types of locations results in fewer rear-end collisions caused by excessive queuing of vehicles. Additionally, by passing through an intersection, drivers may be more attentive to what is going on in front of them and more likely to notice other drivers decelerating to enter the MUT.

Ultimately, the results for the boulevard-level and the site level analyses provide some insight into the safety effects of MUTs. At a boulevard level, the presence and density of MUTs was shown to:

- Reduce total crash frequency and crash frequency for head-on and angle crashes at boulevard intersections, which are typically some of the most severe crashes,
- Be associated with higher sideswipe and rear end crashes along the segment portions of the boulevards,

- At the MUT level, signalized MUTs are associated with higher crash frequency as compared to unsignalized MUTs, largely due to higher traffic volumes attributable to turning movements and adjacent intersections

At the aggregate/site level, the results for total crash frequency generally followed those of the disaggregate level analysis in that:

- Altogether, the presence of MUTs was associated with a decreased crash frequency, although this finding was not highly significant from a statistical standpoint,
- The presence of unsignalized MUTs was associated with lower total crash and angle crash frequency. Signalized MUTs were shown to have an opposite effect, although due to the small sample size, their effects were not significant at the 95% confidence level.

Collectively, these analyses demonstrate that MUTs have safety benefits for arterials, therefore, studying the safety impacts of MUTs at isolated intersections may not fully capture their benefits on the corridor.

CHAPTER 3. COMPARING THE SAFETY PERFORMANCE OF TEMPORARY TRAFFIC CONTROL STRATEGIES IN FREEWAY WORK ZONES

This study involves the development of SPFs for freeway work zones. The Highway Capacity Manual defines work zones as "area of highway in which maintenance and construction operations are taking place that impinge on the number of lanes available to moving traffic or affect the operational characteristics of traffic flowing through the area" (TRB, 2000). The presence of a work zone generally results in both mobility and safety impacts to road users. Minimizing the adverse impacts associated with work zones has become a priority for road agencies, especially since the inception of the *Work Zone Safety and Mobility Rule* (Scriba et al., 2005). Assessing the potential impacts of work zone temporary traffic control strategies on traffic safety (i.e., crashes, injuries, and fatalities) continues to be a primary emphasis of work zone research. In 2010, the *Highway Safety Manual* (*HSM*) was published, providing a framework for road agencies to estimate the safety performance of various road facility types (AASHTO, 2010). The first edition of the HSM provides methods for estimating the effects of work zones on limited access facilities. However, this guidance is very general and this is an area that has been significantly under-researched in the broader safety literature. This study will estimate SPFs that consider freeway geometry and traffic conditions, as well as the effects of various temporary traffic control strategies such as lane shifts, shoulder closures, and lane closures.

3.1 Literature Review

A recent paper summarized most of the work in this area dating back to 1978 (Yang et al., 2014). Much of the work in this area has involved estimating the change in crash risk that under work zone operations as compared to "normal" (i.e., non-work zone) traffic operations. This research has shown work zone crash risk to increase from 20 to 30 percent as compared to normal operations (Ullman, 2008). The crash risk for a given work zone is obviously dependent upon a number of factors, some of which are related to the work activity and others that are related to site-specific factors, such as traffic volumes and roadway geometry. Recent work has aimed to discern how crash risk varies with respect to these factors. Research has shown that when work activity results in the temporary closure of travel lanes, the crash risk for individual motorists increases by 66 percent during daytime conditions and 61 percent at night as compared to similar non-work zone conditions (Ullman, 2008).

As road agencies are faced with a myriad of potential alternatives in developing temporary traffic control strategies for a specific work zone, the ability to estimate the impacts of these alternatives on the frequency or rate of traffic crashes is an important criterion. To this end, the *Highway Safety Manual* (*HSM*) provides a series of crash modification functions (CMFs) that can be used to estimate the increase in crash risk posed by work zone operations (AASHTO, 2010). These CMFs provide an estimate of the increase in crashes that would occur within a given work zone based upon work zone length and project duration. Equation 6 and Equation 7 illustrate the increases in crashes that would be expected to occur as the length of the work zone (in miles) increases or as the project duration (in days) increases, respectively.

$$CMF = 1.0 + \frac{(\%\ increase\ in\ length\ in\ miles \times 0.67)}{100} \quad \text{(Eq. 6)}$$

$$CMF = 1.0 + \frac{(\%\ increase\ in\ duration\ from\ 16\ days \times 1.11)}{100} \quad \text{(Eq. 7)}$$

To utilize these CMFs, an initial baseline estimate of the number of crashes at a given location is required (e.g., the number of crashes that would occur at the work zone location in the absence of a work zone during the same analysis period). This baseline estimate is then multiplied by the appropriate CMF to estimate the total number of crashes that would occur while the work zone is in place. For example, a 10-percent increase in work zone length would result in a 6.7-percent in crashes (1.0+ (10% x 0.67)/100).

The CMFs from the HSM were based upon data from 36 work zones in California (Khattak et al., 2002). Recently, data from the state of Missouri was used to develop similar CMFs as part of a project conducted through the Smart Work Zone Deployment Initiative (Sun et al., 2014). This research, which was based on data from 162 work zones in Missouri, showed similar effects. The magnitude of these effects was slightly less pronounced than the California study. Crashes increased by 0.58 percent for every one-percent increase in work zone length and by 1.01 percent for every one-percent increase in work duration. The research literature includes a several additional studies that have involved the development of CMFs, as well as safety performance functions (SPFs), which can be used to estimate the number of work zone crashes as a function of characteristics such as AADT, work zone length, and project duration.

A 1996 Indiana study showed crash rates in work zones were significantly higher than the same roadways under non-work zone conditions (Pal and Sinha, 1996). Similar models were developed as part of a 2000 study that related crashes to project duration, type of work, AADT and work zone length (Venugopal and Tarko, 2000). Separate models were calibrated for the work zone area, as well as the approaches immediately upstream of the work zone. As a part of NCHRP Project 17-30, data from California, North Carolina, Ohio, and Washington were used to estimate a series of negative binomial models for work zone crashes by severity level (Srinivasan et al., 2011). Based on the results of these models, separate CMFs were estimated for daytime and nighttime conditions. A recent New Jersey study examined the effects of work zone length on crash frequency while accounting for potential errors in length measurement due to deviations from the construction schedule (Ozturk et al., 2013). Results showed that crashes were influenced by work zone length, traffic volumes, speed limit, lighting condition, and the number of operational and/or closed lanes.

Research into the effects of specific temporary traffic control strategies, such as lane closures, has been more limited. A 2014 Indiana study found crashes to be affected by work zone length, traffic volume, and various roadway (e.g., shoulder widths) and work zone (e.g., lane shift, lane split, etc.) features. Crashes were also found to vary by time of year and region (Chen and Tarko, 2014). This study also compared the results of several analytical frameworks that address specific analytical concerns that are common in work zone data. Further research is warranted as to practical and analytical issues involved in the analysis of work zone safety data.

This study will provide an important contribution to the research literature through the analysis of data from 790 closures that were implemented as a part of construction projects throughout Michigan. Safety performance functions (SPFs) are estimated to examine differences in safety performance among the four types of work zones, shoulder closure, single lane closure, multi-lane closure, and lane shifts, while controlling for site-specific factors such as AADT, segment length, and work zone duration.

3.2 Data Sources and Collection

For the purposes of this study, data were collected from work zones that included either a shoulder closure, single-lane closure, double-lane closure, or lane shift. Examples of such work zone types are illustrated in Figure 10.

Figure 10. Examples of the Four Types of Lane Closures

The data for these closures are obtained for projects that occurred between 2008 through 2013. The data sources were:

1. Lane closure reports maintained by the Michigan Department of Transportation (MDOT);
2. Annual average daily traffic estimates from an MDOT roadway inventory file;
3. Traffic crash information from the Michigan State Police crash database, and
4. MDOT Sufficiency Files for years 2007-2013

At the onset of the study, lane closure reports were used to identify those closures that were of at least 0.4 miles in length and at least 3 days in duration. These thresholds were established to ensure: (a) the work zone was sufficiently long such that crash data could be accurately assigned to the associated road segment; and (b) the duration was long enough such that some baseline crash frequency could be established.

When identifying boundaries for the work zones, these limits were established at the nearest upstream/downstream overpass or entrance/exit ramp. Consequently, these limits generally extend outside of the work zone and include portions of the freeway segments that were immediately upstream and downstream of the actual work zone area. Similarly, the closure dates were as noted in the MDOT lane closure database. As some closures were intermittent, it is possible that temporary traffic control was not in place during the entirety of the analysis period. Consequently, the results of this study are likely to be conservative in terms of the estimated impacts for specific traffic control strategies.

In addition to collecting data for the work zone period, traffic crash, volume, and geometric data were also obtained for the same time period from the prior year. These data serve as a baseline, allowing for a comparison of how crash rates change when a work zone is in place as compared to normal roadway operations. Table 32 provides summary statistics for both the pre-work zone period, as well as the period during which a closure was in place. The variables that are included in both data sets are as follows:

- Average annual daily traffic
- Length of analysis segment
- Duration of analysis period

- Geometric characteristics, including left and right shoulder widths, median width, and type of barrier present
- Total, property damage only (PDO), and injury crashes

In addition to these general site characteristics, data were also obtained from the MDOT lane closure file as to the type of closure that was in place at a given site. These include shoulder, single-lane, and multi-lane closures, as well as lane shifts (e.g., redirecting one or more travel lanes onto the shoulder). The length, duration, and AADT data were comparable to those from prior studies, including the California study that was the basis for the HSM methods (Khattak et al., 2002) and the Missouri study (Sun et al., 2014). Traffic volumes were relatively stable over the two analysis periods. The segment lengths and durations of the analysis periods were identical due to the case-control nature of the study design. When examining crash data at the aggregate level, total and PDO crashes were higher when the work zones were in place while injury crashes were marginally lower.

Table 32. Descriptive Statistics for Work Zone Data (N = 790 segments)

	Pre-Work Zone Period		Work Zone (Closure) Period	
Parameter	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Annual Average Daily Traffic (AADT)	38618.12	22205.89	38077.65	21703.39
AADT/Open Lane	13189.44	6198.45	24255.22	16419.58
Length of Work Zone Segment	5.00	5.54	5.00	5.54
Duration of Analysis Period	28.78	46.20	28.78	46.20
Open Lanes	2.83	0.58	1.76	0.76
Percent Commercial Vehicles	10.00	6.63	10.00	6.72
Shoulder Closure	N/A	N/A	0.15	0.36
Single-Lane Closure	N/A	N/A	0.56	0.50
Multi-Lane Closure	N/A	N/A	0.24	0.43
Lane Shift	N/A	N/A	0.04	0.19
Total Crashes	4.74	11.86	5.06	12.95
Property Damage Only Crashes	3.73	9.00	4.08	9.85
Fatal/Injury Crashes	1.01	3.10	0.98	3.43

N/A = not applicable

3.3 Methodology

Once the database was compiled, a series of statistical analyses was conducted to ascertain how these crash trends related to the work zone and other site characteristics. Various count data model frameworks were considered in the development of safety performance functions (SPFs). This included Poisson and negative binomial models, which were explained in the previous section, as well as random effects and random parameter variants. A summary of these methodological frameworks is provided below and further details of the methods can be found in recent state-of-the-art review papers (Lord and Mannering, 2010; Mannering and Bhat, 2014).

One concern is the potential for temporal correlation in crash counts on the same road segments over time. For example, it is anticipated that a freeway segment that experiences a higher number of crashes during the pre-work zone period may also experience an elevated crash risk during the construction period, as well. In order to address such correlation, a random effects framework is utilized, wherein the constant term for the model is allowed to vary across road segments as shown in Equation 8.

$$\beta_i = \beta + \omega_i \qquad \text{(Eq. 8)}$$

where the *i* subscript indexes a specific road segment and ω_i is a random error term that is assumed to follow a specific distribution. The error term is assumed to follow a normal distribution, with a mean of zero and variance to be estimated as a model parameter, which is allowed to vary across road segments and work zones. This effectively results in the constant term being treated as a random parameter, which is able to capture the effects of unobserved heterogeneity that is unique to each segment during both the pre-construction and construction periods. Intuitively, similar heterogeneity can be expected as to the effects of other parameters in the model. For example, specific traffic control strategies may exhibit different safety impacts across different work zones or road segments due to unobserved factors. Consequently, these parameters may be assumed to follow a similar distribution. Under such a framework, the Poisson parameter is now conditioned on the distribution of the error terms as shown in Equation 9.

$$\lambda_{ij}|\omega_j = EXP\ \ \beta X_{ij} \quad \text{(Eq. 9)}$$

Parameters are estimated through the log-likelihood function shown in Equation 10.

$$LL = \sum_{\forall i} ln \int_{\omega_i} g(\omega_i) P(n_i|\omega_i) d\omega_i \quad \text{(Eq. 10)}$$

where *g*(.) is the probability density form of the random error term, which is assumed to be normally distributed. As the log-likelihood function is computationally cumbersome, the parameters are estimated through simulation-based maximum likelihood. The probabilities are approximated by drawing values of the parameters from *g*(.). The procedure is repeated across many samples and the computed probabilities are averaged to compute the likelihood function. Halton draws are used an efficient alternative to random draws. Further details of the random parameters framework can be found in the research literature (Halton, 1960; Bhat, 2003; Greene, 2007; Chen and Tarko, 2014).

In order to interpret the practical impact of the variables affecting work zone crash risk, elasticities are calculated. Elasticities represent the average percent change in crash frequency associated with an increase in one of the independent variables. For continuous variables, the elasticity is calculated as shown in Equation 11.

$$E_{x_{ij}}^{\lambda_i} = \frac{\partial \lambda_i}{\partial x_{ij}} \frac{x_{ij}}{\lambda_i} \quad \text{(Eq. 11)}$$

where *E* represents the elasticity; λ_i is the expected crash frequency for segment *i*; and x_{ij} is the *j*th explanatory variable related to segment *i*. For the purposes of this study, continuous variables (e.g., AADT, work zone length, project duration) were included in the equation in log-form. Consequently, these parameter estimates directly represent the percent increase in crashes associated with a one-percent increase in the specific variable. Alternately, for binary indicator variables (i.e., closure type), a pseudo-elasticity can be calculated using Equation 12.

$$E_{x_{ij}}^{\lambda_i} = \frac{EXP(\beta_j) - 1}{EXP(\beta_j)} \qquad \text{(Eq. 12)}$$

where β_j is the parameter estimate for variable j. The pseudo-elasticity represents the percent change in crashes when x_{ij} is changed from zero to one (e.g., the change in crashes related to a specific closure type).

3.4 Results and Discussion

As a part of the analysis, a series of count data models were estimated, which included Poisson and negative binomial models, as well as random effects (i.e., only the constant term is random) and full random parameters negative binomial models. The goodness-of-fit for these models was compared across models using likelihood ratio (LR) tests with the results illustrated in Table 33. The LR statistic is distributed as chi-squared with degrees of freedom equal to the difference in the number of parameters between the restricted model and the more flexible, unconstrained model. The null hypothesis for the LR test is that the log-likelihood of the more flexible model does not provide improved fit as compared to the more restrictive model. The log-likelihood results in Table 33 show consistent improvements in fit that are statistically significant at a 99-percent confidence level when moving from the most restrictive (Poisson) model to the more flexible (random parameters negative binomial) model. Ultimately, the random parameters negative binomial model is able to accommodate the three key analytical concerns noted previously:

(1) overdispersion, wherein the variance of crash counts is significantly greater than the mean as indicated by the overdispersion parameter, which is shown to be significantly greater than zero;

(2) site-specific temporal correlation due to common, unobserved factors that are present at each segment during the pre- and during-work zone periods as reflected by the standard deviation of the constant term, which is found to be significantly greater than zero; and

(3) unobserved heterogeneity as demonstrated by those predictors that show significant variability from segment to segment, which are also indicated by standard deviations of several coefficients that are also significantly greater than zero. This is especially important in the case of AADT, which as mentioned previously, was not reflective of traffic volumes while the work zones were in place. The framework allows for capturing the effect of sites with lower or higher than "normal" volumes.

Table 33. Goodness-of-Fit Comparison

Model Formulation	Log-Likelihood	LR statistic	df	Significance	Mc-Fadden R^2
Constant-Only Poisson	-11388.4	N/A	N/A	N/A	N/A
Poisson	-3121.3	16534.2	7	<0.001	0.726
Negative Binomial	-2829.0	584.6	1	<0.001	0.752
Random Effects Negative Binomial	-2788.2	81.6	1	<0.001	0.755
Random Parameters Negative Binomial	-2783.8	8.8	8	<0.001	0.756

N/A = not applicable

Table 34 presents the final model results, which include details of each coefficient, the associated standard error, t-statistic, and p-value. All variables, except for the shoulder closure indicator, are found to have an impact that is statistically significant at a 95-percent confidence level. Random parameters are indicated by those variables that have a standard deviation that is significantly different from zero. For those variables where the standard deviation is not significant different from zero (indicated by N/S), these parameter effects are found to be fixed (i.e., constant across segments).

Table 34. Results of Random Parameters Negative Binomial Model

Variable	Coefficient	Std. Error	t-statistic	P-value
Intercept	-14.112	0.344	-41	<0.001
Std. dev.	0.315	0.017	18.38	<0.001
Log of Annual Average Daily Traffic	1.096	0.03	36.46	<0.001
Std. dev.	0.012	0.002	7.32	<0.001
Log of Segment/Work Zone Length	0.821	0.02	40.3	<0.001
Std. dev.	0.023	0.009	2.4	0.016
Log of Duration of Analysis Period	0.897	0.013	67.2	<0.001
Std. dev.	N/S	N/S	N/S	N/S
Shoulder Closed (1 if yes; 0 otherwise)	N/S	N/S	N/S	N/S
Std. dev.	N/S	N/S	N/S	N/S
One Lane Closed of Two per Direction (1 if yes; 0 otherwise)	0.238	0.081	2.93	0.003
Std. dev.	0.477	0.069	6.87	<0.001
One Lane Closed of Three-plus per Direction (1 if yes; 0 otherwise)	0.126	0.043	2.89	0.004
Std. dev.	0.134	0.039	3.45	<0.001
Multiple Lanes Closed (1 if yes; 0 otherwise)	0.15	0.056	2.68	0.007
Std. dev.	0.155	0.052	2.99	0.003
Lane Shift (1 if yes; 0 otherwise)	0.505	0.079	6.42	<0.001
Std. dev.	0.177	0.083	2.15	0.032
Overdispersion parameter (α)	0.077	0.011	7.23	<0.001

N/S = not statistically significant

Table 35 presents a summary of the elasticities based upon these model results. For those parameters that are found to vary across road segments, three elasticities are presented: one for the lower bound (calculated based on coefficient minus 1.96 standard deviations), one for the average effect, and one for the upper bound (calculated based on coefficient plus 1.96 standard deviations). These bounds demonstrate the variability in each parameter’s effects across the entire sample of segments/work zones.

Table 35. Summary of Elasticities from Random Parameters Negative Binomial Model

Parameter	Lower Bound	Average Effect	Upper Bound
Annual Average Daily Traffic (AADT)[a]	1.07	1.10	1.12
Segment/Work Zone Length[a]	0.78	0.82	0.87
Duration of Analysis Period[a]	N/S	0.90	N/S
Shoulder Closed[b]	N/S	N/S	N/S
One Lane Closed of Two per Direction[b]	-104.6	21.2	69.6
One Lane Closed of Three-plus per Direction[b]	-15.3	11.8	32.6
Multiple Lanes Closed	-17.4	13.9	36.9
Lane Shift[b]	14.0	39.6	57.6

[a]Elasticities represent the percent change associated with a one-percent increase in a continuous variable.
[b]Pseudo-elasticities represent the percent change associated with changing indicator variable from zero to one.
N/S = not statistically significant

Turning to the practical aspects of these results, annual average daily traffic (AADT) is found to have an effect that is roughly elastic (i.e., a one-percent increase in volume results in an increase in crashes of 1.07 to 1.12 percent). The effects of traffic volume are found to vary across study locations (as indicated by the random parameter), which may reflect the effects of unobserved differences specific to these road segments or work zones. This heterogeneity may also be reflective of imprecision in the volume estimates for each location. It is important to note that the AADT estimates used in the development of these models reflect annual averages. Consequently, these results may actually underestimate the effects of AADT since volumes are expected to be lower during the period when a work zone is in place due to diversion by travelers. Subsequent research is warranted, which considers actual volumes under work zone conditions to capture potential impacts due to diverted traffic for example. To this end, recent work in Wisconsin has demonstrated the integration of crash data with information on real-time traffic and lane closures (Greene, 2007).

In contrast to AADT, the effects of segment length and duration were slightly inelastic. Table 36 provides a comparison of these results with prior empirical results from California (Khattak et al, 2012), Missouri (Sun et al, 2014), and Indiana (Chen and Tarko, 2014). The

Michigan data show work zone length to exhibit a slightly larger influence while project duration exhibits a less pronounced influence.

Table 36. Comparison of Work Zone Duration and Length Effects to Prior Studies

Variable	California	Missouri	Indiana	Michigan
Work Zone Length	0.67	0.58	0.80	0.82
Project Duration	1.11	1.01	1.00	0.90

Crashes increased by 0.9 percent for every one-percent increase in project duration. This finding suggests crash risk is highest at short duration work zones and tends to level off over time. This may be reflective of drivers acclimatizing themselves to a work zone over time. It is important to note that the Michigan work zones included a number of projects with shorter durations (a minimum of 3 days) than the California and Missouri studies, both of which established minimum project durations of 15-16 days. The Indiana study compared per-month averages for longer duration work zones.

The effects of segment length varied from one work zone to another, with crashes increasing from 0.78 percent to 0.87 percent for a one-percent increase in length. This finding may be interpreted similarly to the duration effect as crash risk tends to level off, a possible indication of adaptation in driver behavior over longer work zones. Table 36 shows the duration effect tended to be less pronounced in Michigan as compared to findings from other states.

Focusing on the potential effects of traffic control strategies, crash frequencies were not significantly different when a shoulder closure was in effect as compared to normal (i.e., pre-work zone) traffic conditions. This is interesting and may be reflective of shoulder closures having minimal impacts on driver behavior. Driving simulator research has shown crash risk to be lower where shoulder work is occurring as opposed to where lane closures are present (Cheng et al, 2015). Subsequent research is warranted to investigate whether the type or intensity of work occurring on the shoulder may have an impact on crash risk.

In contrast to shoulder closures, crashes increased by 21.2 percent on average for single-lane closures that occurred along two-lane (per direction) freeways and by 11.8 percent where single-lane closures occurred on freeways with more than two lanes per direction. Crashes were approximately 13.9 percent higher where multi-lane closures were in place. There was substantial variability in these effects across work zones, with some locations exhibiting lower crash rates (i.e., fewer crashes than during similar pre-work zone conditions) and others experiencing significantly higher crash rates than during the pre-work zone period. These differences may be due to additional unobserved characteristics (e.g., temporary traffic control, roadway geometry) or to variability in normal traffic volumes when the work zones were in place.

The most pronounced construction related crash increases occurred where lane shifts were present. In these cases, crashes increased by 39.6 percent on average as compared to the pre-construction periods. This is consistent with prior research, which has shown significant increase in crashes at work zones where lane shifts or lane splits were utilized (Chen and Tarko, 2014). This result is consistent with a priori expectations as lane shifts are more variable, both geometrically and from a human performance standpoint, compared to standard lane closures. Lane shifts typically include movement of traffic onto the shoulder or a temporary lane (or shoulder extension), which creates several potential issues. First, the quality of the lane-to-shoulder (or lane-to-temporary lane) transition may impact the ability for drivers to negotiate the lane shift, which may be further exacerbated by the presence of shoulder rumble strips. Secondly, the loss of usable shoulder area greatly reduces the shy line, thereby positioning vehicles closer to the pavement edge and any barriers that may be present, further increasing the risk of lanedeparture collisions. The reduced length of shifting tapers compared to merging tapers may also negatively impact human performance. Furthermore, because the capacity is not reduced to the level of a standard lane closure, lane shifts create the potential for higher speeds while approaching the work zone and within the transition area. As lane shifts comprised only four percent of the total sample, additional research is warranted to better understand the reasons for this increase.

CHAPTER 4. CONCLUSIONS

Ultimately, this research provides findings that can be utilized by state agencies as part of more well-informed decision-making processes, which would allow agencies to strategically plan to optimize safety in consideration of issues of pertinence to two specific settings:

- in the vicinity of median U-turns on urban and suburban arterials, and
- in freeway work zones under various temporary traffic control strategies

The following sections summarize the key findings in each of these areas, in addition to outlining the limitations associated with each study and identifying prospective avenues for future research.

4.1 Safety Performance of MUTs on Urban and Suburban Arterials

MUTs have been present in urban and suburban arterials in the state of Michigan since the mid-1960s. While initially they were designed and constructed to combat congestion problems due to interlocking left turn movement, they have also been studied for their safety effects. The first portion of this study presents the results and findings from the analysis of 637 MUTs located in 4-lane, 6-lane, and 8-lane divided arterials. Considering that the installation of MUTs in Michigan is widespread at the boulevard level and not simply in isolated cases of intersections along these boulevards, the first part of the examination of the effects of MUTs was conducted on a boulevard level separately for intersections, segments, and lastly an MUT-specific crash frequency model was developed. The presence of MUTs and the prohibition of left turn movements at intersections were accompanied by lower crash frequencies, especially for head-on crashes and angle crashes, which are some of the most severe crashes that occur at traditional intersections. Other variables that are related to higher traffic volumes, such as number of lanes, or introduce conflict points in the vicinity of the intersection, such as the presence of right turn lanes, were found to have an increasing effect on total crash and angle crash frequency. The highest impact by left turn prohibition and/or the presence of MUTs was seen on head on crash frequency. This is to be expected given that head-on and head-on-left turn crashes should, for the most part, occur when left turn movements are allowed at the intersection. On a segment level, the MUT density (the number of MUTs per mile length of the segment) was associated with higher total crash, sideswipe, and rear end crash frequency. This is expected given that more traffic is present downstream of the intersection if the left turn is prohibited. Other variables that had a decreasing effect on intersection and segment crash frequencies were the presence of parking and presence of schools. The presence of parking near intersections could provide a calming effect on traffic while both of these variables might make drivers more aware of their surroundings and driving behavior, thus lowering the odds for conflicts. MUT specific crash frequency was affected by traffic volumes on the roadway as well as the MUT turning lane(s) and the type of traffic control of the MUT. Given that not all other states have fully embraced the MUT as an intersection design alternative, this study provides important findings with regards to the safety performance of such configurations.

One limitation to this study could be the limited size of the intersection sample. The intersections sampled from the pool of intersections that were manually reviewed and for which extensive data was manually collected. Additionally, the second constraint was that these intersections had to be located on the divided arterials to assess the safety impacts of MUTs, which are only present in divided roadway facilities. This allowed for 69 signalized intersections (27 of 3SG and 42 of 4SG) and 59 stop controlled intersections (43 of 3ST and 16 of 4ST). One caveat is that 4ST intersections generally exist in suburban or rural locations where traffic is not as large, whereas 3ST intersections are very frequent along arterials in urban areas. A solution for this could be to manually collect intersection geometric data for additional intersections located along divided arterials. This can, however, be a cumbersome task as previously explained in Section 2.2.

The second portion of the study examined the safety performance of MUTs at a site level, or in other words, for isolated intersections and the road segment following the intersections up to and including the MUT installations. Sites with MUTs present were compared to similarly long sites with left turns. Results showed that the presence of MUTs was associated with lower total crash frequency overall. At a more granular level, various combinations of intersection-to-MUTs by traffic control were examined. It was found that for locations with unsignalized MUTs, a safety benefit was observed for both signalized and unsignalized intersections. Additionally, unsignalized MUTs were associated with lower angle crash frequency, whereas signalized MUTs were associated with higher sideswipe and rear-end crash frequency. Ultimately, this cross-sectional analysis presents a snap shot of the relationship between various intersections as they currently exist. MUTs may be utilized as a context-sensitive solution to existing operational or safety problems, therefore, one way in which this study could be improved is through the implementation of a before-after framework. Unfortunately, data from far enough in the past was not readily available, as MUTs have frequently been used in Michigan for some time.

MUTs may be utilized as a context-sensitive solution to existing operational or safety problems, therefore, one way in which this study could be improved is through the implementation of a before-after framework. Unfortunately, data from far enough in the past was not readily available, as MUTs have frequently been used in Michigan for some time. Future work could monitor road infrastructure upgrades for additional MUT construction sites to conduct a B/A study. An additional point that cannot be overstated is that MUTs are not necessarily a treatment with effects specific to an intersection. In fact, MUTs likely affect the upstream and downstream traffic.

Locations that utilize MUTs typically do not have direct median access to driveways and minor roads up and down stream of the intersection, therefore, more vehicles may be funneled through intersections than would have otherwise. In this sense, focusing solely on the safety performance of the area immediately around the intersection likely underestimates the actual safety benefit of the MUT.

Future research could involve the study of RCUTs and J-turns in the state of Michigan could potentially add to these findings for a more comprehensive list of intersection design alternatives. Other areas for research include the signage at such designs, especially given that the intersection design alternatives are not installed in every state. This in turn, leads to a lack of uniform signing, which could create issues with driver comprehension and compliance with existing signs.

4.2 Safety Performance of Temporary Traffic Control Strategies in Freeway Work Zones

This study provides high-level estimates of how crash frequency varies under various temporary traffic control strategies that are commonly used in freeway work zone settings. The specific strategies evaluated include shoulder closures, single- and multi-lane closures, and lane shifts.

Interestingly, no difference was found between the crash rates at work zones where shoulder closures were in effect and normal (pre-work zone) conditions on these same segments. Both single- and multi-lane closures showed increased crash rates, which were generally similar in magnitude. The increase was more pronounced when the single-lane closure occurred along a two-lane (per direction) freeway as compared to freeways with greater numbers of travel lanes. Crash rates were also significantly higher where lane shifts were utilized, which is likely a function of higher travel speeds and human factors associated with the transition from a normal travel path to the work zone environment.

Ultimately, there was significant variability in the effects of single- and multi-lane closures, as well as lane shifts, across different work zones and road segments. These differences may be reflective of a variety of important unobserved factors that were unique to either the specific freeway segment or work zone temporary traffic control plan. A principal advantage of the random parameter negative binomial model estimated as a part of this study is its ability to accommodate such unobserved heterogeneity. This analysis framework was also able to address concerns related to temporal correlation among crash counts on the same road segments (i.e., some segments tend to experience a higher or lower number of crashes than average over time due to unobserved site-specific factors).

The research also provides estimates of the impacts of changes in traffic volumes, work zone length, and construction period duration. Collectively, these results provide information that can be used as a part of high-level, sketch planning exercises in comparing various temporary traffic control strategies. However, additional research is warranted in order to better understand the specific factors that influence these aggregate work zone safety trends. The following are a few of the factors that could not be examined as a part of this study that could be included in future analyses:

- whether work activity was ongoing at the time of a closure and, if so, the type of activity;
- specific elements of the temporary traffic control plan that was in place, including the type and locations of specific traffic control devices; and
- detailed geometric characteristics associated with each of the road segments.

One limitation to such research is the general lack of comprehensive work zone data in a usable format for analysis purposes. Many state departments of transportation (DOTs) utilize daily logbooks, which are typically not in a format that can be easily linked together with existing crash, volume, and roadway inventory databases. Another limitation is the lack of sufficient traffic volume data during periods when a work zone is in place. While various states are now monitoring real-time traffic information for high-volume work zones, there remains a gap in the research literature as to work zone related diversion and the related impacts on crash rates. The random parameter framework utilized as a part of this study allowed for this variability in traffic volumes to be accounted for. However, explicit consideration of work zone specific AADT would allow for increased precision in determining the impacts of specific traffic control strategies.

In lieu of addressing these types of data issues, another approach would be the utilization of a case-control design, wherein the specific temporary traffic control features can be varied from one work zone to another while maintaining consistency with respect to other key factors. However, such an approach introduces additional issues and may require substantive involvement with both the DOT and any involved contractors. The use of naturalistic driving data, such as through the second Strategic Highway Research Program (SHRP2), represents another potential avenue by which challenging data collection hurdles may be addressed in order to better understand driver response in work zone environments. Such high-fidelity data will provide an important complement to the higher-level assessments of work zone safety such as that presented in this study.

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