SAFETY PERFORMANCE OF MEDIAN U-TURN INTERSECTIONS

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ABSTRACT

The use of alternative intersection designs can provide both safety and operational benefits for road users at potentially lower costs when implemented in the appropriate setting. The Federal Highway Administration has previously recognized a subset of alternative intersections designs broadly referred to as "reduced left-turn conflict intersections" as a proven safety countermeasure that have been shown to decrease the risk of potentially severe crash types by reducing conflict points through the use of indirect left-turn movements. Median U-turn intersections (also referred to as "Michigan lefts" or "boulevard turnarounds") are one such alterative design that accommodates indirect left-turn movements via directional U-turn crossovers located within the median along one or both of the intersecting roadways. Michigan has long been a pioneer in the implementation of median U-turns along urban and suburban divided boulevards, with initial installations dating back several decades. Additionally, various indirect left-turn configurations have been implemented along rural highways and frontage roads for urban freeways.

While prior work has consistently demonstrated that median U-turn intersection designs represent an effective countermeasure that can improve operational performance and reduce the frequency of severe crash types when implemented in the appropriate context, much of the extant research is outdated and several important areas of investigation remain unexplored. This includes defining the appropriate crash influence area, the impacts of pre-conversion characteristics, impacts to pedestrian and bicycle collisions, and evaluating crashes pre/post conversion (e.g., longitudinal panel data) compared to a purely cross-sectional evaluation. To address these and other knowledge gaps, research was performed to quantify the safety performance characteristics and develop analytical tools related to the utilization of median U-turn intersections. Historical traffic crash data were collected for signalized and unsignalized intersections in Michigan where left-turns are accommodated by a median U-turn design. To allow for comparison of the performance between the median U-turn and traditional designs, data were also collected for a sample of reference intersections (divided and undivided) where conventional direct left-turn movements were maintained. A novel approach was developed to define the safety performance influence area of a median U-turn intersection, which subsequently improved the method of identifying and collecting target crash data. Utilizing the traffic crash data, a series of analyses were performed to identify the differences between conventional and median U-turn intersections, and to also identify the differences in safety performance between various median U-turn design

characteristics. The analyses compared crash rates, types, severity distributions, and severe injury collision patterns, and included development of a series of safety performance functions and crash modification factors. The results were then generalized into a series of recommendations for roadway agencies considering future implementation of median U-turn intersections, including specific design recommendations intended to improve safety performance for all road users.

Ultimately, it was concluded that median U-turn designs represent an effective safety countermeasure to target the reduction of severe crash types for both unsignalized and signalized intersections. While there are some potential tradeoffs with respect to non-injury crash frequencies for specific pre-conversion configurations, the use of these indirect left-turn intersection designs is consistent with the Safe System approach adopted by the United States Department of Transportation within the *National Roadway Safety Strategy*.

Unsignalized median U-turn intersections offer superior fatal and injury crash performance compared to conventional unsignalized intersections. The removal of the crossing conflict points at unsignalized median U-turn designs (which include a closed median at the intersection) essentially eliminates the pattern of severe head on left-turn and angle collisions occurring within conventional intersections. However, it is important to recognize that non-injury crashes were shown to increase when converting a conventional unsignalized intersection to a median U-turn at locations with an existing median on the major roadway.

Signalized median U-turn intersections offer superior safety performance for both injury and non-injury crashes compared to conventional signalized intersections along undivided roadways. However, the comparison of median U-turns locations to conventional divided signalized intersections was limited by a lack of reference sites with comparable traffic volumes. Annual average frequencies of severe pedestrian and bicycle crashes were similar between the signalized median U-turn and conventional undivided sites. Finally, several design features of signalized median U-turn intersections were identified as having a significant impact on safety performance, including the distance to crossovers from the main intersection, the length of weaving areas, the number of signalized crossovers, and the number of storage lanes.

TABLE OF CONTENTS

1.0 INTRODUCTION 1
1.1 Background 1
1.2 Knowledge Gaps and Research Needs 2
1.3 Study Objectives and Overview 4
1.4 Unsignalized Median U-Turn Intersections 5
1.5 Signalized Median U-Turn Intersections 6

2.0 LITERATURE REVIEW 8
2.1 Safety Concepts Specific to MUT Designs 8
2.2 Prior Safety Performance Evaluations 16
2.3 Analytical Methods 18
2.4 Summary of Findings 20

3.0 DATA COLLECTION 21
3.1 Site Identification 21
3.2 Intersection Characteristic Data 25
3.3 Traffic Volume Data 30
3.4 Traffic Crash Data 31

4.0 ANALYTICAL METHODOLOGY 34
4.1 Traditional Safety Performance Metrics 34
4.2 Safety Performance Functions 35
4.3 Crash Modification Factors 37

5.0 UNSIGNALIZED MEDIAN U-TURN INTERSECTIONS 40
5.1 Descriptive Statistics 40
5.2 Traditional Safety Performance Metrics 43
5.3 Fatal and Serious Injury Crash Patterns 44
5.4 Development of Safety Performance Functions 51
5.5 Development of Crash Modification Factors 57

6.0 SIGNALIZED MEDIAN U-TURN INTERSECTIONS 60
6.1 Descriptive Statistics 60
6.2 Traditional Safety Performance Metrics 63
6.3 Fatal and Serious Injury Crash Patterns 66
6.4 Development of Safety Performance Functions 81
6.5 Development of Crash Modification Factors 89

7.0 CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK 90
7.1 Summary of Findings 90
7.2 Recommendations 92
7.3 Limitations and Future Work 94

REFERENCES 97

APPENDIX 102

1.0 INTRODUCTION

The use of alternative intersection designs can provide both safety and operational benefits for road users at potentially lower costs when implemented in the appropriate setting [*1*]. Further, the Safe System approach adopted by the United States Department of Transportation (USDOT) within the *National Roadway Safety Strategy* emphasizes prioritizing safety treatments which help to eliminate fatalities and serious injuries [*2*]. The Federal Highway Administration has previously recognized a subset of alternative intersections designs broadly referred to as "reduced left-turn conflict intersections" as a proven safety countermeasure that have been shown to decrease the risk of potentially severe crash types by reducing conflict points through the use of indirect left-turn movements [*3*]. Median U-turn intersections (also referred to as "Michigan lefts" or "boulevard turnarounds") are one such alterative design that accommodates indirect left-turn movements via directional U-turn crossovers located within the median along one or both of the intersecting roadways. (**Figure 1**).

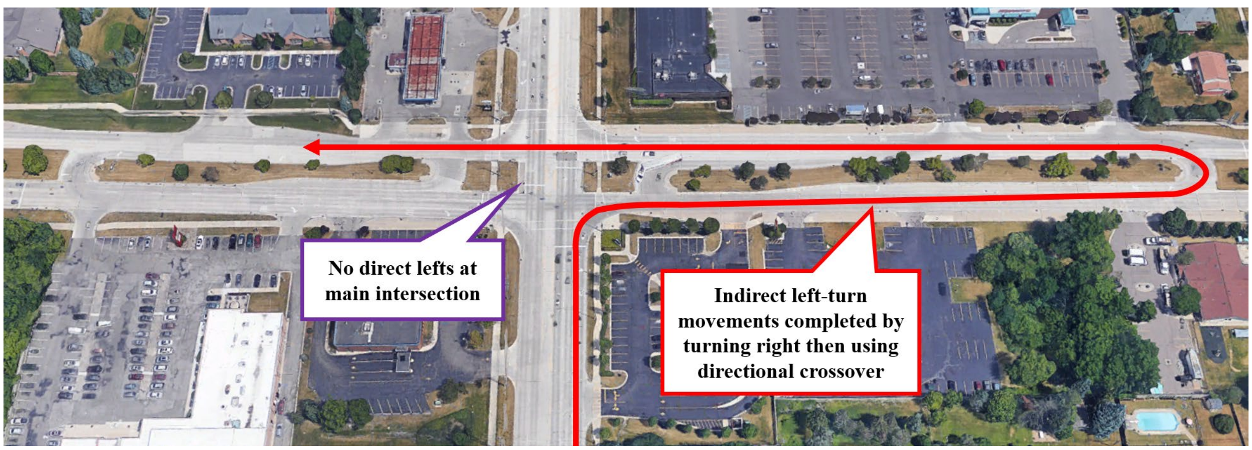


Figure 1. Example of Median U-Turn Intersection in Michigan [*4*]

1.1 Background

Michigan has long been a pioneer in the implementation of median U-turns (MUTs) along urban and suburban divided boulevards, with initial installations dating back several decades [*5*]. Additionally, these designs have been implemented along rural highways and frontage roads for urban freeways. Other states have also implemented MUTs or related reduced left-turn conflict intersections in a variety of configurations [*1, 6-8*]. Many states employ a similar design referred to as a restricted crossing U-turn (RCUT, also referred to as "J-turns" or "superstreets") that allows direct left-turn movements from the major approaches (**Figure 2**).

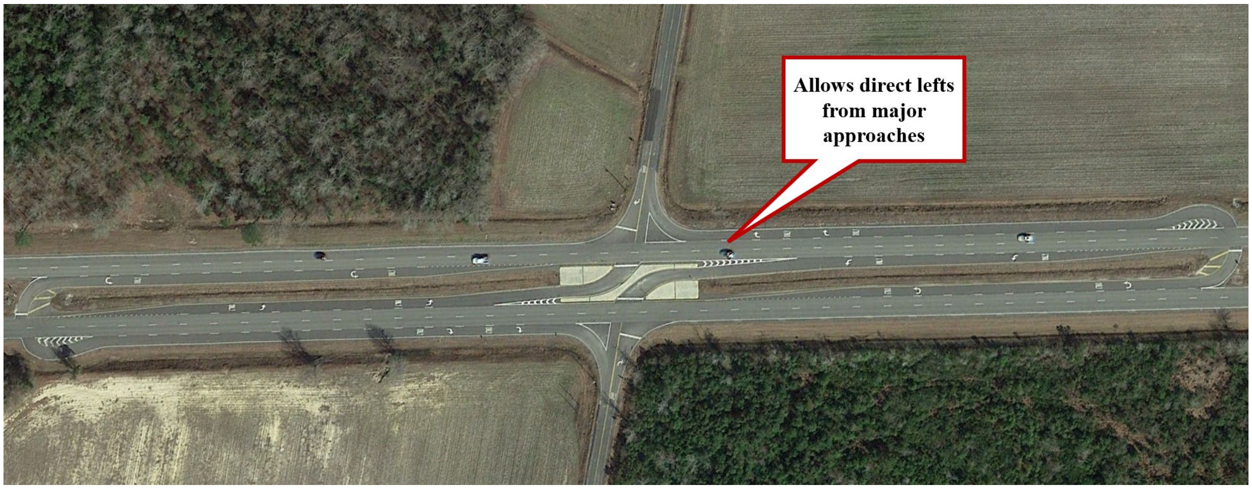


Figure 2. Example of Restricted Crossing U-Turn Intersection in South Carolina [*4*]

The use of reduced left-turn conflict intersections is recognized within the national *Towards Zero Death* strategy on highway safety [*9*] and represents an opportunity to reduce the more than 10,000 intersection-related fatalities that occur annually in the United States [*10*]. More than 6,000 of these fatalities occur at unsignalized intersections [*10*] where approximately 61 percent involve left-turn or angle collisions [*11*]. Additionally, more than 3,000 fatalities occur annually at signalized intersections [*10*] where approximately 20 percent involve left-turn collisions [*12*]. Similar trends are observed in Michigan, where crashes involving left-turn movements at intersections resulted in 477 fatalities and 3,568 serious injuries from 2015 to 2019, representing approximately 15 percent of all fatal and serious injuries in the state [*13*].

1.2 Knowledge Gaps and Research Needs

While prior work has consistently demonstrated that MUTs can offer superior safety [*1, 3, 5-8, 14-20*] and operational [*1, 6-8, 14, 16, 17, 20-22*] performance when implemented in the appropriate setting, there are several areas of investigation related to MUT safety performance which remain unexplored. Research specific to unsignalized reduced left-turn conflict intersections continues to be limited to the studies conducted prior to the American Association of State Highway and Transportation Officials' (AASHTO) *Highway Safety Manual* (HSM) [*5, 7, 8*] or which includes RCUT intersections [*23-26*]. Al-Omari et al. [*18*] developed crash modification factors (CMFs) specific to signalized MUT intersections based on a cross-sectional approach using MUT and reference sites from Michigan. CMFs were developed for two configurations of signalized MUTs that demonstrated significantly lower fatal and injury crash frequency and property damage only crash frequency. These reductions were driven by lower occurrences of head-on, head-on left-turn, angle, rear end, and sideswipe opposite crashes. Single-vehicle and non-motorized crash occurrence was greater at MUT intersections when compared to conventional signalized intersections.

However, additional research is necessary to better define the influence area of MUT designs as a part of the safety performance assessment. FHWA's *Median U-Turn Informational Guide* [*1*] notes that it would be fundamentally unfair to compare "a conventional intersection to just the main junction of a MUT" and the analysis area should be large enough to include all crossovers. This has been a limitation of prior research that has focused on the main intersection of the MUT or used a limited buffer around the adjacent directional crossovers. This concept is particularly important for the analysis of collisions involving non-motorized road users which may occur across the entire influence area.

It also should be noted that the cross-sectional study design employed by Al-Omari et al. [*18*] to estimate CMFs for signalized MUTs represented an appropriate approach given that pre-conversion period data is limited for the signalized MUTs in Michigan which have been in place for several decades. However, a before-and-after approach is preferred where sufficient pre- and post-conversion data is available as the difference in safety performance observed via cross-sectional studies can be due to either known or unknown factors, including the countermeasure under evaluation [*27*]. Therefore, the comparison of CMFs developed for MUT intersections estimated via both before-and-after and cross-sectional study designs can help to provide important context when considering the use of CMFs which have been developed using a cross-sectional study design only (such as the research conducted by Al-Omari et al. [*18*]).

Prior research to develop CMFs specific to MUTs also has not considered the impact of the pre-conversion design characteristics. The safety performance of both unsignalized and signalized conventional intersections will vary between sites that have either undivided or divided approaches. Therefore, CMFs intended to estimate the impact on crash frequency when converting a conventional intersection to a MUT design should consider this pre-conversion condition.

Finally, research into specific design elements that impact the safety performance of signalized MUT intersections remains unexplored. This could include design features such as the distance to the crossovers from the main intersection, the length of the area where a right-turning vehicle attempting to complete an indirect left-turn movement weaves across through lanes to reach the main directional crossover, as well as other geometric- or traffic control-related elements.

1.3 Study Objectives and Overview

This work begins to address these underexplored areas by evaluating historical traffic crash data for locations across the state of Michigan where MUT designs have been implemented. Reference sites at locations which maintain a conventional design with both undivided and divided major approaches were also included. Ultimately, the objectives of this work are intended provide a comprehensive picture of the MUT safety performance experience in Michigan:

- Define the safety performance influence area of MUT intersections.
- Quantify the safety performance of MUT intersections via both traditional evaluation methods (i.e. traffic crash rates) and the modern methods outlined in the *HSM* [*28*], including the development of safety performance functions (SPFs).
- Identify fatal (K) and serious (A) injury crash patterns at MUT intersections and compare these trends to conventional designs, including a specific focus on collisions involving pedestrians and bicyclists at signalized intersections.
- Compare the relative safety performance of MUT designs with conventional intersections, including the development of CMFs for distinct conversion scenarios.
- Quantify the safety performance impacts of various MUT-specific design features
- Provide a series of recommendations for practitioners to make data-driven design decisions related to MUT intersections.

First, a comprehensive literature review was conducted specific to MUT intersections and statistical methods for the analysis of geometric safety treatments (**Section 2.0**). Intersections from across the state of Michigan were identified (including 95 unsignalized sites and 167 signalized sites) and relevant traffic crash data, traffic volume data, geometric characteristics, and other intersection data were collected for subsequent evaluation (**Section 3.0**). Appropriate analytical methods were identified based on the findings of the literature review and the data available for analysis (**Section 4.0**). Distinct evaluations of safety performance were then conducted specific to unsignalized MUTs (**Section 5.0**) and signalized MUTs (**Section 6.0**). The major findings from these evaluations were summarized and a series of recommendations for practitioners were identified (**Section 7.0**).

The unsignalized MUT intersections (**Section 1.4**) and signalized MUT intersections (**Section 1.5**) are defined in the subsequent subsections, including the conversion scenarios considered as a part of this evaluation.

1.4 Unsignalized Median U-Turn Intersections

Unsignalized MUT intersections (**Figure 3**) allow for uncontrolled traffic flow along the major approach by employing stop-control along the minor approach. Unsignalized MUTs are typically implemented along high-speed divided suburban and rural arterials. Note that in most cases, minor approach through movements are prevented via closing the median at the intersection. The pair of directional crossovers are typically stop-controlled with a single storage lane. It should be noted that truck loons are often included in order to accommodate truck turning radii [*1*]. The minor approaches are undivided and typically severe relatively low traffic volumes. The two unsignalized conversion scenarios considered within this evaluation are shown in **Figure 4**.

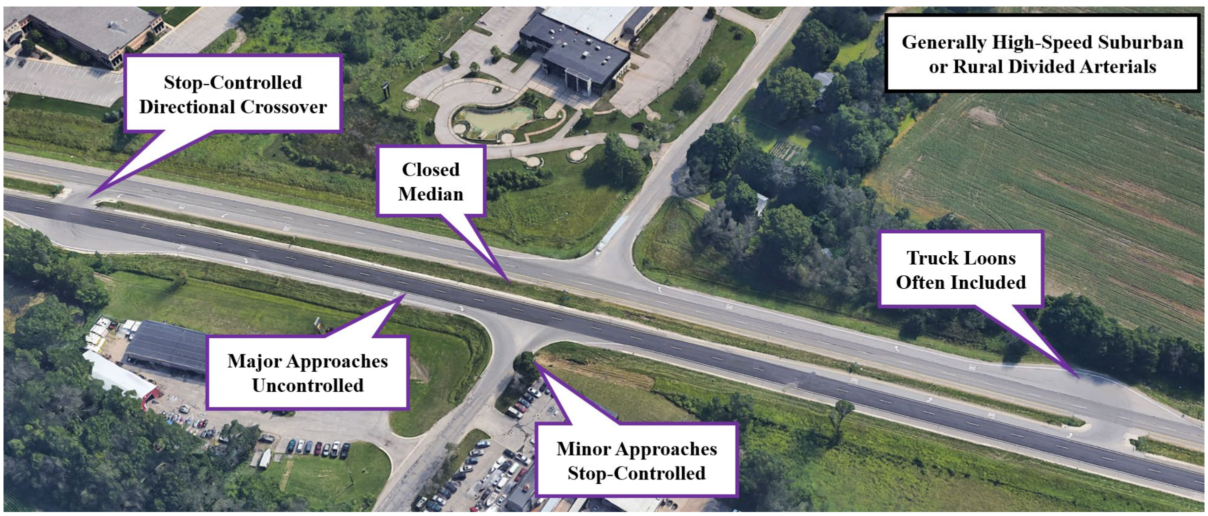


Figure 3. Example of an Unsignalized Median U-Turn Intersection in Michigan [*4*]

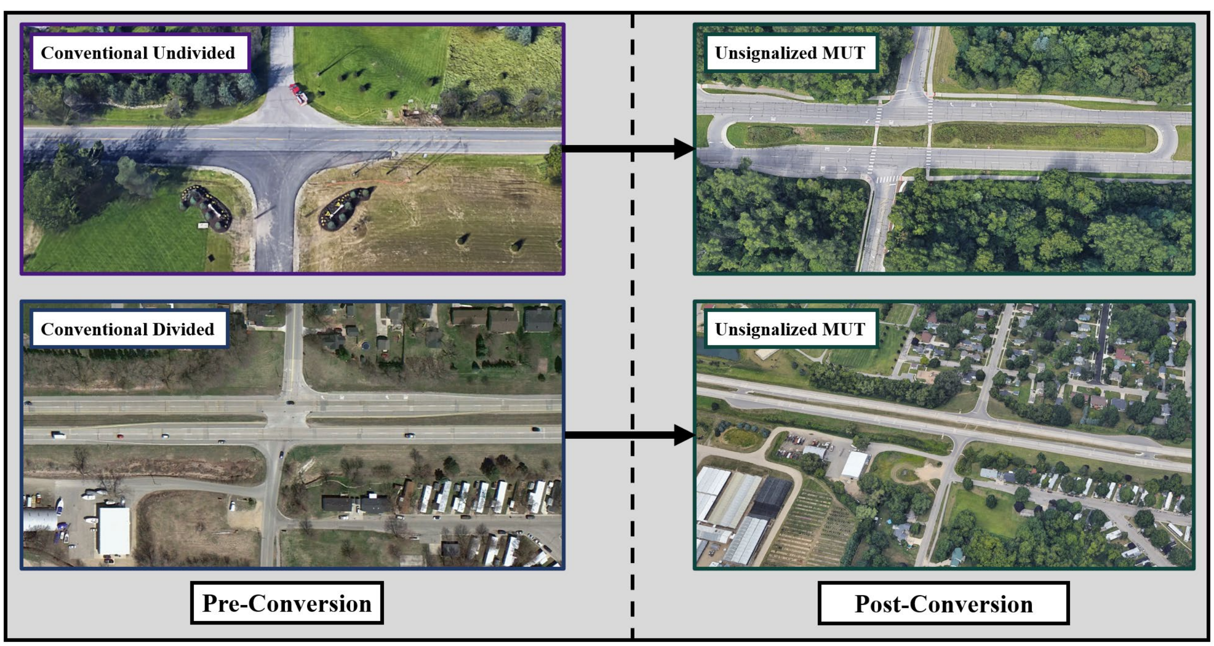


Figure 4. Examples of Unsignalized MUT Intersection Conversions [*4*]

The "conventional undivided" scenario involves converting a two-way two-lane highway to a four-lane boulevard as a part of a larger project that would commonly include multiple intersections along a single corridor. The "conventional divided" scenario involves less extensive modifications, where the median opening is simply closed along a four-lane divided boulevard and appropriate directional crossovers are installed to support the indirect left-turn movements.

1.5 Signalized Median U-Turn Intersections

Signalized MUT intersections (**Figure 5**) include signal control for both the major and minor approaches at the "main" intersection. The directional crossovers may also be signalized if traffic volumes meet criteria to warrant signal control. Signalized MUT designs are typically implemented along urban or suburban arterials in Michigan where traffic volumes exceed the capacity which can be served by conventional intersection designs. Operational benefits are obtained by the elimination of left-turn signal phases, which improves signal capacity and corridor progression while reducing subsequent delays [*1,6*]. The directional crossovers may include multiple storage lanes or storage lanes which begin upstream of the main intersection. Interior directional crossovers are often included which provide access along the divided highway.

Figure 5. Example of a Signalized Median U-Turn Intersection in Michigan [*4*]

The two signalized conversion scenarios considered within this evaluation are shown in **Figure 6**. The "conventional undivided" scenario involves converting a conventional signalized intersection with all undivided approaches to a MUT design with divided major approaches. The "conventional divided" scenario involves prohibiting direct left-turns at conventional signalized intersections where the major approach is already divided and implementing directional crossovers to accommodate the indirect left-turns.

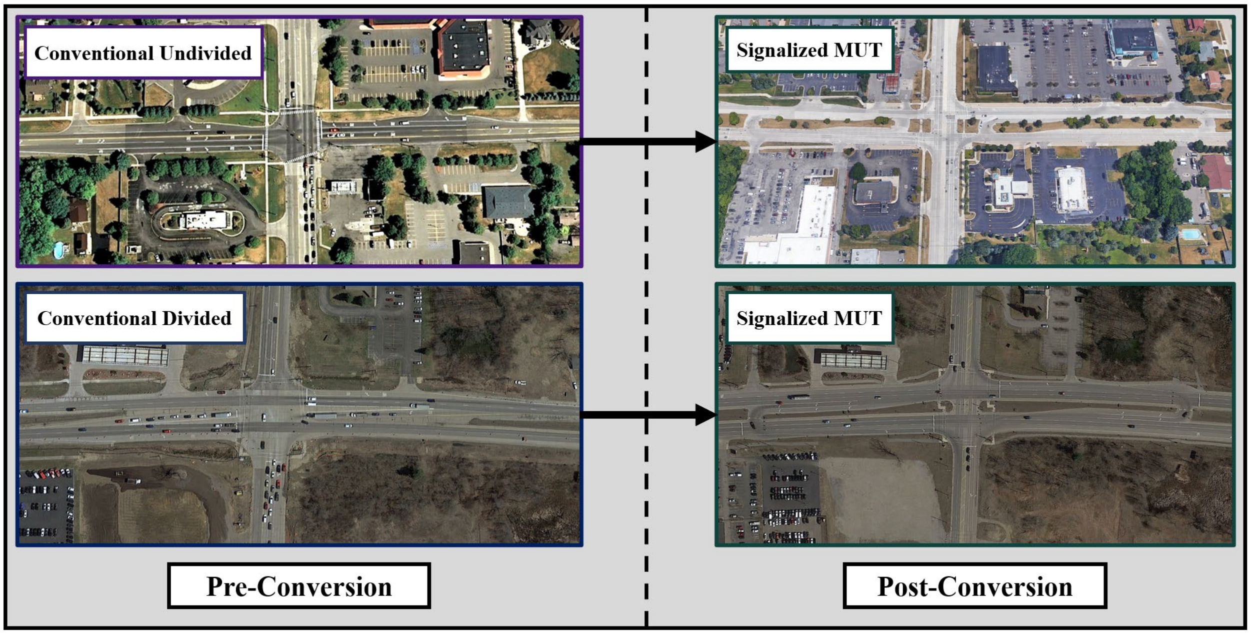


Figure 6. Examples of Signalized MUT Intersection Conversions [*4*]

While there are variety of configurations of signalized MUTs in place across the state of Michigan (including cases where both the major and minor approaches are divided as well as cases where only the minor approach is divided), this evaluation included only the predominant configuration where the major approach is divided and the minor approach is undivided (**Figure 7**). This allowed for the consolidation of analytical factors to consider in the study given consistent the geometric characteristics (i.e., crossovers are only present along the major approaches).

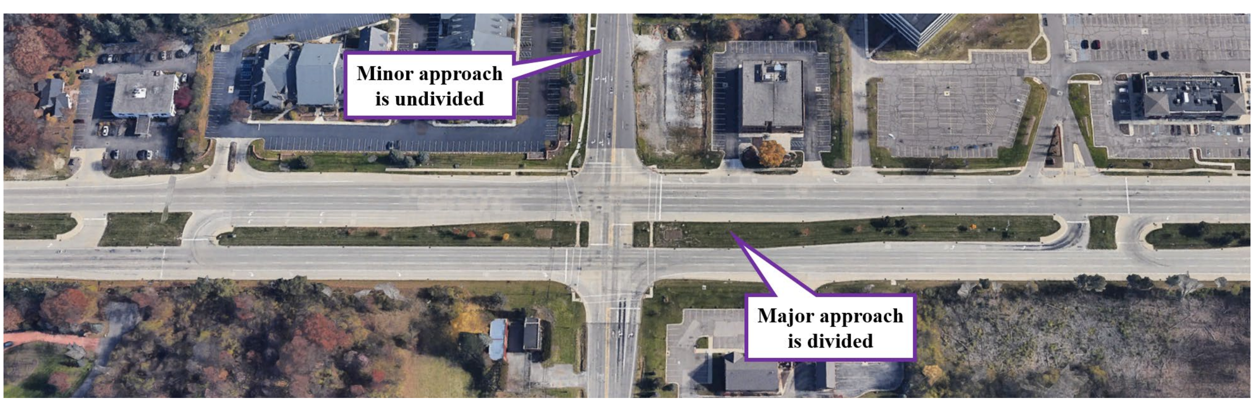


Figure 7. MUT with Divided Major Approaches and Undivided Minor Approaches [*4*]

2.0 LITERATURE REVIEW

First, a comprehensive literature review was conducted intended to identify the state-of-the-art with a focus on the two following concepts:

- The safety performance of MUT intersections (or related RCUT studies), directional crossovers, divided boulevards, or other related geometric design features; and
- Statistical methods for the analysis of geometric safety treatments, including work which has employed both before and after as well as cross-sectional approaches.

This review included a search of project reports from agencies ranging from FHWA, NCHRP, as well as state DOTs. Relevant articles from transportation engineering journals were also identified via TRB's TRID bibliographical database and other relevant search engines. The following subsections summarize safety concepts specific to MUT designs (**Section 2.1**), prior safety performance evaluations (**Section 2.2**), and analytical methods (**Section 2.3**). A summary of the key findings from the literature review is provided in **Section 2.4**.

2.1 Safety Concepts Specific to MUT Designs

Signalized MUT intersection designs are often implemented as a part of boulevard conversions or at specific locations due to the potential operational benefits, including reductions in delay and improvements to progression [*1*]. There have been several prior efforts which have focused on quantifying the operational benefits of MUT designs and other related aspects [*1, 3, 5-8, 14-22*]. However, MUTs can also potentially offer safety benefits by reducing the number of conflict points and/or the number of stops by vehicles [*1*]. While conventional intersections have 32 conflict points, MUT designs include only 16 conflict points (unless intersections or driveways are present at the turnarounds) [*1*]. Both **Table 1** and **Figure 8** demonstrate that the four angle crossing conflict points remain, but there is a reduction in the merging/diverging conflict points from 16 to 12 and the left-turn crossing conflicts are removed.

Table 1. Comparison of Conflict Points – Conventional vs. MUT Intersections [*1*]

Conflict Type	Conventional Intersection	MUT Intersection
Merging or Diverging	16	12
Crossing (Left-Turn)	12	0
Crossing (Angle)	4	4
Total	**32**	**16**

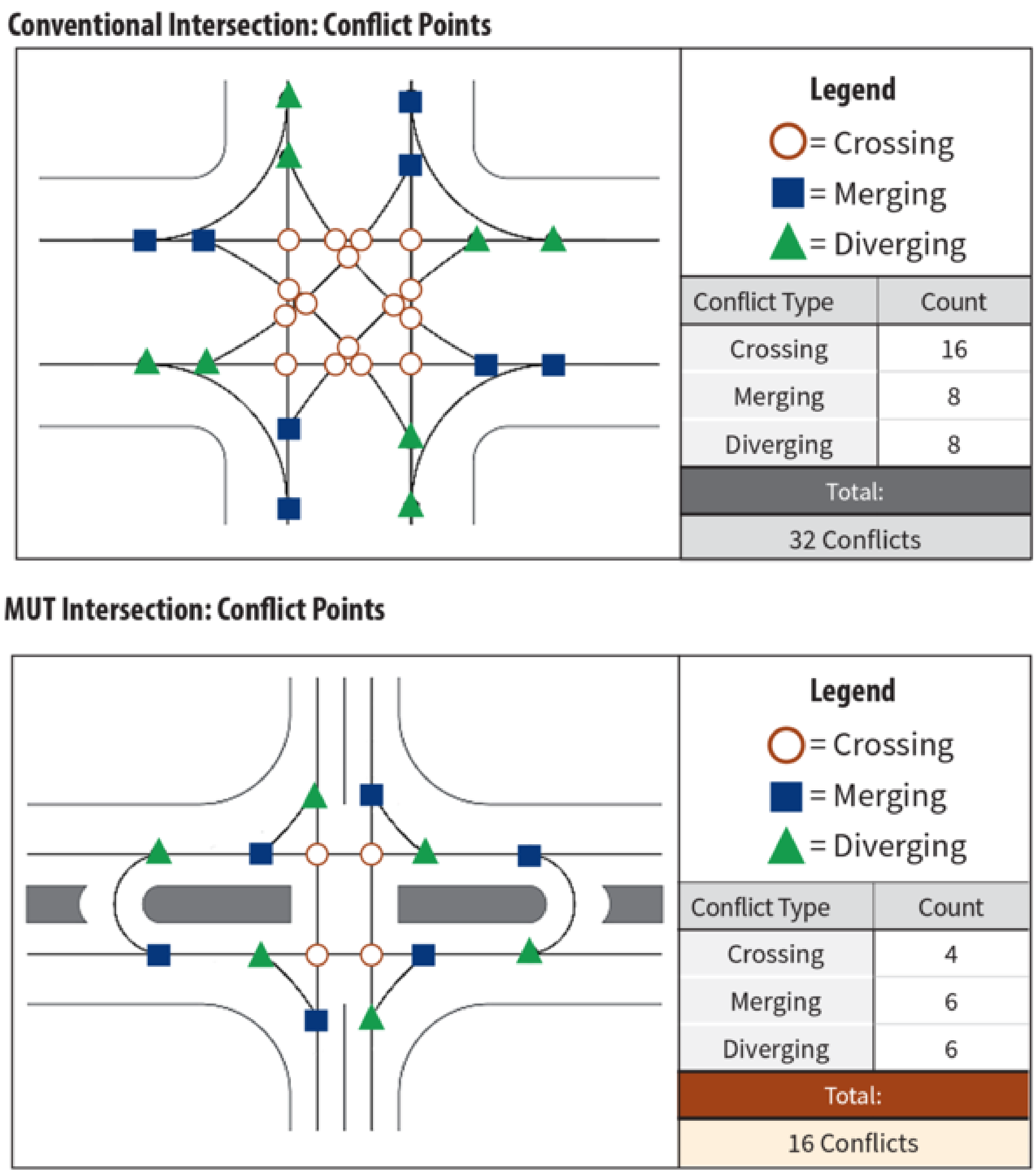


Figure 8. Conflict Points – Conventional Intersection vs. MUT Intersection [*29*]

The number of conflict points is further reduced to only eight for unsignalized MUT designs with a closed median. **Figure 9** provides a comparison of a conventional unsignalized intersections and an unsignalized MUT design with a closed median which incorporates four merging conflict points and four diverging conflict points.

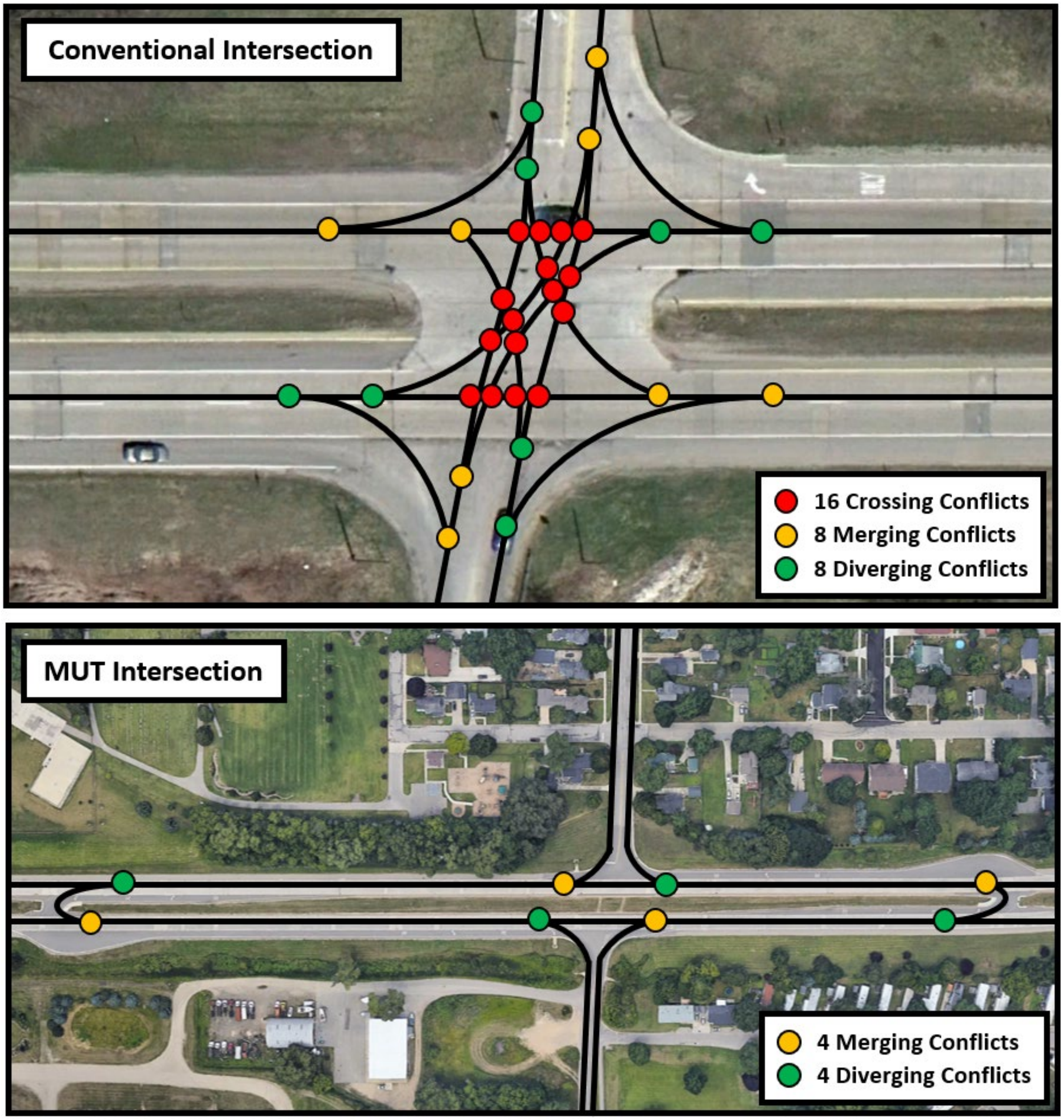


Figure 9. Conventional Intersection and MUT Intersection Conflict Points [*4*]

While the conflict point diagrams presented in **Figures 8 and 9** demonstrate that MUT designs offer fewer conflict points compared to conventional intersections, it is critical to recognize that frequency of conflicts at the remaining conflict points increases due to the implementation of indirect left-turn movements [*1, 30*]. Vehicles completing left-turn movements from both the major and minor approaches must use the directional turnaround to complete indirect movements which routes drivers through the main intersection area twice instead of one time, as shown in **Figure 10**. This concept also applies to vehicles attempting to make through movements at unsignalized MUT intersections with a closed median. This concept is particularly important for non-motorized road users as vehicles completing left-turn movements will potentially conflict with three crosswalks as opposed to only two with conventional direct left-turns.

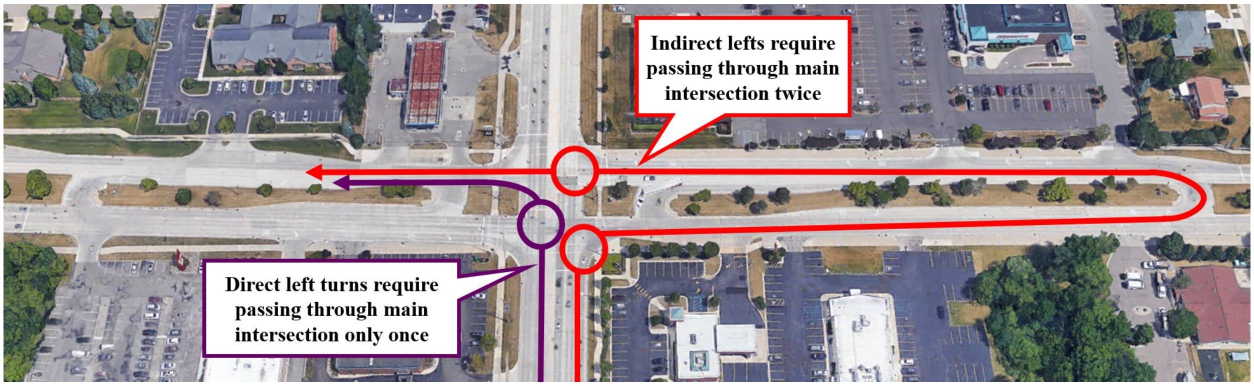


Figure 10. Example of Direct versus Indirect Left Turn Movements [*4*]

The FHWA *Median U-Turn Intersection Informational Guide* [*1*] has also identified several safety considerations for MUT intersections which are not present at conventional intersections. These considerations are summarized below with imagery from MUTs in Michigan.

2.1.1 Right-Turn/U-Turn Conflicts

Intersections or driveways may be aligned with the directional crossovers, resulting in a potential conflict between vehicles completing a U-turn movement and vehicles making a right-turn movement from the adjacent intersection or driveway (**Figure 11**). Bus stops along the major route may also conflict with these movements [*1*]. Distinct signal phases for each movement may help address this concern and can be considered as determined by an engineering study [*1*].

Figure 11. Example of Right-Turn/U-Turn Conflict at MUT Intersection [*4*]

2.1.2 Wrong-Way Movement Potential

While MUT designs employ directional crossovers to incorporate indirect left-turn movements – many agencies use bi-directional crossovers as a part of divided highways. This results in the potential for a wrong-way entry into the directional crossover. While wrong-way movements remain an important consideration, directional crossovers with appropriate channelization can mitigate this concern [*1*] (**Figure 12**).

Figure 12. Example of Channelized Directional Crossover [*4*]

2.1.3 Weaving to Reach Crossover

There is also a potential conflict between vehicles making a through movement and vehicles completing a right-turn movement in order to make an indirect left-turn. Vehicles making the right-turn movement to complete an indirect left must weave across multiple lanes of traffic with a speed differential compared to vehicles completing a through movement, resulting in a potential conflict while attempting to reach the directional crossovers (**Figure 13**).

Figure 13. Example of Right-Turn Conflict with Through Vehicles [*4*]

2.1.4 Potential Violations of Left-Turn Prohibitions

Despite the use of signing (**Figure 14**) and geometric design features intended to communicate the prohibition of direct left-turn movements at MUT intersections, there is no physical barrier which prevents drivers from attempting an illegal left-turn (except at unsignalized MUTs with a closed median). This concern may be compounded if drivers are unfamiliar with the MUT intersections. Therefore, potential violations remain an important safety consideration.

Figure 14. Regulatory Traffic Control Devices for Direct Left-Turn Prohibition [*4*]

2.1.5 Truck Navigation of Directional Crossovers

It is also important to accommodate the turning radii of large trucks in the design of directional crossovers. While truck loons can be included to help accommodate large truck turning radii (**Figure 15**), the design should consider vehicle tracking through the entire crossover [*1*].

Figure 15. Example of Loons to Accommodate Truck Turning Radii [*4*]

2.1.6 Sight Distance from the Directional Crossover Stop Bar

Adequate sight distance from the stop bar of the directional crossover is another important safety consideration of MUTs (**Figure 16**). Guidance from MDOT suggests spacing directional crossovers at a minimum of 100 feet with 150 feet being desirable in order to address this concern [*31*]. If this spacing is not available, signalization and a prohibition of left-turns on red can be implemented [*1*].

Figure 16. Example of Upstream Sight Distance from Directional Crossover [*4*]

2.1.7 Pedestrian and Bicycle Considerations

Given the unique characteristics of MUT designs (such wide medians or a reduction in signal phases), these intersections can result in both benefits and challenges to non-motorized road users [*1*]. The reduced number of signal phases results in additional pedestrian phases per hour as well as less time in between WALK phases [*1*]. Further, the presence of a median allows for a two-stage crossing which represents an advantage over a conventional undivided intersection [*1*]. Pedestrians and bicyclists may be exposed to additional right-turning conflicts due to the fact all left-turning vehicles must also turn right to complete the indirect left-turn movement [*1*]. Directional crossovers may also be controlled via a traffic signal or pedestrian hybrid beacon in order to implement a midblock pedestrian crossing [*1*]. While guidance for accessible MUT intersections is not yet available on a national level, crossing should be similar for pedestrians with vision, mobility, or cognitive impairments [*1*]. Bicyclists completing a left-turn movement have three options, shown in **Figure 17**.

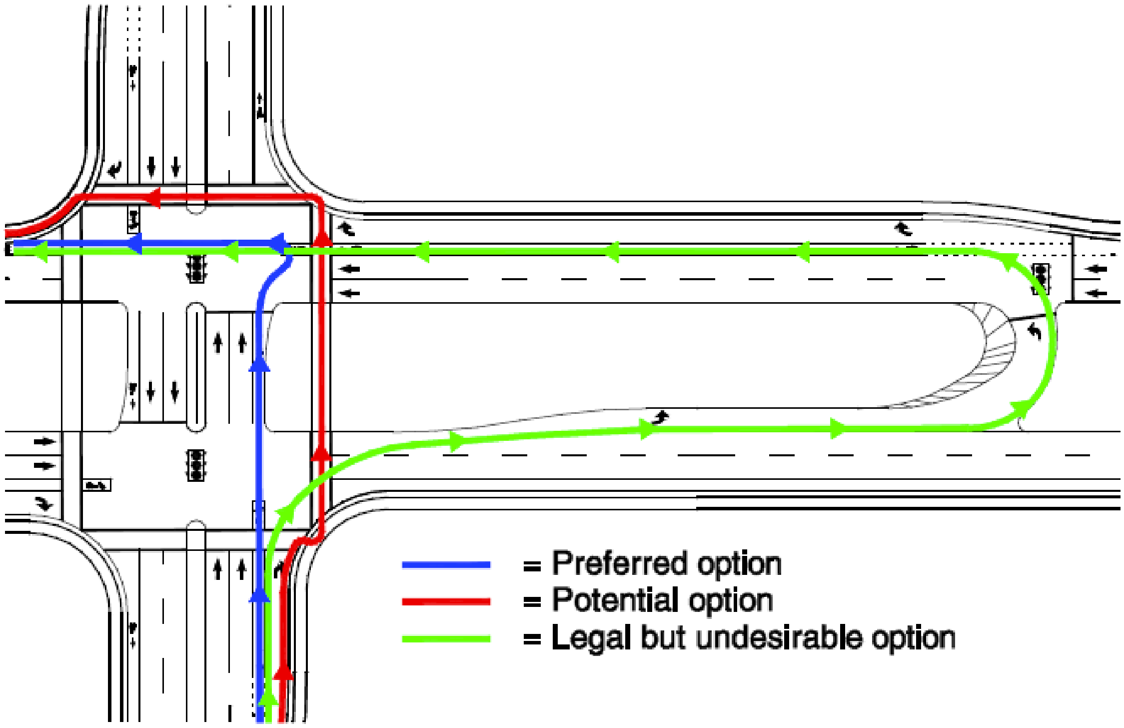


Figure 17. Bicycle Left-Turn Options at MUT Intersections [*1*]

While National Cooperative Highway Research Program (NCHRP) Research Report 948: *Guide for Pedestrian and Bicycle Safety at Alterative and Other Intersections and Interchanges* [*30*] provides design guidance to accommodate non-motorized road users at MUT intersections, several aspects of pedestrian and bicycle safety performance related to MUTs remain unexplored. It is worth noting that the Al-Omari et al. [*18*] study identified increases in pedestrian and bicycle crash frequencies. However, pedestrian and bicycle exposure data were not included and the impacts of not considering the entire influence area may also have impacted these findings.

2.1.8 Access Management

It should also be noted that the implementation of a MUT design can help from an access management perspective if the initial condition includes undivided intersection approaches. The raised median eliminates left-turns in and out of driveways and consolidates access to the directional crossovers [*1*]. However, the MUT design may result in some drivers passing through the main intersection twice as well as reduce access to driveways between the main intersection and the directional crossover [*1*].

2.2 Prior Safety Performance Evaluations

The safety performance impacts of directional crossovers, divided boulevards, as well as reduced left-turn conflict intersections (including MUT and RCUT designs) has been evaluated in prior work. However, the majority of this work was completed prior to the publication of the AASHTO *Highway Safety Manual* in 2010 [*28*].

MUT intersections are often implemented as a component of a boulevard highway design which incorporates a median and a system of directional crossovers to provide access. While this evaluation was focused solely on individual MUT intersections, studies which have investigated the safety performance aspects specific to directional crossovers and boulevard highways are summarized in **Table 2.**

Table 2. Summary of Prior Studies of Directional Crossovers and Boulevard Highways

Study	Findings
Investigation of the Effectiveness of Boulevard Roadways - 1998 [*5*]	Study which evaluated the impact on crash rates of boulevard highways in Michigan vs. roadways with a continuous two-way left-turn lane. The work showed that mean crash rates of the boulevard highways were 50 percent of those observed along roadways with a continuous two-way left-turn lane. Signalized corridors had higher crash rates than unsignalized corridors.
Effect on Crashes After Construction of Directional Median Crossovers - 2001 [*15*]	Study of eight road segments in Michigan where a total of 54 bidirectional crossovers were replaced with directional crossovers. Findings included an average reduction of more than 30 percent in both total and injury crashes after the conversion to directional crossovers.
Optimal Location of U-Turn Median Openings on Roadways – 2003 [*32*]	Study which included a field evaluation of eight sites with directional median openings in Florida in order to provide insight into operational and safety performance. Crash data was collected for a single site demonstrated a 68 percent reduction in total crashes after it was converted from a bidirectional cross over to a directional crossover.
NCHRP Report 524: Safety of U-Turns at Unsignalized Median Openings – 2004 [*7, 8*]	NCHRP Report 524 investigated the safety and operational performance of unsignalized median openings, including the development of design guidance. Field studies of median openings were conducted in order to assess driver behavior. The research found that U-turn-related collisions were relatively infrequent, with an average of 0.41 U-turn-related collisions occur per year along urban arterials, and 0.20 U-turn-related collisions occur per year along rural arterials.
Safety Effects of the Separation Distances between Driveway Exits and Downstream U-Turn Locations – 2008 [*33*]	Study conducted in Florida of 140 roadway segments to determine the safety implications of the spacing between driveways and crossover locations. The work demonstrated that a 10 percent increase in separation distance will result in a 3.3 percent decrease in total crashes. The work also demonstrated that providing crossovers at signalized intersections was associated with an increase in crashes within weaving sections.

Table 3 summarizes the prior studies which have investigated the safety performance of MUT intersections. Selected studies which have evaluated RCUT designs that are potentially relevant to MUT intersections are also included for reference.

Table 3. Summary of Prior Studies of MUT and RCUT Safety Performance

Study	Findings
The Comparative Accident Experience of Directional and Bi-Directional Signalized Intersections – 1992 [*19*]	Study which compared crash rates of 15 MUT intersections to 30 conventional intersections in Michigan. The work demonstrated that significantly lower crash rates for MUT intersections both for individual intersections as well as corridors where MUTs had been installed.
Michigan's Preferred Left-Turn Strategy – 1996 [*20*]	Research performed in Michigan after the conversion of a corridor in Wayne County suggests reductions in fatal and injury crash rate (30 percent), property damage only (PDO) crash rate (9 percent), and total crash rate (16 percent).
Indirect Left Turns – The Michigan Experience – 2000 [*16*]	Study which summarizes the operational and safety benefits of MUT intersections and boulevards with directional crossovers in Michigan.
Safety Evaluation of Right-Turns Followed by U-turns as an Alternative to Direct Left Turns: Crash Data Analysis – 2001 [*23*]	Study performed in Florida which investigated the safety impacts of intersections which incorporated indirect left-turns (125 sites) instead of direct left turns (133 sites). Crash rates per million miles traveled were 3.20 for intersection with direct left-turns and 2.63 for indirect left-turns.
Field Evaluation of a Restricted Crossing U-turn Intersection – 2012 [*26*]	Study of nine RCUT intersections in Maryland which included both a naïve before and after analysis of crash data as well as an empirical Bayes analysis which employed the SPFs included in the HSM. Results from the naïve analysis showed a 28 percent reduction in total crashes, while the empirical Bayes analysis showed a 44 percent reduction in crashes. The proportion of fatal and injury crashes out of the total crashes also decreased by 9 percent.
Empirical Evaluation of J-Turn Intersection Performance: Analysis of Conflict Measures and Crashes – 2015 [*24*]	Study of five "J-turn" intersections in Missouri, including field studies, crash analysis, and traffic conflict analysis. An empirical Bayes analysis was conducted using SPFs from the HSM calibrated for Missouri. A CMF of 0.64 for fatal and injury crashes as well as a CMF of 0.31 for total crashes were estimated.
System-Wide Safety Treatments and Design Guidance for J-Turns – 2016 [*25*]	Study of twelve "J-turn" intersections in Missouri, which included a mix of both RCUT and MUT intersections. The study reviewed detailed crash reports to identify trends and concluded that the major crash types at such intersections include major road sideswipe (31.6 percent), major road rear end (28.1 percent), minor road rear end (15.8 percent), loss of control (14 percent) and U-turn related (10.5 percent).
Safety Evaluation of Signalized Restricted Crossing U-Turn Intersections – 2017 [*14*]	Multi-state study which evaluated 11 signalized intersections which were converted from a conventional to RCUT design in order to develop crash modification factors. The authors employed before and after with comparison sites methodology – contending that regression to the mean was not a concern given that the agencies had implemented the RCUT conversion for the operational benefits. A CMF of 0.85 for total crashes and 0.78 for injury crashes was recommended by the research team, however, these findings were not statistically significant.

Table 3 (cont'd)

Study	Findings
Design Guidance for J-Turns on Rural High-Speed Expressways – 2017 [*34*]	Study which included a safety evaluation and simulation-based assessment of 12 RCUT intersections in Missouri. The safety analysis demonstrated that major approach sideswipes (31.6 percent), major approach rear ends (28.1 percent), minor approach rear end (15.8 percent), loss of control (14 percent) and merging from the crossover (10.5 percent) were the most common types of collisions observed at the study intersections. Intersections with larger crossover spacing exhibited lower crash rates.
Development of Safety Performance Functions for Restricted Crossing U-Turn (RCUT) Intersections – 2019 [*35*]	Study conducted for the Florida Department of Transportation which included the development of SPFs and CMFs for RCUT intersections based upon data from multiple states. The authors employed a cross-sectional approach. These results can be used as a part of future intersection control evaluations specific to RCUT intersections.
Investigating Safety Impact of Center Line Rumble Strips, Lane Conversion, Roundabout and J-Turn Features on Louisiana Highways – 2019 [36]	A safety performance evaluation of ten RCUT conversions in Louisiana where the authors used both an "improved prediction method" and the EB method without a comparison group in order to estimate CMFs. The authors attempted to distinguish between crashes specific to the "main intersection" and the directional crossovers. A CMF of 0.80 was estimated via the EB method for total crashes for the "main intersection" only.
Safety Evaluation of Median U-Turn Crossover-Based Intersections – 2020 [*18*]	Study which evaluated 73 MUT intersections and 12 RCUT intersections to develop crash modification factors using both before and after as well as cross-sectional methodologies. CMFs for MUTs ranged between 0.6330 and .6508 for total crashes and 0.7175 and 0.7732 for fatal and injury crashes, depending on the condition. CMFs for RCUTs included 0.7632 for total crashes and 0.5669 for fatal and injury crashes.

2.3 Analytical Methods

While much of the work specific to MUTs was conducted prior to the publication of the HSM and the popularization of the empirical Bayes (EB) method, there has been a significant number of research efforts which have used modern analytical techniques to quantify the safety performance impacts specific to safety engineering countermeasures. This research was reviewed to identify the appropriate statistical approach to develop CMFs specific to MUT intersection conversions.

While the analytical approach used in developing CMFs for engineering safety countermeasures is highly dependent on the circumstances specific to each study (such as the availability of "before" period data), most of the recent work has employed either a before and after approach [*37-46*], a cross-sectional approach [*18*, *47*], or a combination of both [*48-51*].

FHWA's *A Guide to Developing Quality Crash Modification Factors* [*27*] details various evaluation methodologies, including relevant potential issues and data considerations. The EB before and after approach is preferred where sufficient data before the implementation of a specific countermeasure is available, however, there are often situations where such before period data is limited. A cross-sectional approach may be used in these circumstances; however, the results of such cross-sectional studies should be interpreted with caution as the difference in safety performance can be due to either known or unknown factors, including the countermeasure under evaluation [*27*].

2.3.1 Selection of Reference Sites

Prior efforts which have used a group of reference sites as a part of the analytical methodology to quantify changes in safety performance were reviewed. This review was focused on the identification of relevant factors which should be considered as a part of selecting appropriate comparison group locations for MUT intersections.

Many of the recent studies have faced limitations in the selection of reference sites, such as situations where the reference group is the remaining relevant sites which do not possess the feature of interest [*37, 46, 52*], or situations where there are only a limited number of appropriate reference sites with available data [*43-45, 47, 51*]. Other studies provided only limited information specific to the selection of reference sites [*48, 49, 54*]. In general, where data is available, researchers have selected reference sites which have similar characteristics as the study sites while minimizing the impacts of concerns like spillover effects [*39-42, 50*]. Several of these studies have also used an approach where reference sites were matched with study sites via propensity scores or other similar techniques.

Hummer and Rao [*55*] used a before and after with comparison sites methodology as a part of an evaluation of RCUT intersections, contending that regression to the mean was not a concern given that the agencies had implemented the RCUT conversion for the operational benefits. The authors identified comparison sites such that they were located geographically in close proximity far enough away to not observe spillover effects. The reference sites included locations which did not undergo obvious changes (such as adjacent development or reconstruction) during the study period. Additionally, the sites were similar to the pre-conversion design – signalized intersections with a relatively large footprint.

2.4 Summary of Findings

The use of indirect left-turn intersection designs (including both MUTs and RCUTs) represents a common practice adopted by highway agencies across the United States which is employed in a range of configurations and roadway settings [*1, 6-8*]. The FHWA has also previously recognized such "reduced left-turn conflict intersections" as a proven safety countermeasure that have been shown to decrease the risk of potentially severe crash types [*3*]. Key findings from the literature review presented in **Sections 2.1-2.3** include:

- MUT intersections offer potential safety benefits due to the reduced number of conflict points as well as potential reductions in stops by vehicles. However, it is important to recognize that there may be tradeoffs due to the number of conflicts through these remaining conflict points increasing to support the indirect left-turns. This may have particularly important impacts for pedestrians and bicyclists.
- Specific features of MUT designs can also result in potential safety concerns that are not present at conventional intersections, including crossover conflicts, wrong-way movements, weaving movements, potential left-turn prohibition violations, and the accommodation of trucks at directional crossovers.
- Prior research specific to MUT safety performance has consistently demonstrated that these designs provide improved safety performance compared to conventional intersection designs that include direct left-turn movements.
- However, much of the extant research is either outdated, does not consider pre-conversion characteristics, or includes potential methodological limitations. Therefore, several important areas of investigation remain unexplored:
  - Additional research is necessary to better define the influence area of MUT designs as a part of the safety performance assessment.
  - While guidance acknowledges that MUTs may have both positive and negative aspects for non-motorized road users, safety research in this area is limited.
  - There remains a need for CMFs to evaluate both unsignalized and signalized MUT conversions for a range of pre-conversion conditions.
  - There is limited research related to the influence of MUT-specific design features on safety performance and related design guidance.

3.0 DATA COLLECTION

Intersection data were collected across the state of Michigan for subsequent analysis to support the study objectives outlined in **Section 1.1**. This included the identification of sites that currently incorporate a MUT design as well as conventional intersections (that maintain direct left-turn movements) to serve as reference sites (**Section 3.1**). After the identification of study sites, a series of intersection characteristics (**Section 3.2**), traffic volume data (**Section 3.3**), and traffic crash data were collected for each site (**Section 3.4**).

3.1 Site Identification

Four-leg unsignalized and signalized intersections were identified across the state of Michigan. While MDOT maintains a range of roadway inventory data, MUT intersections can not be systematically identified within spatial datasets. Instead, an algorithm was developed specific to the *Michigan Geographic Framework* [*56*] to identify locations where MUTs may be present which were subsequently reviewed with Google Maps [*4*] historical satellite (**Figure 18**) and street view (**Figure 19**) imagery to confirm the MUT design. The year(s) of conversion were identified within the period in which consistent systemic statewide traffic crash data was available, which included the period from 2004 to 2019.

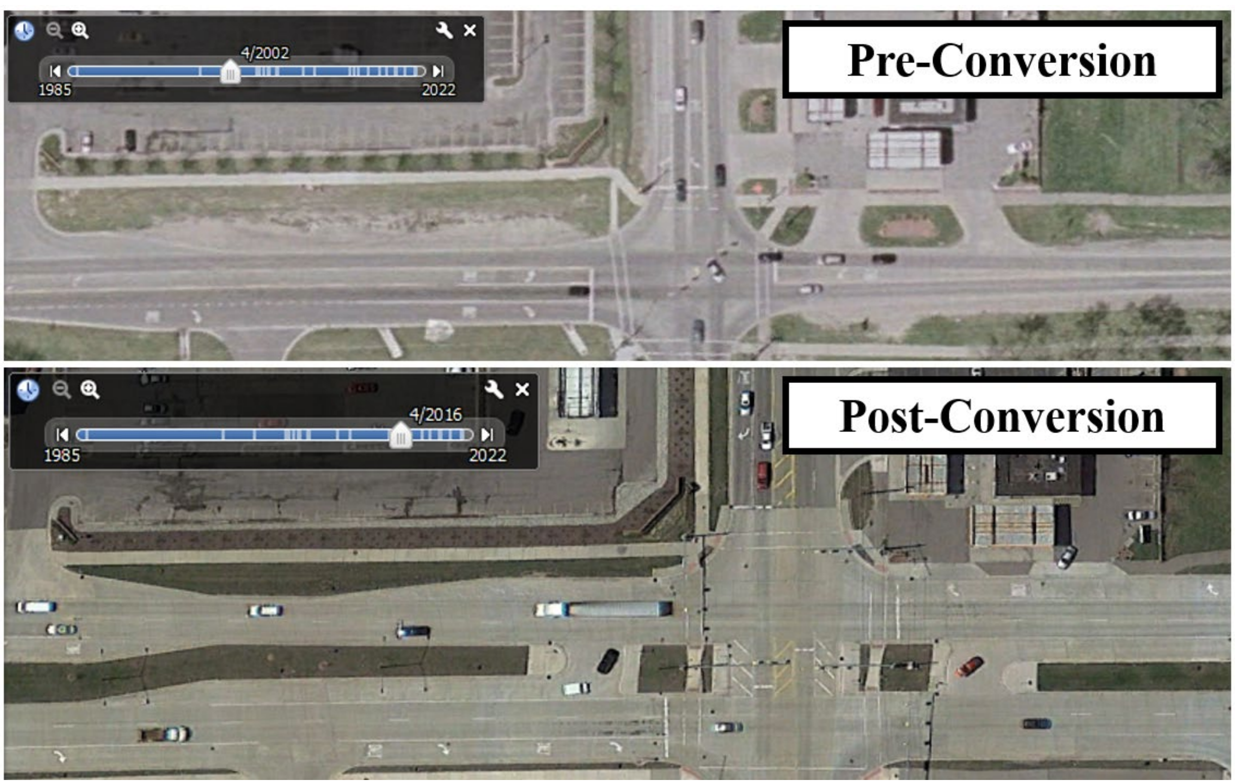


Figure 18. Example of Historical Satellite Imagery to Identify Conversion Year [*4*]

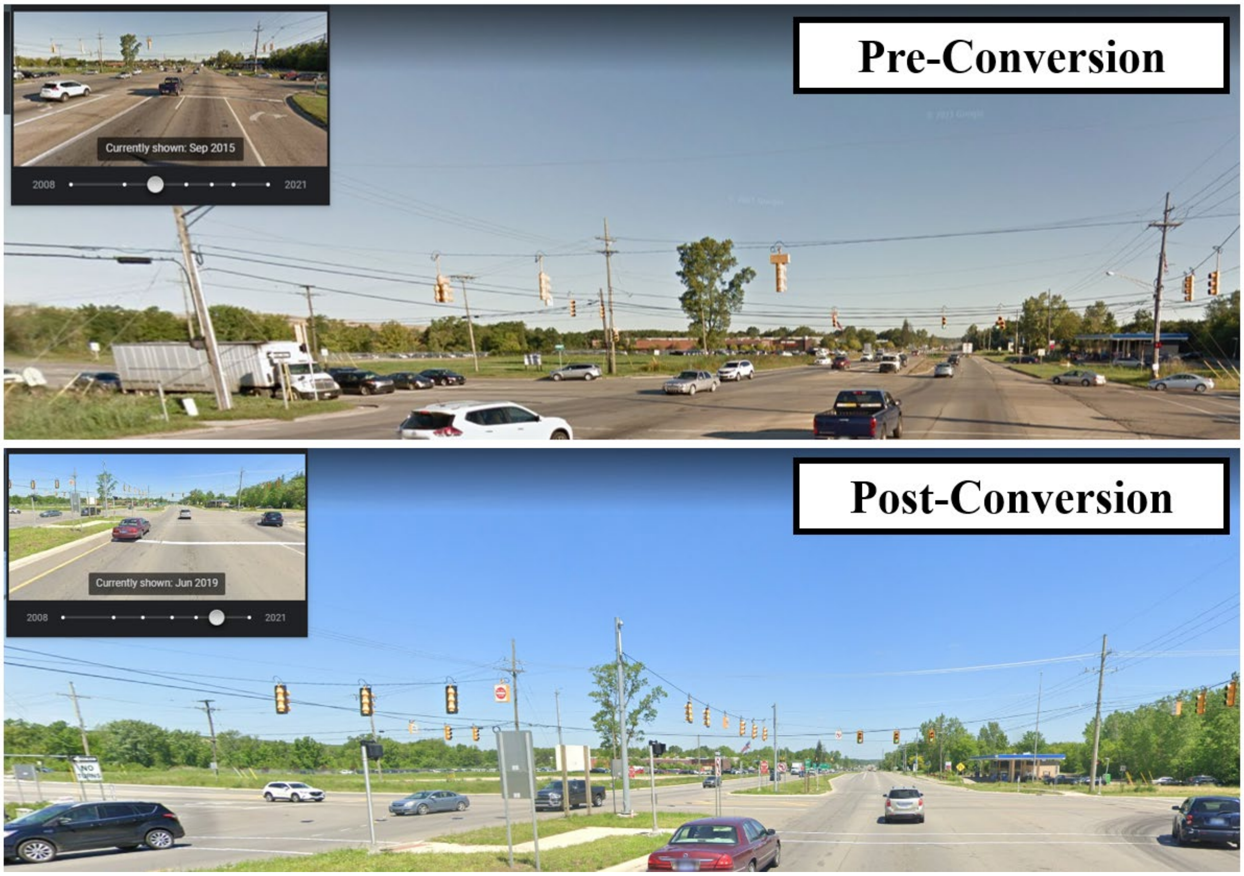


Figure 19. Example of Historical Street View Imagery to Identify Conversion Year [*4*]

The year(s) of conversion were eliminated from subsequent analysis for the particular location. In some instances, the review of satellite and street view imagery were supplemented with a review of Michigan UD-10 crash report form diagrams which occurred within the intersection as well as local news stories to narrow down the year of conversion. Reference sites (which maintain direct-left turn movements as shown in **Figures 4 and 6**) were identified that possessed geometric and other design characteristics which were similar to the pre-conversion MUT sites (i.e., they represented an appropriate and realistic candidate for conversion).

A total of 95 unsignalized intersections (including 39 MUT sites and 56 reference sites) and 167 signalized (including 85 MUT sites and 82 reference sites) were identified via this process. **Figure 20** (unsignalized) and **Figure 21** (signalized) show the location the study sites, Michigan's state trunkline arterial highway network, and the adjusted census urban boundaries which identify areas with greater than 5,000 population. A summary of the number of MUT and reference sites, including the number of pre- and post-conversion years available for analysis, is provided in **Tables 4** (unsignalized) and **Table 5** (signalized).

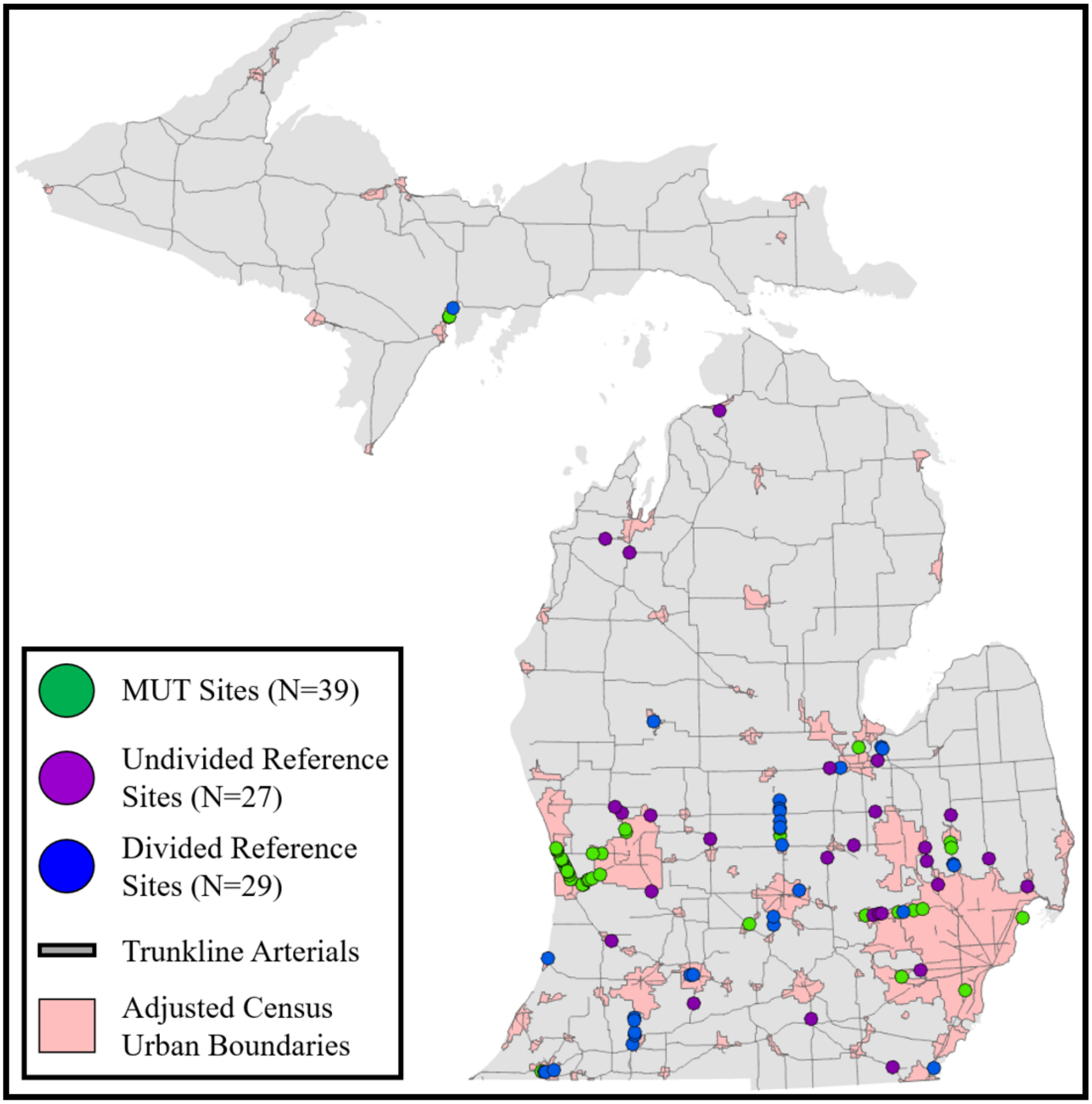


Figure 20. Map of Unsignalized MUT Intersection and Conventional Reference Sites

Table 4. Summary of Unsignalized MUT Intersection and Conventional Reference Sites

Pre-Conversion Configuration	Analysis Type	Number of Sites	Pre-Conversion Years	Post-Conversion Years
Undivided	Reference Sites (Conventional Only)	27	432	na
	MUT Sites (Pre- and Post-Conversion)	3	8	33
Divided	Reference Sites (Conventional Only)	29	461	na
	MUT Sites (Pre- and Post-Conversion)	24	136	192
No Pre-Conversion Data Available	MUT Sites (Post-Conversion Only)	12	na	166

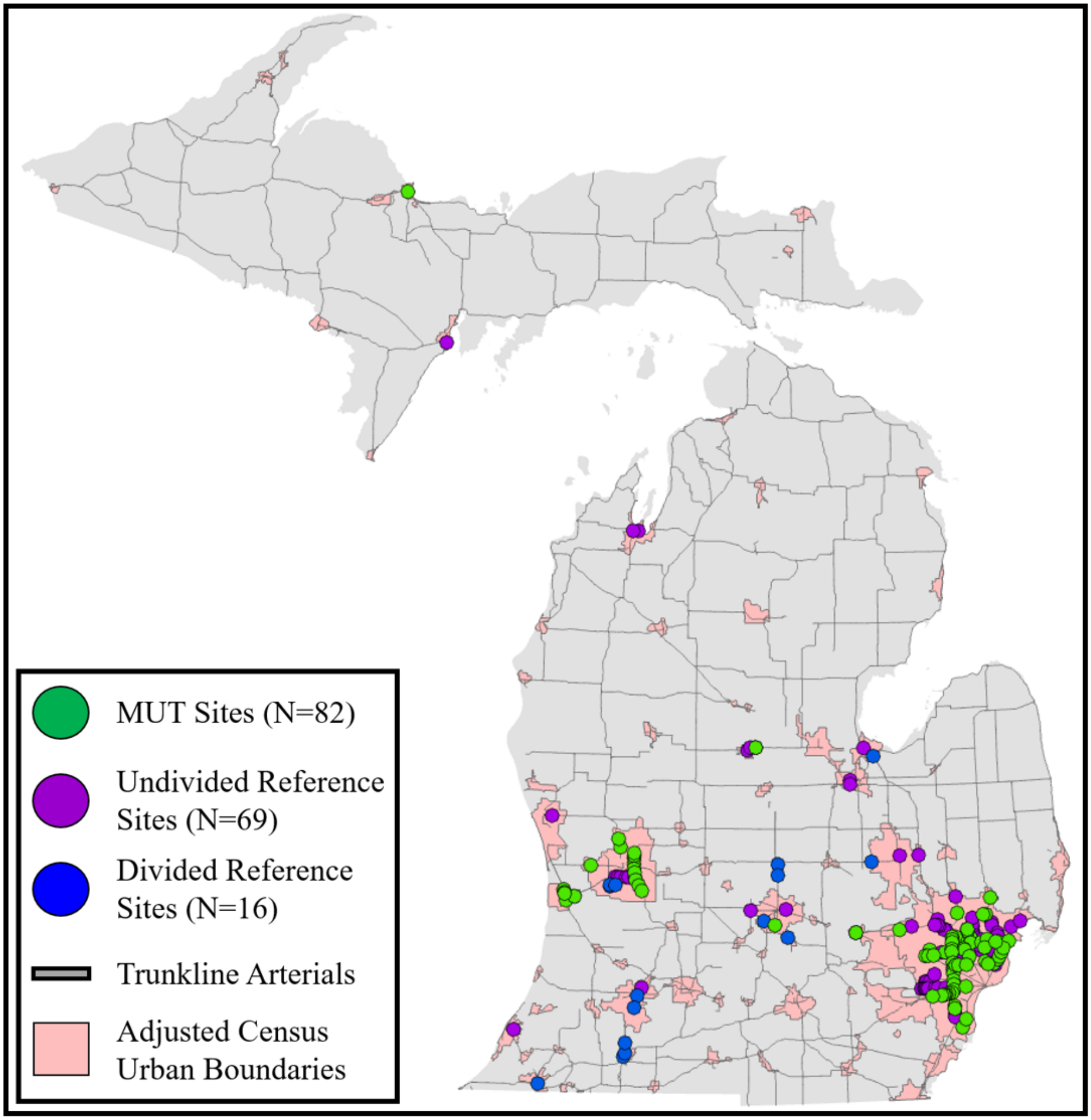


Figure 21. Map of Signalized MUT Intersection and Conventional Reference Sites

Table 5. Summary of Signalized MUT Intersection and Conventional Reference Sites

Pre-Conversion Configuration	Analysis Type	Number of Sites	Pre-Conversion Years	Post-Conversion Years
Undivided	Reference Sites (Conventional Only)	69	1,104	na
	MUT Sites (Pre- and Post-Conversion)	4	17	39
Divided	Reference Sites (Conventional Only)	16	256	na
	MUT Sites (Pre- and Post-Conversion)	0	0	0
No Pre-Conversion Data Available	MUT Sites (Post-Conversion Only)	78	na	1,235

3.2 Intersection Characteristic Data

Intersection characteristic data were collected for each study and reference site from historical satellite and street view imagery. While these data included characteristics associated with the default CMFs identified within recent safety performance function (SPF) research conducted in Michigan [*57, 58*], additional relevant features specific to MUT intersections were also identified. Specific characteristics apply to either the pre-conversion period, post-conversion, or both periods. These characteristics are summarized in **Table 6**. Figures are also provided to describe specific characteristics.

Table 6. Summary of Intersection Characteristic Data Collected in the Study

Characteristic	Description
Posted Speed Limit	The posted speed limit for both the major and minor approaches was obtained from street view imagery. The maximum speed limit was selected if the posted speed limit varied on either side of the intersection.
Functional Classification	The national functional classification for both the major and minor approaches was obtained from the *Michigan Geographic Framework* [*56*]. The highest functional classification was selected if the classification varied on either side of the intersection.
Lighting Presence	The presence of lighting was obtained by reviewing street view imagery for the presence of lighting structures (**Figure 22**).
Number of Approach Lanes	The number of approach lanes were collected for both the major and minor approaches by reviewing historical satellite imagery. Note that this applied to the signalized intersections only as the unsignalized sites included the same number of lanes.
Exclusive Left-Turn Lanes	The total number of exclusive left-turn lanes at the intersection was obtained by reviewing historical satellite imagery. Note that this would not be included for the MUT sites.
Exclusive Right-Turn Lanes	The total number of exclusive right-turn lanes at the intersection was obtained by reviewing historical satellite imagery. Note that distinct counts were collected for the major and minor approaches of signalized MUT sites only.
Skew	The skew angle of the intersection measured via satellite imagery. Note: an orthogonal intersection would have a skew angle of 0.
Driveways	The total number of public driveways within the intersection influence area.
Intersections	The total number of minor intersections within the intersection influence area.

Table 6 (cont'd)

Characteristic	Description
Roadway Context	The roadway context was obtained by reviewing satellite imagery in a manner consistent with NCHRP Research Report 855 [*59*]. Note that this was collected for the unsignalized intersections only to distinguish between sites located in suburban and rural environments.
Median Openings or Crossovers	The total number of median openings or crossovers within the intersection influence area. Note that this would only apply to conventional divided sites and MUT sites.
Median Width	The width of the median was measured via satellite imagery and rounded to the nearest five feet. Note that this would only apply to conventional divided sites and MUT sites.
Distance to the Main Crossovers	The distance to the crossover (measured from the center of the intersection to the edge of the directional crossover) was obtained via satellite imagery and rounded to the nearest five feet (**Figure 23**). Note that this would only apply to conventional divided sites and MUT sites.
Storage Lane Begins Upstream	The presence of a crossover storage lane which begins upstream of the main intersection was obtained by reviewing satellite imagery (**Figure 24**). Note this applies to MUT sites only.
Truck Loon Present at Crossover	The presence of truck loons at the directional crossovers were obtained by reviewing satellite imagery (**Figure 3**). Note this applies to MUT sites only.
Crossover Storage Lane Length	The length of the storage lane for the directional crossovers in feet was obtained by reviewing satellite imagery (**Figure 25**). Note this applies to MUT sites only.
Weave Area Length	The length of the area where a right-turning vehicle attempting to complete an indirect left-turn movement weaves across through lanes to reach the directional crossover was obtained by reviewing satellite imagery (**Figure 26**). Note this applies to MUT sites only.
Driveway or Intersection Directly Aligned with Crossover	The number of driveways or intersections which are directly aligned with directional crossovers, thereby also allowing for left turns at the crossover opening, was obtained by reviewing satellite imagery (**Figure 27**). Note this applies to MUT sites only.
Number of Interior Crossovers	The total number of interior crossovers within the intersection influence area was obtained by reviewing satellite imagery (**Figure 5**). Note this applies to MUT sites only.
Number of Main Crossovers which are Signal Controlled	The total number of main crossovers which are signal controlled was obtained by reviewing satellite imagery (**Figure 5**). Note this applies to MUT sites only.
Average Number of Storage Lanes at Main Crossovers	The average number of storage lanes included for the main crossovers was obtained by reviewing satellite imagery (**Figure 5**). Note this applies to MUT sites only.

Figure 22. Lighting Structures Present at Median U-Turn Intersection in Michigan [*4*]

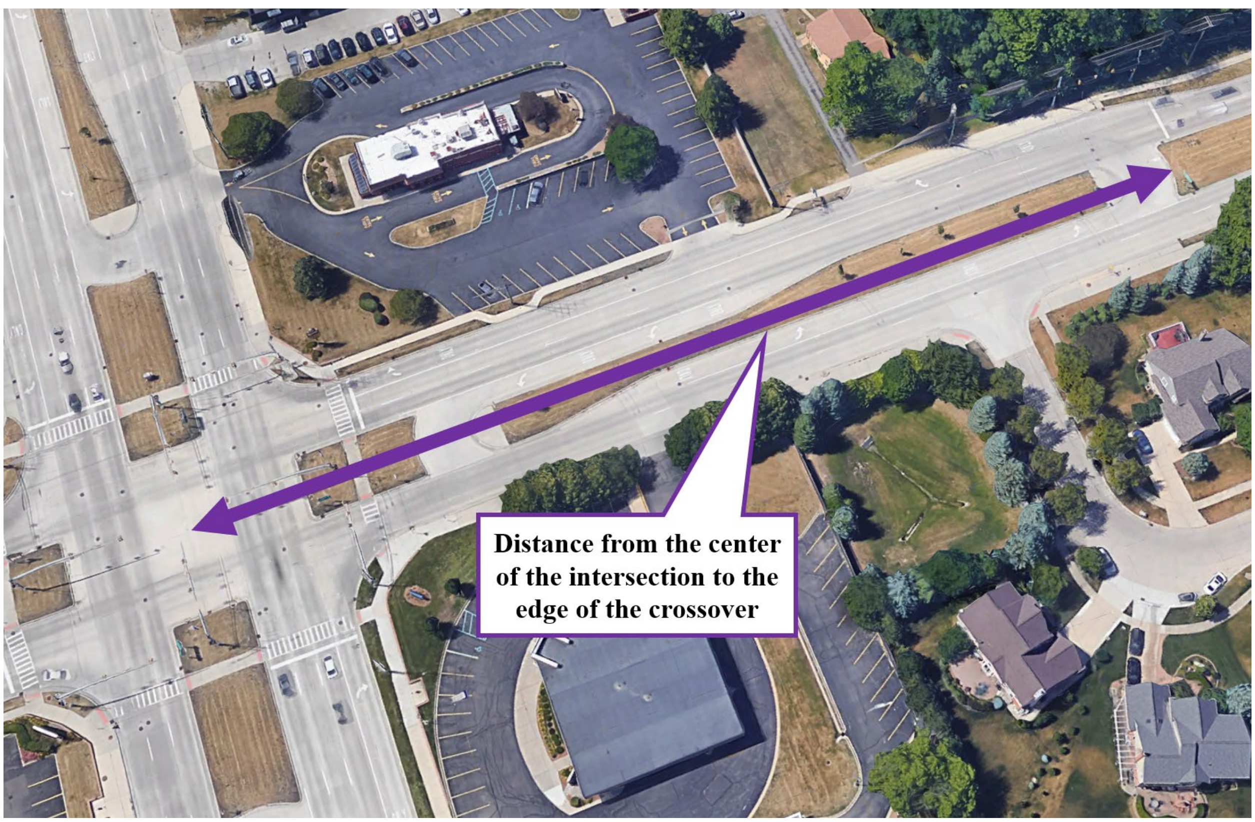


Figure 23. Example Measurement of Distance to the Main Crossovers [*4*]

Figure 24. Example Crossover Storage Lane Upstream of Intersection [*4*]

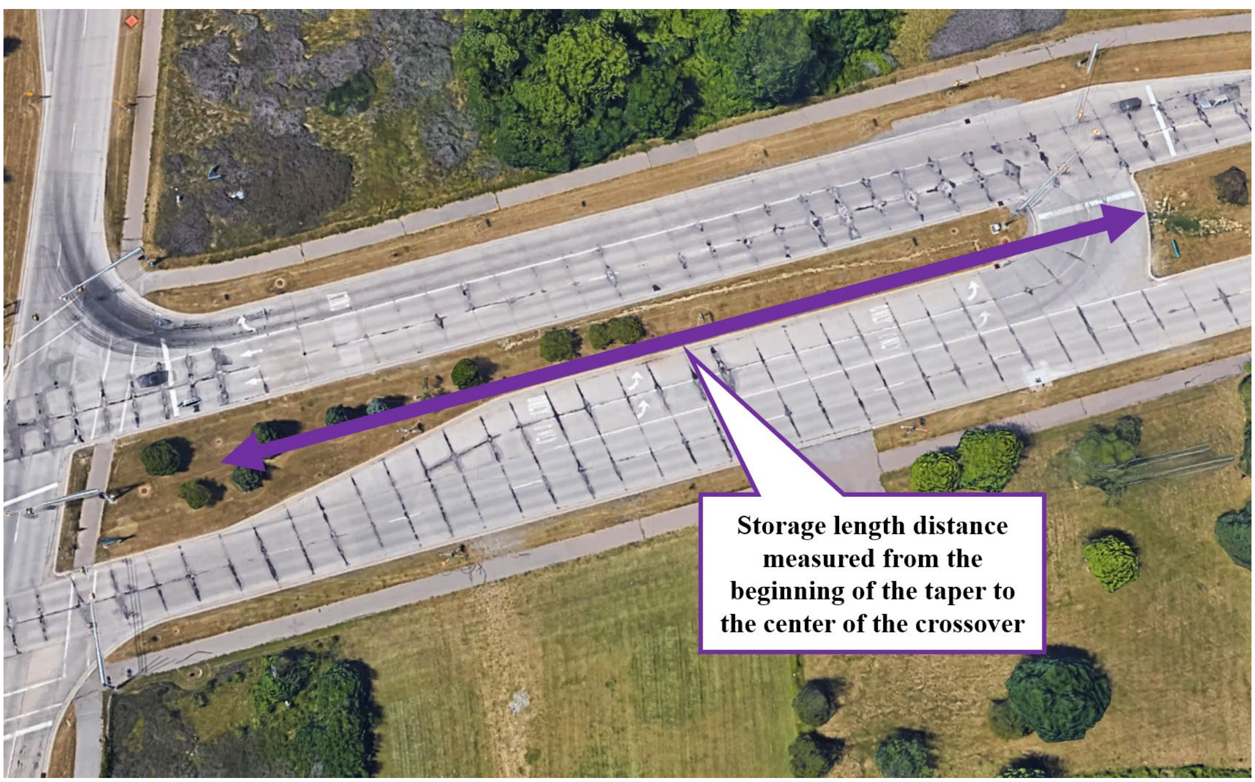


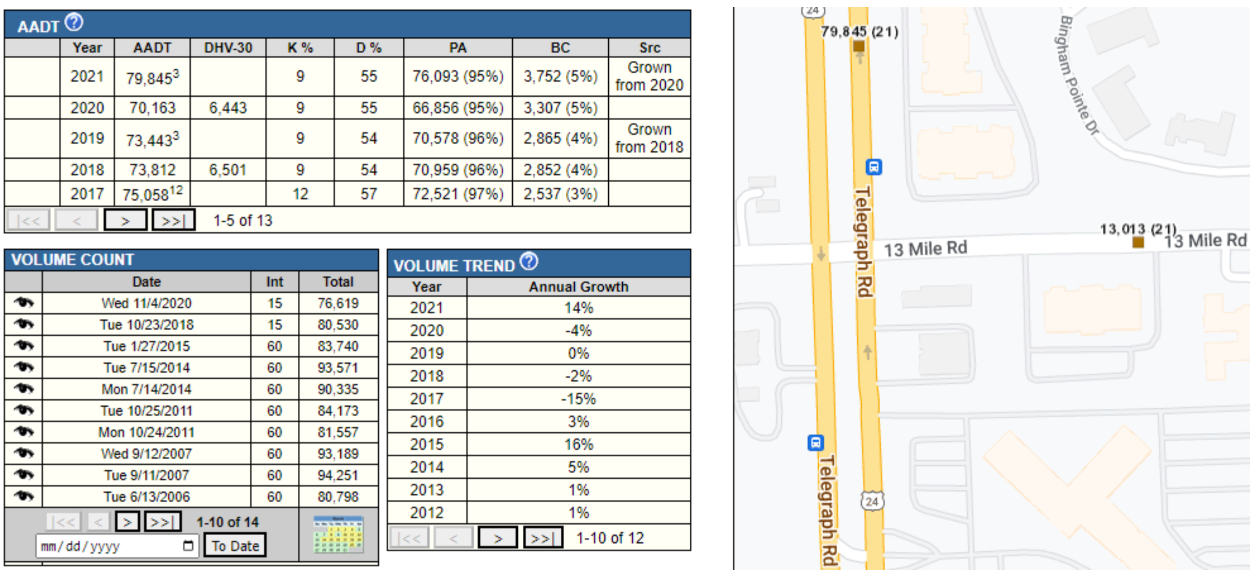
Figure 25. Example Measurement of Crossover Storage Length [*4*]

Figure 26. Example Measurement of Weaving Area Length [*4*]

Figure 27. Example Minor Intersection Direct Aligned with Crossover [*4*]

3.3 Traffic Volume Data

Estimates of daily entering vehicles for both the major and minor approaches were developed for each site as well as each year evaluated as a part of this study. This was completed by collecting annual average daily traffic (AADT) estimates maintained by the Michigan Department of Transportation (MDOT) for both the state- and locally-owned highway network adjacent to each site (**Figure 28**). AADT estimates maintained by counties and metropolitan planning organizations were collected where no data was available within the statewide resources. Years in which no AADT estimates were available were either interpolated between AADT estimates or extrapolated based upon statewide VMT trends (**Figure 29**).



AADT

	Year	AADT	DHV-30	K %	D %	PA	BC	Src
	2021	79,845[3]		9	55	76,093 (95%)	3,752 (5%)	Grown from 2020
	2020	70,163	6,443	9	55	66,856 (95%)	3,307 (5%)	
	2019	73,443[3]		9	54	70,578 (96%)	2,865 (4%)	Grown from 2018
	2018	73,812	6,501	9	54	70,959 (96%)	2,852 (4%)	
	2017	75,058[12]		12	57	72,521 (97%)	2,537 (3%)	

1-5 of 13

VOLUME COUNT

	Date	Int	Total
	Wed 11/4/2020	15	76,619
	Tue 10/23/2018	15	80,530
	Tue 1/27/2015	60	83,740
	Tue 7/15/2014	60	93,571
	Mon 7/14/2014	60	90,335
	Tue 10/25/2011	60	84,173
	Mon 10/24/2011	60	81,557
	Wed 9/12/2007	60	93,189
	Tue 9/11/2007	60	94,251
	Tue 6/13/2006	60	80,798

1-10 of 14

mm/dd/yyyy To Date

VOLUME TREND

Year	Annual Growth
2021	14%
2020	-4%
2019	0%
2018	-2%
2017	-15%
2016	3%
2015	16%
2014	5%
2013	1%
2012	1%

1-10 of 12

Figure 28. Traffic Volume Data - MDOT's *Transportation Data Management System* [*60*]

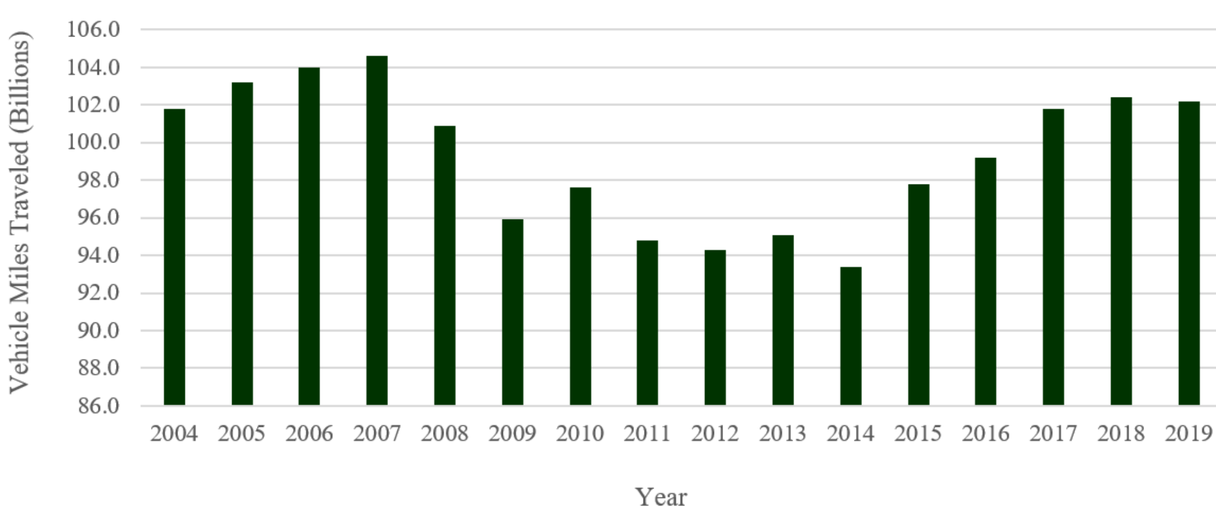


Figure 29. Statewide Vehicle Miles Traveled (in Billions) – 2004 to 2019 [*13*]

3.4 Traffic Crash Data

Historical traffic crash data which occurred within the influence area of each study site were obtained from the annual databases maintained by the Michigan State Police (MSP). This included crash records which occurred across the entire study period (2004 to 2019) in which consistent systemic statewide traffic crash data was available. While this study period is relatively long (and therefore opens up the potential concern for unobserved factors to influence the evaluation), this was necessary in order to maximize the number of years available for analysis. Additionally, data from 2020 and 2021 were excluded to avoid the impacts of the COVID-19 pandemic influencing the analysis.

Consistent with the study objectives (**Section 1.1**), a critical element of this evaluation involved the identification of the appropriate safety performance influence area of MUT intersection designs. FHWA's *Median U-Turn Informational Guide* [*1*] notes that it would be fundamentally unfair to compare "a conventional intersection to just the main junction of a MUT" and the analysis area should be large enough to include all crossovers. The conventional process for conducting intersection network screenings involves applying a circular buffer around the center of intersection with a specified radius, commonly set at 250 feet (**Figure 30**).

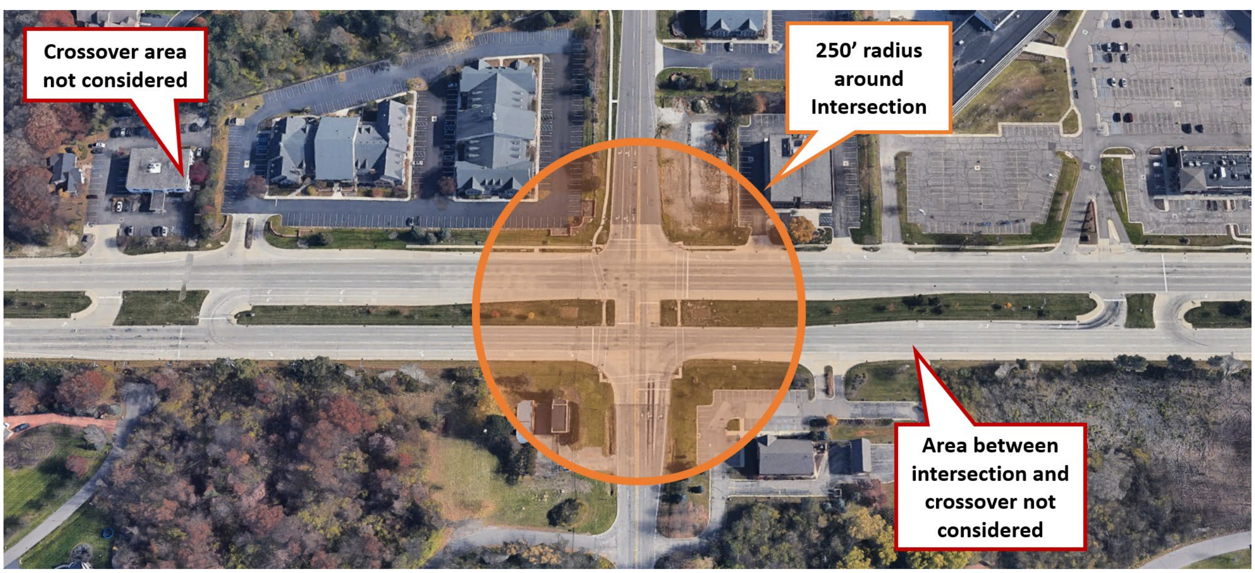


Figure 30. Conventional 250' Buffer around Main Intersection [*4*]

However, this approach to determining the safety performance influence area has a variety of important limitations specific to evaluating MUT designs. Given the relatively wide medians present along divided boulevards, the influence area must be of sufficient to include intersection-related collisions that occur along the minor approaches (which the 250-foot radius may not sufficiently cover). Additionally, the crossover areas and the areas in between the main intersection and the crossover are not considered. The Al-Omari et al. [*18*] study improved this approach by adding a 50-foot buffer around the directional crossovers (**Figure 31**). However, this approach still does not consider the area in between the directional crossovers and the main intersection. Additionally, this approach may exclude collisions which occur upstream of signalized crossovers.

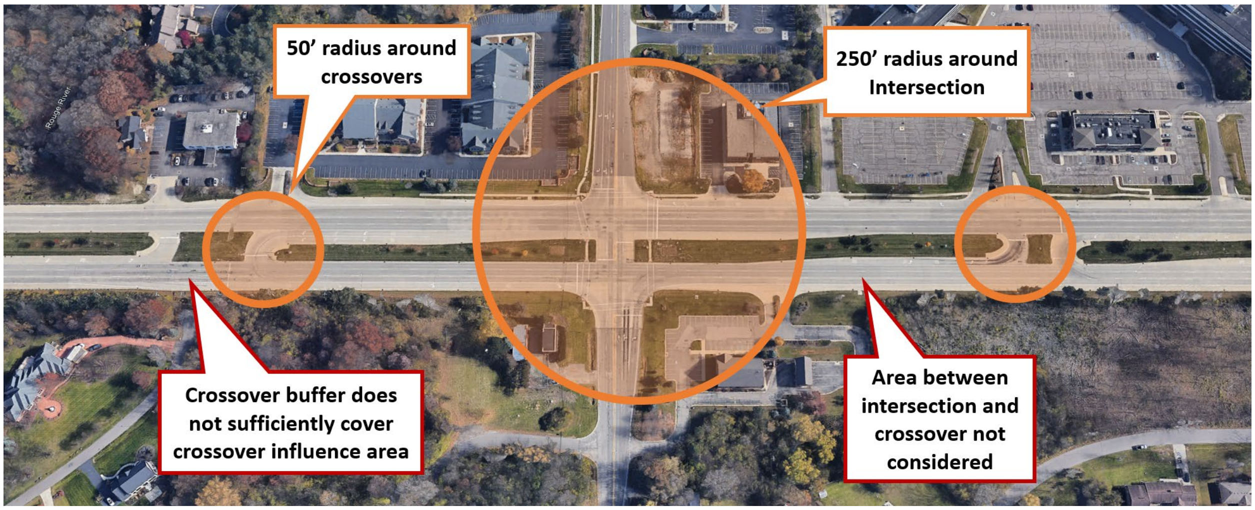


Figure 31. MUT Influence Area Applied within Al-Omari et al. Study [*4, 18*]

A novel approach was developed to ensure comprehensive coverage of the entire influence area, consistent with the recommendation in the FHWA *Median U-Turn Informational Guide* [*1*], shown in **Figure 32** (unsignalized intersections) and **Figure 33** (signalized intersections).

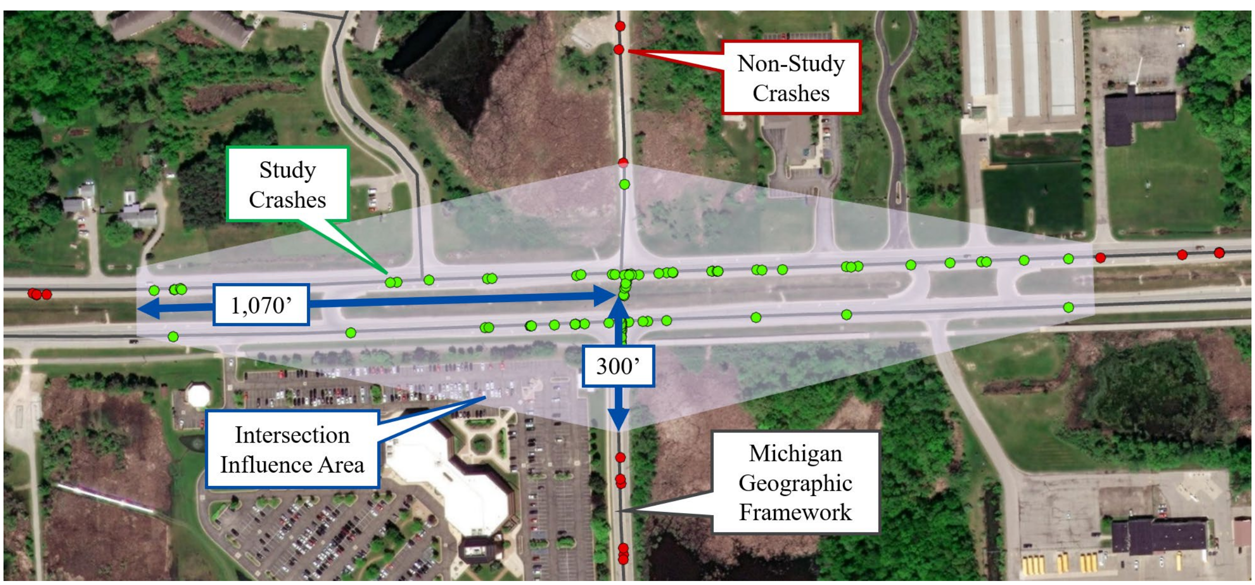


Figure 32. Crash Data Collection Process and Influence Area – Unsignalized Intersections

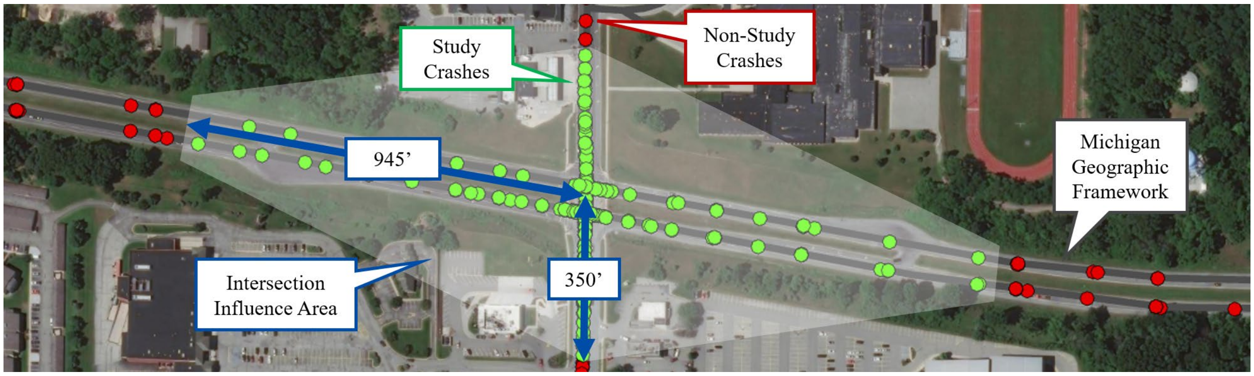


Figure 33. Crash Data Collection Process and Influence Area – Signalized Intersections

Unique influence areas were drawn in ArcGIS for each MUT and reference site based on the dimensions shown in **Figures 32 and 33**. These dimensions were the same for both the pre- and post-conversion conditions to allow for a comparison between the MUT and conventional designs. The major approach dimension for the unsignalized intersections was selected to ensure the influence area extended to the largest distance to the crossover in the study (which was 1,070 feet). The major approach dimension for the signalized intersections was selected to ensure at least 150 feet of influence area was included beyond the edge of the largest distance to the main crossover in the study (which was 795 feet). This is critical for designs which include signalized crossovers as a pattern of end-of-queue collisions may occur upstream of the stop bar.

The major approach dimensions (300 feet for unsignalized intersections and 350 feet for signalized intersections) were selected to ensure coverage of intersection-related collisions occurring along the minor approaches. It is important to note that sites were selected such that no conflicting signalized intersections or atypical geometry are present within these boundaries.

Relevant traffic crash records were identified via a spatial join conducted in ArcGIS based on the influence areas shown in **Figures 32 and 33** and the annual statewide crash databases maintained by MSP. Crash records which occurred within the year(s) of conversion (as identified in **Section 3.1**) were removed from the analysis. Additionally, crash records that involved animals were removed from the analysis, consistent with prior SPF research in Michigan [*58*]. The selected crash records were combined with the intersection data (outlined in **Sections 3.2 and 3.3**) to develop datasets for subsequent analysis. Finally, the Michigan UD-10 crash report forms were obtained for all fatal (K) and serious injury (A) collisions and manually reviewed. The precise location, crash type (if different from the coding by the responding officer), and a categorization of these collisions was determined by reviewing the narrative and diagram. Crashes which were erroneously located within the influence area were subsequently removed from the analysis.

4.0 ANALYTICAL METHODOLOGY

After developing the MUT and reference site datasets (**Section 3.0**), appropriate analytical methods were identified based on the findings of the comprehensive literature review (**Section 2.0**). Distinct evaluations of safety performance were then conducted specific to unsignalized MUTs (**Section 5.0**) and signalized MUTs (**Section 6.0**). This included the use of traditional safety performance metrics (such as crash patterns or aggregate crash rates, **Section 4.1**), the development of a series of SPFs (**Section 4.2**), and CMFs for the four conversion scenarios shown in **Figures 4 and 6** (**Section 4.3**).

4.1 Traditional Safety Performance Metrics

A series of traditional safety performance metrics that have historically been used as a part of safety performance analyses are included for both the unsignalized and signalized evaluations. This includes total crash frequencies, annual average crash frequencies, and aggregate crash rates per one million total entering vehicles (or the summation of both the major and minor approaches):

$$Crash\ Frequency = \sum Crash\ Counts\ for\ All\ Study\ Years \tag{1}$$

$$Annual\ Average = \frac{Crash\ Frequency}{Number\ of\ Study\ Years} \tag{2}$$

$$Crash\ Rate = \frac{Crash\ Frequency\ \ x\ 1{,}000{,}000}{Daily\ Total\ Entering\ Volume\ x\ 365\ Days\ x\ Number\ of\ Study\ Years} \tag{3}$$

The distribution of crashes by both type and severity are also provided to characterize safety performance as well as serve a reference when conducting analyses consistent with the HSM [*28*]. Data from the manual review of K+A collisions were used to provide an additional review of crash patterns related to these severe incidents. Crash concentration diagrams were developed using the kernel density tool in ArcGIS which provide a visualization of the common K+A crash locations by type and category. These findings were used to further characterize safety performance and identify patterns which could potentially be mitigated with appropriate design treatments.

However, it is important to recognize that these traditional metrics should be interpreted with caution (particularly the aggregated crash rates) and the use of modern analytical methods are required to determine if there are statistical differences in safety performance. This includes not only comparisons between the MUT and conventional designs, but also analyses intended to identify the safety performance impacts of specific MUT design features.

4.2 Safety Performance Functions

A series of negative binomial regression models were estimated specific to the datasets developed as a part if this evaluation (**Section 3.0**) in order to develop SPFs that relate the annual number of crashes at a given intersection to site characteristics (including traffic volume, pre- and post-conversion status, and design characteristics). The SPFs estimated within the unsignalized (**Section 5.4**) and signalized (**Section 6.4**) evaluations vary depending on the analytical purpose and the explanatory variables included in the model. First, SPFs are developed specific to each site type in order to benchmark safety performance and identify potential design features which impact crash frequency. SPFs were also developed to support both use of the empirical Bayes (EB) before-and-after as well as cross-sectional analytical methods of comparing MUT and conventional intersection performance. Distinct SPFs were developed for fatal and injury (FI) and property damage only (PDO) crashes.

The negative binomial was employed to develop SPFs which is a generalized form of the Poisson model. In the Poisson regression model, the probability of intersection *i* experiencing y_i crashes during a specific period (or one year for this evaluation) is given by:

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!} \quad (4)$$

where $P(y_i)$ is probability of intersection *i* experiencing y_i crashes during the one-year period and λ_i is equal to the intersection's expected number of crashes, $E[y_i]$. Poisson regression models are estimated by specifying the Poisson parameter λ_i as a function of explanatory variables. The most common functional form of this equation is λ_i = EXP(βX_i), where X_i is a vector of explanatory variables (including traffic volume, conversion status, and other intersection characteristics) and β is a vector of estimable parameters.

The negative binomial model was derived by rewriting the Poisson parameter for each intersection i as λ_i = EXP(βX_i + ε_i), where EXP(ε_i) is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows for the variance to differ from the mean as $VAR[y_i] = E[y_i] + \alpha E[y_i]^2$. The α term is also known as the overdispersion parameter which reflects the additional variation in crash counts beyond the Poisson model (where α is assumed to equal zero, i.e., the mean and variance are assumed to be equal). A site-specific random effect (intercept) was also included to accommodate the fact that each intersection includes observations for each year available for analysis within the study period. This repeated-measure study design introduces potential correlation between crash counts at each intersection over time due to site-specific factors which are not included in the model, leading to biased, inefficient, or inconsistent parameter estimates without accommodation.

The SPFs used in the evaluation vary by the site type and analytical purpose, but the generalized functional form is show below:

$$N_{spf} = e^{\beta_0}\left(AADT_{Major\ Approach}{}^{\beta_1}\right)\left(AADT_{Minor\ Approach}{}^{\beta_2}\right)e^{\beta_i X_i} \quad (5)$$

Where,

N_{spf} = Predicted number of crashes occurring within the influence area per year,

β_0 = Intercept term,

$AADT_{Major\ Approach}$ = Number of daily entering vehicles along the major approaches,

$AADT_{Minor\ Approach}$ = Number of daily entering vehicles along the minor approaches

β_1 = Coefficient term specific to major approach traffic volume

β_2 = Coefficient term specific to minor approach traffic volume

β_i = Vector of coefficient terms that relate to the explanatory variables in the study

X_i = Vector of binary indicator that relate to the explanatory variables in the study

4.3 Crash Modification Factors

CMFs were developed specific to the conversion scenarios shown in **Figures 4 and 6** via both an EB method before-and-after approach as well as a cross-sectional approach as outlined in prior work [*27, 28*]. It should be noted that the use of these methods varies by the site type (unsignalized vs. signalized) as well as the pre-conversion condition being evaluated due to the limited availability of pre-conversion data for specific scenarios. While both methods are used where feasible, only the cross-sectional method is included where the availability of pre-conversion data limited the practical significance of the EB method. Distinct CMFs were developed for fatal and injury (FI) and property damage only (PDO) crashes.

4.3.1 EB Before-and-After Approach

Under the EB before-and-after approach, historical crash data are combined with predicted values from obtained from a SPF (developed using the reference sites) to determine the best estimate of crashes during the post-conversion period had a particular safety treatment not been applied [*27*]. In practical terms, data from the pre-conversion period are given greater weight as the analysis time period increases (i.e., as more years of data are available for analysis) or as the regression estimates become more precise (i.e., as the variance of the regression estimate decreases). A conceptual diagram of the EB method before-and-after approach employed to estimate CMFs for MUT conversions is shown in **Figure 34**.

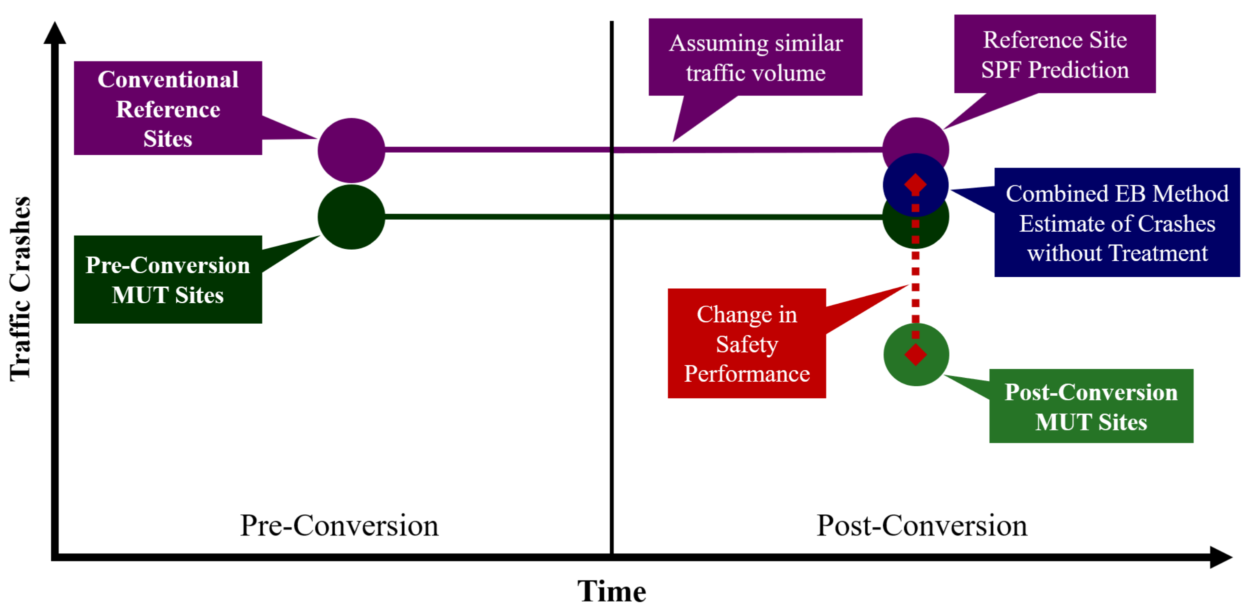


Figure 34. Conceptual Diagram of EB Approach for MUT CMF Development

Under the EB before-and-after design, the change in safety performance is given by the difference between the EB-calculated expected number of crashes that would have occurred in the post-conversion period without the MUT conversion and the observed number of crashes in the post-conversion period. The estimate of crashes which would have occurred without conversion is obtained by using the EB procedure and is calculated with the predicted number of crashes based on a SPF (developed using reference sites) and the observed number of crashes that occurred at that site during the pre-conversion period:

$$N_{expected} = w \; x \; N_{predicted} + (1 - w) \; x \; N_{observed} \quad (6)$$

Where,

$N_{expected}$ = Expected crash frequency within the influence area without conversion

$N_{predicted}$ = Predicted crash frequency obtained from SPF developed using reference sites

$N_{observed}$ = Observed crash frequency within the pre-conversion influence area

w = weighting factor that is determined using the overdispersion parameter from the reference site SPF (as defined in **Section 4.2**) to combine the predicted and observed values into a weighted average expected value based on the variance of the SPF:

$$w = \frac{1}{1 + \alpha \; x \; N_{predicted}} \quad (7)$$

Where,

α = Overdispersion parameter from the reference site SPF

Ultimately, CMFs for MUT conversion scenarios with available pre-conversion data were estimated by calculating the index of effectiveness ($\hat{\theta}$) for all sites:

$$\hat{\theta} = \frac{N_{observed\,MUT}}{N_{expected}\left[1 + Var\left(N_{expected}\right) / N_{expected}{}^{2}\right]} \quad (8)$$

Where,

$N_{observed\,MUT}$ = Observed crash frequency within MUT influence areas

4.3.1 Cross-Sectional Approach

The cross-sectional CMFs were estimated by taking the exponent of the parameter estimate from a status (MUT vs. conventional) indicator variable included within the cross-sectional models. The standard error for the cross-sectional CMFs were approximated via the delta method outlined in prior research [*61*]. A conceptual diagram of the cross-sectional approach employed to estimate CMFs for MUT conversions is shown in **Figure 35**.

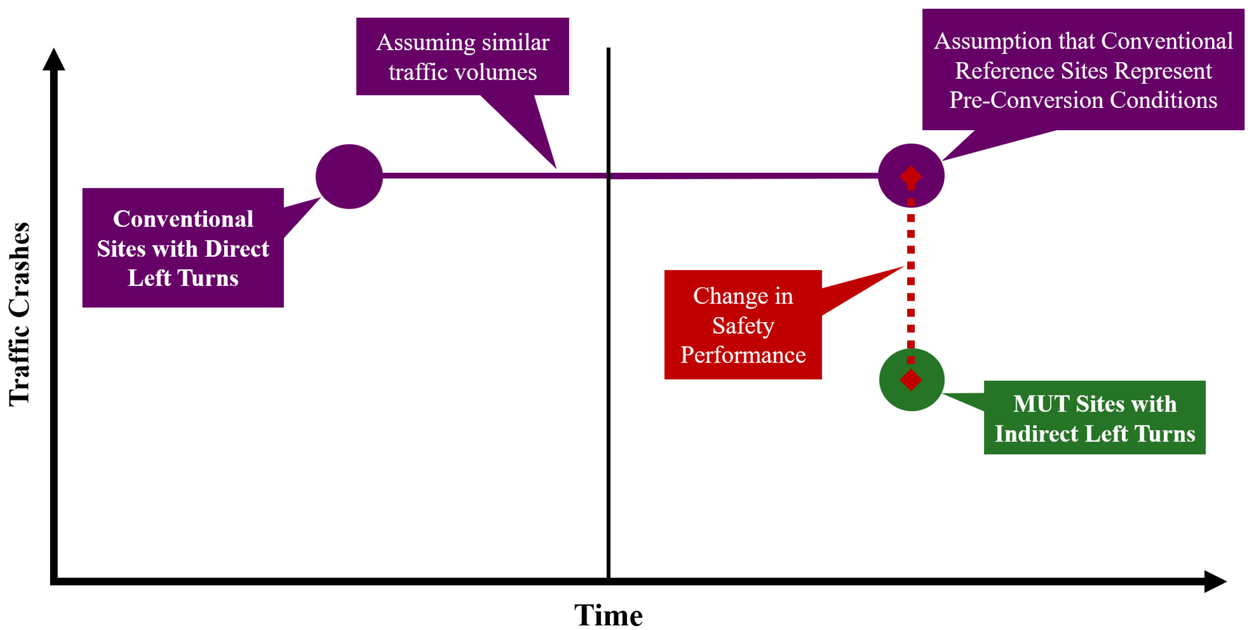


Figure 35. Conceptual Diagram of Cross-Sectional Approach for MUT CMF Development

5.0 UNSIGNALIZED MEDIAN U-TURN INTERSECTIONS

The 95 unsignalized intersections identified in **Section 3.1** (including 39 MUT sites and 56 reference sites) were evaluated consistent with the analytical methods outlined in **Section 4.0**. First, descriptive statistics are presented (**Section 5.1**) which summarize the traffic volume data, traffic crash data, and other intersection characteristics specific to both the MUT and conventional unsignalized intersections. Next, aggregate traffic crash frequencies and rates are provided in addition to distributions of crashes by type and severity (**Section 5.2**). A detailed analysis of crashes which resulted in fatal (K) and severe (A) injuries to either vehicle occupants or non-motorized road users is included to identify severe collision patterns (**Section 5.3**). The development of the SPFs used in the evaluation are summarized (**Section 5.4**) and ultimately CMFs are presented (**Section 5.5**) for the two conversion scenarios outlined in **Section 1.4**.

5.1 Descriptive Statistics

The traffic volume data (or the number of entering vehicles per day along the major and minor approaches, traffic crash data (disaggregated by worst injury severity), and intersection data specific to the unsignalized MUT sites as well as the undivided and divided conventional sites are summarized in **Table 7**.

Table 7. Summary of Entering Volumes, Traffic Crash Data, and Intersection Characteristics – Unsignalized MUTs and Conventional Reference Sites

Characteristic	Conventional Undivided Sites (N=30)			Conventional Divided Sites (N=53)			Median U-Turn Sites (N=39)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Major Approach Vehicles per Day	6,540	12,944	24,479	3,855	15,870	30,663	7,320	20,983	37,443
Minor Approach Vehicles per Day	337	1,611	6,283	119	1,547	8,099	176	2,105	7,844
Annual K+A Crashes*	0.00	0.17	3.00	0.00	0.17	3.00	0.00	0.10	2.00
Annual K+A+B+C Crashes	0.00	1.29	7.00	0.00	1.04	6.00	0.00	0.92	7.00
Annual PDO Crashes	0.00	3.01	14.00	0.00	2.50	16.00	0.00	5.39	27.00
Annual Total Crashes	0.00	4.30	16.00	0.00	3.54	20.00	0.00	6.31	31.00
Major App. Posted Speed Limit	55.0	55.0	55.0	35.0	55.3	65.0	40.0	54.2	65.0
Minor App. Posted Speed Limit	35.0	53.5	55.0	25.0	46.4	55.0	25.0	43.6	55.0
Major App. Principal Arterial	0.00	0.56	1.00	0.00	0.76	1.00	0.00	0.82	1.00
Major App. Minor Arterial	0.00	0.44	1.00	0.00	0.24	1.00	0.00	0.18	1.00
Minor App. Minor Arterial	0.00	0.15	1.00	0.00	0.06	1.00	0.00	0.13	1.00
Minor App. Major Collector	0.00	0.63	1.00	0.00	0.39	1.00	0.00	0.37	1.00
Minor App. Minor Collector	0.00	0.11	1.00	0.00	0.05	1.00	0.00	0.00	0.00
Minor App. Local	0.00	0.12	1.00	0.00	0.50	1.00	0.00	0.51	1.00

Table 7 (cont'd)

Characteristic	Conventional Undivided Sites (N=30)			Conventional Divided Sites (N=53)			Median U-Turn Sites (N=39)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Lighting Present	0.00	0.73	1.00	0.00	0.33	1.00	0.00	0.64	1.00
Exclusive Left-Turn Lanes Present	0.00	0.41	1.00	0.00	0.60	1.00	-	-	-
Exclusive Right-Turn Lanes	0.00	0.52	2.00	0.00	0.65	2.00	0.00	1.69	2.00
Skew	0.00	6.72	40.00	0.00	15.63	60.00	0.00	12.22	40.00
Driveways	0.00	5.29	14.00	0.00	3.12	14.00	0.00	4.10	17.00
Intersections	0.00	0.11	1.00	0.00	0.35	2.00	0.00	0.31	2.00
Rural Roadway Context	0.00	0.77	1.00	0.00	0.61	1.00	0.00	0.54	1.00
Suburban Roadway Context	0.00	0.23	1.00	0.00	0.39	1.00	0.00	0.46	1.00
Median Openings or Crossovers	na	na	na	0.00	0.87	4.00	2.00	2.76	4.00
Median Width	na	na	na	10.0	34.1	125.0	20.0	47.2	125.0
Distance to Crossovers	na	na	na	na	na	na	260.0	638.2	1,070.0
Storage Lane Begins Upstream	na	na	na	na	na	na	0.00	0.32	1.00
Truck Loon Present at Crossover	na	na	na	na	na	na	0.00	0.27	1.00
Crossover Storage Lane Length	na	na	na	na	na	na	240.0	559.6	890.0
Weave Area Length	na	na	na	na	na	na	0.00	125.4	560.0
Driveway or Intersection Directly Aligned with Crossover	na	na	na	na	na	na	0.00	0.18	2.00

**Note that fatal (K) and serious injury (A) crashes were manually reviewed as a part of a distinct process*

Major approach volumes at the MUT sites ranged from 7,320 to 37,433 vehicles per day with an average of approximately 21,000 vehicles per day. Unsignalized MUTs tended to serve larger major approach volumes than either the conventional undivided (mean of 12,944 vehicles per day) and conventional divided (mean of 15,870 vehicles per day) sites included in the study. Despite the efforts to identify reference sites that possessed geometric and other design characteristics which were similar to the pre-conversion MUT sites, there is lack of available conventional sites with volumes to match the upper end of the range of major approach volumes served by unsignalized MUTs. This is due the widespread adoption of the MUT design along arterial highways practiced by both MDOT and local roadway agencies in Michigan. These differences should be considered when evaluating the aggregated crash rates presented in **Section 5.2** and subsequent analytical methods will attempt to help account for these differences in major approach volume (**Section 5.4 and 5.5**). Minor approach volumes were in general agreement across the unsignalized MUT, conventional undivided, and conventional divided sites.

While the average number of all traffic crashes at unsignalized MUT intersections (6.31) was larger than either the undivided (4.30) or divided (3.54) conventional sites, the average number of K+A crashes was lower at the MUT sites (0.10) than the conventional sites (0.17). A similar trend can also be observed for fatal and all injury crashes (K+A+B+C). Conversely, the average number of PDO crashes was larger at the MUT sites (5.39) than the conventional undivided (3.01) and divided (2.50) sites.

The overwhelming majority of all study sites are located along high-speed arterial highways with a posted speed limit of 55 miles per hour. Select sites are included with posted speed limits as low as 35 miles per hour and as high as 65 miles per hour. Posted speed limits along the minor approaches ranged from 25 miles per hour local streets up to 55 miles per hour arterials. The MUT sites are located predominately along principal arterial routes (82 percent), whereas the conventional undivided (56 percent) and divided (76 percent) include a higher share of minor arterial major approaches. The minor approaches include a mix of minor arterials, collectors, and local roadways.

Lighting was present more often at the MUT (64 percent) and conventional undivided (73 percent) sites than the conventional divided (33 percent) sites. Conventional divided sites tended to include more exclusive left-turn lanes (60 percent) than conventional undivided sites (41 percent). The MUT sites tended to include more exclusive right turn lanes (mean of 1.69 lanes) than the conventional undivided (0.52 lanes) or divided (0.65 lanes) sites. Skew angles tended to be higher at the MUT (mean of 12.22 degrees) and conventional divided (15.63 degrees) sites than the undivided sites (6.72 degrees). While driveway counts within the intersection influence area were relatively similar across all three site types, there tended to be more minor intersections at the MUT (mean of 0.31 minor intersections) and conventional divided (0.35 minor intersections) sites than the conventional undivided sites (0.11 minor intersections). All three site types include a mix of intersections located in both suburban and rural roadway contexts.

Median openings at the conventional divided sites ranged from zero to four with an average of 0.87. Intuitively, the average number of directional crossovers was larger at the MUT sites (2.76) given that each site includes a minimum of two directional crossovers. The distance to main crossover ranged from 260 to 1,070 feet with an average of 638.2 feet (in general agreement with Michigan's design guidance of 600 to 700 feet [*31*]). The storage lane began upstream of the main intersection at 32 percent of MUT sites, the average storage lane length was approximately 560 feet and the average weave area length was approximately 125 feet. Truck loons were present at 27 percent of MUT sites and an average of nine percent of the directional crossovers included a driveway or intersection in direct alignment.

5.2 Traditional Safety Performance Metrics

The total frequency of crashes, annual average, and crash rate per one million entering vehicles for the 39 unsignalized MUT sites is shown in **Table 8** disaggregated by police-reported crash type and worst injury in the crash. **Table 9** provides a comparison between the crash rates observed at the MUT and conventional site types.

Table 8. Traffic Crash Frequency, Annual Average, and Rate – Unsignalized MUTs (N=39)

Police-Reported Crash Type	Frequency	Annual Average	Crash Rate	Percent
Single Vehicle	591	1.51	0.179	23.9%
Head On	13	0.03	0.004	0.5%
Head On Left-Turn	4	0.01	0.001	0.2%
Angle	216	0.55	0.066	8.8%
Rear End	1,314	3.36	0.399	53.2%
Sideswipe Same	254	0.65	0.077	10.3%
Sideswipe Opposite	18	0.05	0.005	0.7%
Other	58	0.15	0.018	2.4%
Total	**2,468**	**6.31**	**0.749**	**100.0%**
Worst Injury in Crash	**Frequency**	**Annual Average**	**Crash Rate**	**Percent**
K (Fatal)	10	0.03	0.003	0.4%
A (Serious Injury)	27	0.07	0.008	1.1%
B (Minor Injury)	85	0.22	0.026	3.4%
C (Possible Injury)	238	0.61	0.072	9.6%
PDO (No Injury)	2,108	5.39	0.640	85.4%
Total	**2,468**	**6.31**	**0.749**	**100.0%**

Table 9. Crash Rates per 1M Ent. Vehicles – Unsignalized MUTs vs. Conventional Designs

Police-Reported Crash Type	Conventional Undivided vs. MUT Sites			Conventional Divided vs. MUT Sites		
	Undivided (N=30)	MUT (N=39)	Percent Difference	Divided (N=53)	MUT (N=39)	Percent Difference
Single Vehicle	0.159	0.179	13.0%	0.155	0.179	16.0%
Head On	0.017	0.004	-76.4%	0.004	0.004	7.0%
Head On Left-Turn	0.023	0.001	-94.7%	0.008	0.001	-84.1%
Angle	0.205	0.066	-68.0%	0.198	0.066	-66.9%
Rear End	0.311	0.399	28.2%	0.115	0.399	245.6%
Sideswipe Same	0.037	0.077	109.5%	0.043	0.077	78.4%
Sideswipe Opposite	0.023	0.005	-75.9%	0.010	0.005	-44.0%
Other	0.035	0.018	-49.8%	0.025	0.018	-28.2%
Total	**0.809**	**0.749**	**-7.4%**	**0.557**	**0.749**	**34.5%**
Worst Injury in Crash	**Conventional Undivided vs. MUT Sites**			**Conventional Divided vs. MUT Sites**		
	Undivided (N=30)	**MUT (N=39)**	**Percent Difference**	**Divided (N=53)**	**MUT (N=39)**	**Percent Difference**
Fatal	0.006	0.003	-45.4%	0.003	0.003	-4.0%
Serious Injury	0.027	0.008	-69.6%	0.024	0.008	-65.4%
Minor Injury	0.076	0.026	-66.1%	0.042	0.026	-38.4%
Possible Injury	0.134	0.072	-46.2%	0.094	0.072	-23.4%
PDO (No Injury)	0.566	0.640	13.0%	0.394	0.640	62.5%
Total	**0.809**	**0.749**	**-7.4%**	**0.557**	**0.749**	**34.5%**

Rear end collisions represented the majority (53 percent) of traffic crashes occurring within the unsignalized MUT influence area, followed by single vehicle (24 percent), sideswipe same (10 percent), and angle (9 percent) collisions. A total of 37 fatal and serious injury collisions occurred at the MUT sites during the study period, representing approximately 1.5 percent of all traffic crashes. Property damage only collisions represented more than 85 percent of all traffic crashes within the unsignalized MUT influence areas.

Table 9 presents some considerable differences in aggregate average traffic crash rates at the MUT sites compared to both the conventional undivided and divided sites. The MUT sites observed lower average rates of head on (76.4 percent), head on left-turn (94.7 percent), angle (68.0 percent), and sideswipe opposite (76 percent) crashes compared to the conventional undivided sites. The average rates were greater for single vehicle (13.0 percent) rear end (28.2 percent) and sideswipe same (109.5 percent) collisions. These differences drove lower rates of FI crashes at the MUT sites compared to the conventional divided sites. Although the rate of PDO crashes was larger at the MUT sites, the total crash rate was approximately 7.4 percent lower due to the lower rate of FI crashes.

The comparison of rates between the MUT and conventional divided sites exhibits similar trends to the comparison with the conventional undivided sites. However, the larger rates of rear end (256.6 percent) and sideswipe same (78.4 percent) collisions resulted in the property damage crash rate being approximately 63 percent larger at the MUT sites compared to the conventional divided sites. As a result, the total crash rate was also approximately 35 percent larger at the MUT sites compared to the conventional divided sites. Given that the major approach is already divided, the rates of head on collisions were relatively similar for both the MUT and conventional divided sites. As previously noted, these aggregate crash rates should be interpreted with caution and the application of modern analytical approaches are required (**Sections 5.4 and 5.5**) to determine if there is a statistical difference in the FI or PDO crash frequencies associated with the MUT design.

5.3 Fatal and Serious Injury Crash Patterns

The additional manual review of K+A crash report forms (outlined in **Section 3.4**) allowed for a more in-depth evaluation these severe collisions in order to identify common circumstances. A summary of the annual average number of K+A crashes by crash type, location, and category is provided in **Table 10** for each site type. Subsequently, a series of crash concentration diagrams are presented for specific crash types that identify common locations for K+A crashes.

Table 10. Annual Average K+A Crashes by Type, Location, and Category – Unsignalized MUTs vs. Conventional Designs

Crash Type	Undivided		Divided		Median U-Turn	
	Average	Percent	Average	Percent	Average	Percent
Single Vehicle	0.009	5.3%	0.022	12.7%	0.036	37.8%
Head-On	0.018	10.5%	0.002	1.0%	0.010	10.8%
Head-On Left-Turn	0.009	5.3%	0.007	3.9%	0.000	0.0%
Angle	0.091	52.6%	0.111	64.7%	0.010	10.8%
Rear End	0.039	22.4%	0.013	7.8%	0.015	16.2%
Sideswipe Same	0.002	1.3%	0.007	3.9%	0.018	18.9%
Sideswipe Opposite	0.000	0.0%	0.002	1.0%	0.000	0.0%
Car-Pedestrian	0.005	2.6%	0.005	2.9%	0.003	2.7%
Car-Bike	0.000	0.0%	0.003	2.0%	0.003	2.7%
Total	**0.173**	**100.0%**	**0.171**	**100.0%**	**0.095**	**100.0%**
Crash Location	**Undivided**		**Divided**		**Median U-Turn**	
	Average	**Percent**	**Average**	**Percent**	**Average**	**Percent**
Major Approach	0.055	31.6%	0.039	22.5%	0.051	54.1%
Minor Approach	0.011	6.6%	0.002	1.0%	0.003	2.7%
Within Intersection	0.107	61.8%	0.129	75.5%	0.018	18.9%
Crossovers	na	na	0.002	1.0%	0.023	24.3%
Total	**0.173**	**100.0%**	**0.171**	**100.0%**	**0.095**	**100.0%**
Category	**Undivided**		**Divided**		**Median U-Turn**	
	Average	**Percent**	**Average**	**Percent**	**Average**	**Percent**
Wrong Way	na	na	0.002	1.0%	0.008	8.1%
Lane Departure	0.025	14.5%	0.028	16.7%	0.038	40.5%
Disregard Traffic Control/Fail to Yield	0.095	55.3%	0.117	68.6%	0.020	21.6%
Speed Too Fast	0.036	21.1%	0.013	7.8%	0.018	18.9%
Crossing not at Crosswalk	0.005	2.6%	0.005	2.9%	0.003	2.7%
Careless/Reckless Driving	0.011	6.6%	0.005	2.9%	0.008	8.1%
Total	**0.173**	**100.0%**	**0.171**	**100.0%**	**0.095**	**100.0%**

Consistent with the traffic crash rates presented in **Table 9**, the MUT sites observed fewer K+A crashes on an aggregate annual average basis than both conventional site types. The primary difference between the MUT and conventional sites is the considerable shift away from angle collisions occurring within the intersection. Only a limited number of K+A pedestrian and bicycle crashes occurred during the study period. Crash concentration diagrams for all K+A crashes are shown in **Figure 36** for each of the three intersection types. The precise location data obtained from the crash report form review was used to map each collision to an example intersection into order to visualize the relative crash location within the example intersection's influence area. The kernel density tool in ArcGIS was subsequently used to common patterns of severe crashes which occurred at each of the three site types over the entire study period.

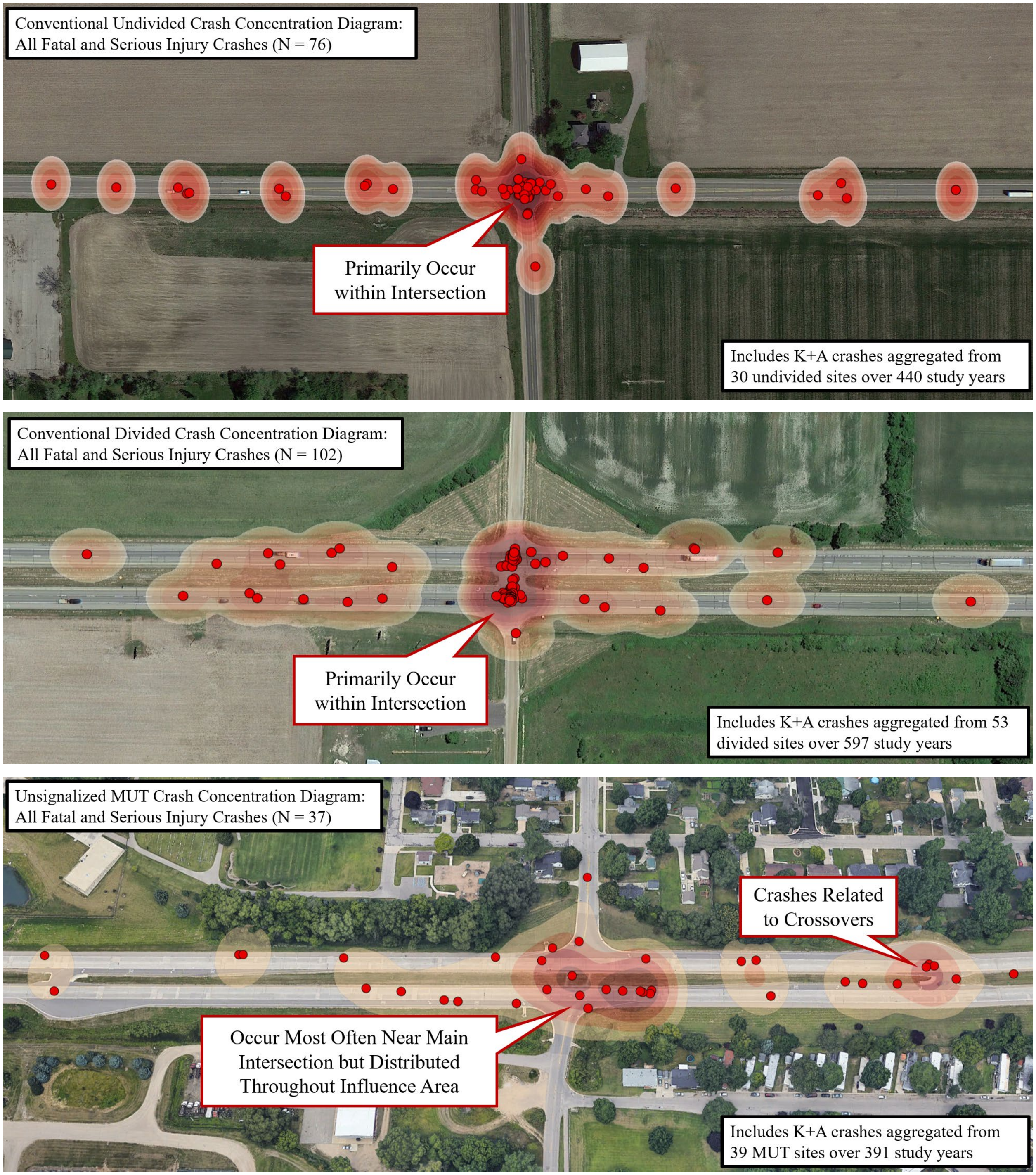


Figure 36. K+A Crash Conc. Diagrams – Unsignalized MUT vs. Conventional Sites

The crash concentration diagrams presented in **Figure 36** demonstrate the shift away from severe crashes occurring within the intersection at the MUT sites (19 percent) compared to the conventional undivided (62 percent) and divided (76 percent) sites. Crash concentration diagrams for single vehicle K+A crashes at the MUT and divided sites is shown in **Figure 37**.

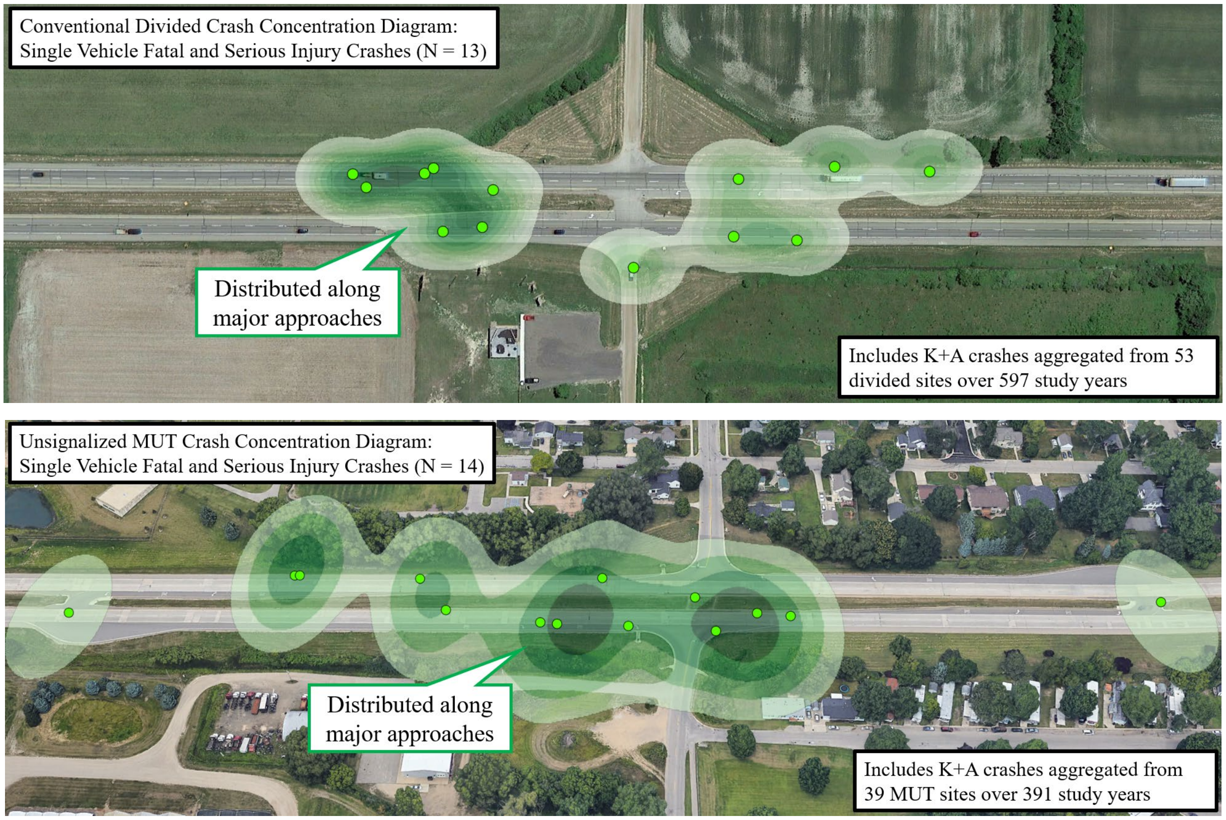


Figure 37. Single Vehicle K+A Crash Concentration Diagrams – Unsignalized MUT vs. Conventional Divided Sites

Single vehicle K+A crashes are distributed along the major approaches for both the MUT and conventional divided sites. Single vehicle K+A crashes were rare at the conventional undivided sites (a total of four occurred during the entire study period). A crash concentration diagram for head on and angle K+A crashes at the MUT sites is shown in **Figure 38**.

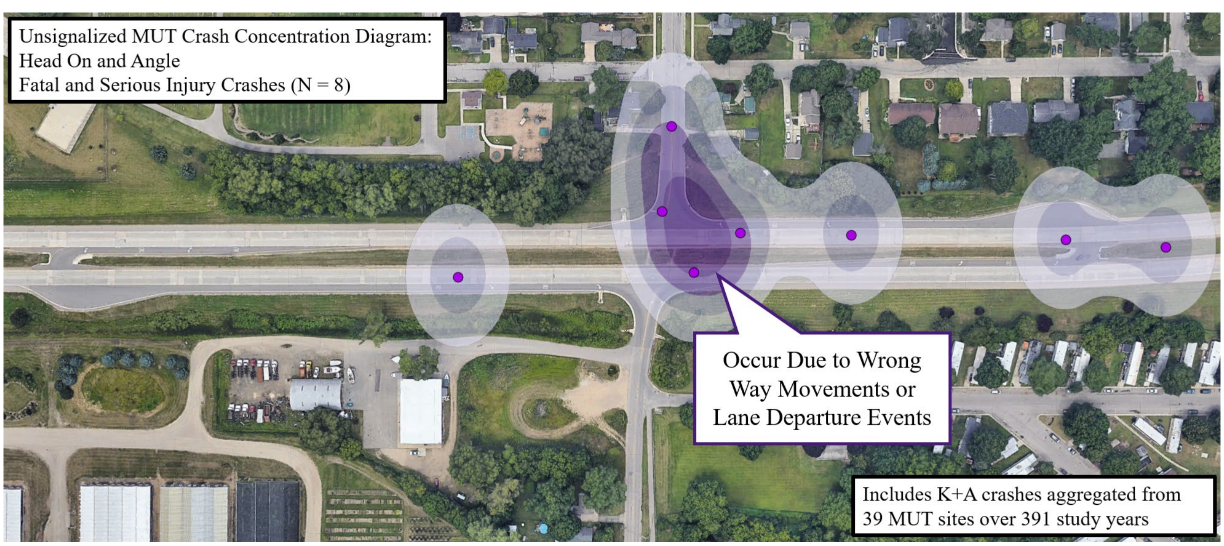


Figure 38. Head On and Angle K+A Crash Concentration Diagram – Unsignalized MUTs

Severe head on and angle collisions were relatively rare at the MUT sites and occur due to either wrong way movements or lane departure events. Severe collisions involving drivers crossing the closed median from the minor approaches were also rare. Crash concentration diagrams for head on left-turn K+A crashes are shown in **Figure 39** for the conventional sites which allow direct left-turn movements.

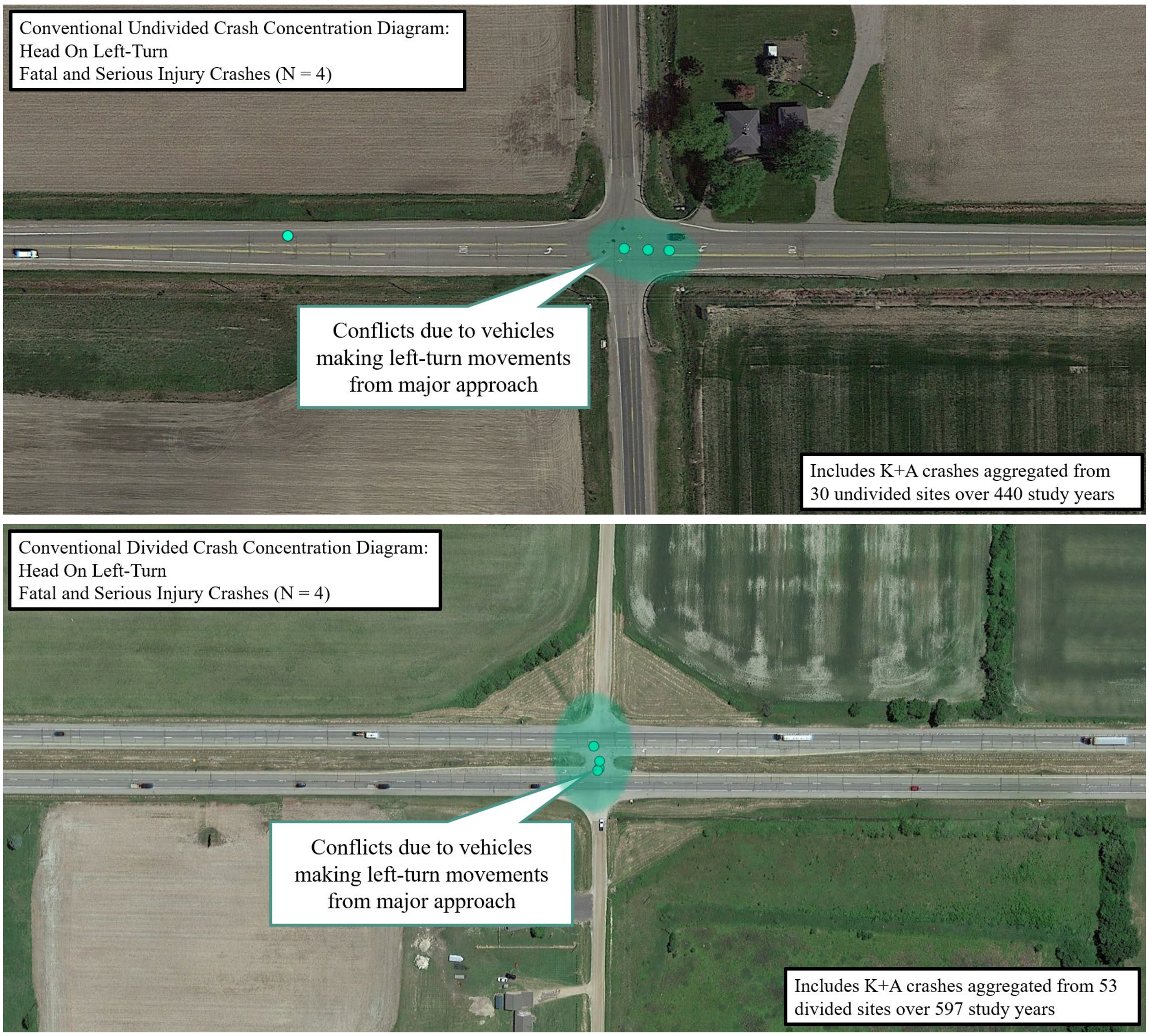


Figure 39. Head On Left-Turn K+A Crash Concentration Diagrams –Conventional Undivided and Divided Sites

Head on left-turn collisions at the conventional sites primarily occur within the intersection area due to conflicts related to vehicles attempting to complete left-turn movements from the major approaches. Intuitively, zero head on left-turn collisions occurred at the MUT sites during the study period. While head on left-turn collisions resulting in a fatality or serious injury were relatively rare at the conventional sites (a total of eight occurred during the entire study period), such collisions are likely to result in severe injuries to involved occupants when they do occur. Therefore, the elimination of head on left-turn collisions represents a notable advantage of the MUT design. Crash concentration diagrams for angle K+A crashes are shown in **Figure 40** for the conventional undivided and divided sites.

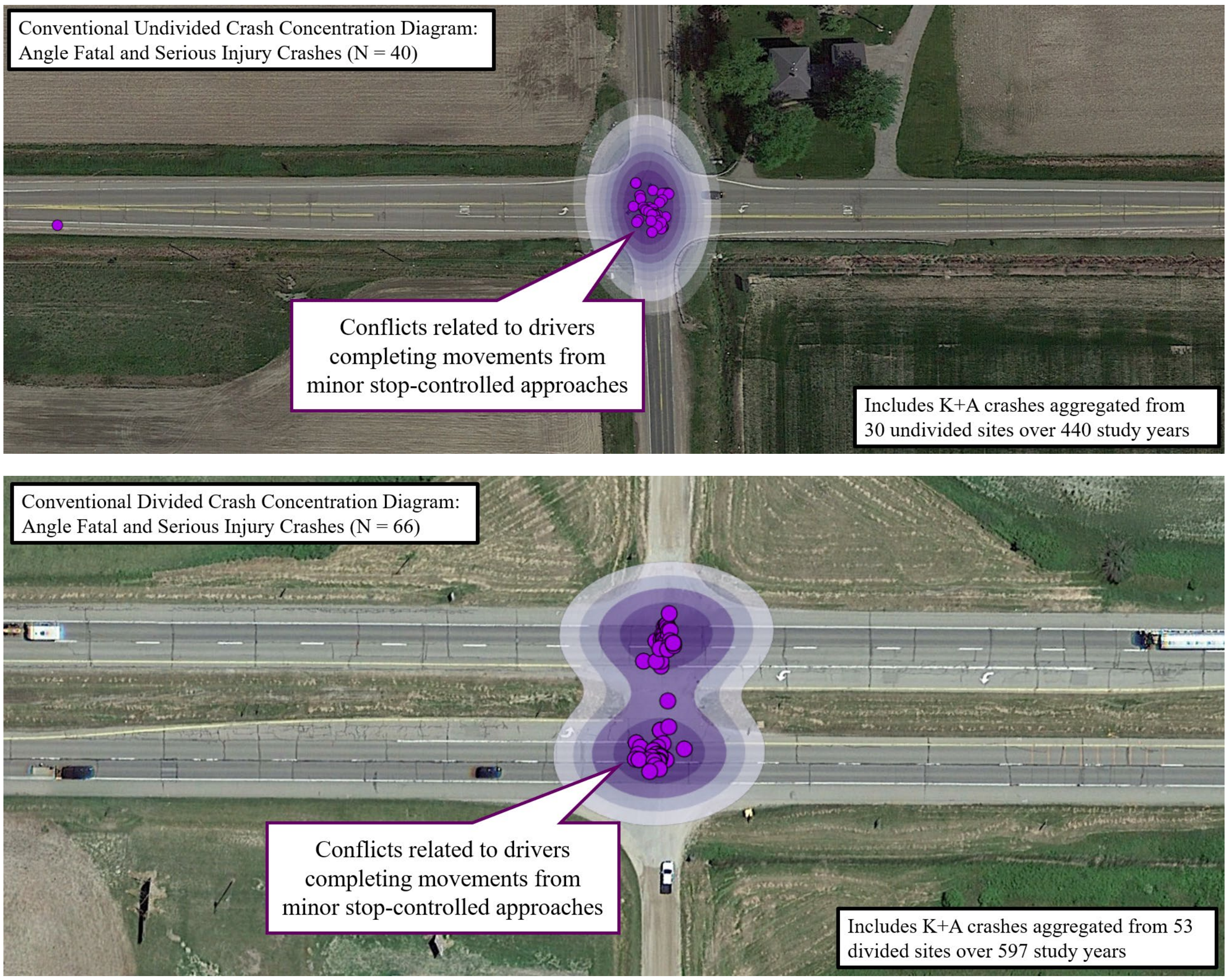


Figure 40. Angle K+A Crash Conc. Diagrams –Conventional Undivided and Divided Sites

Angle collisions represented the majority of K+A crashes occurring at the conventional undivided (53 percent) and divided (65 percent) sites. These patterns are driven by drivers from the minor approach either disregarding the stop sign or failing to select an appropriate gap. Given that angle collisions were relatively rare at the MUT sites (a total of four occurred during the entire study period), this highlights another major advantage of unsignalized MUT designs with a closed median. Crash concentration diagrams for rear end K+A crashes are shown in **Figure 41** for the conventional undivided sites and MUT sites.

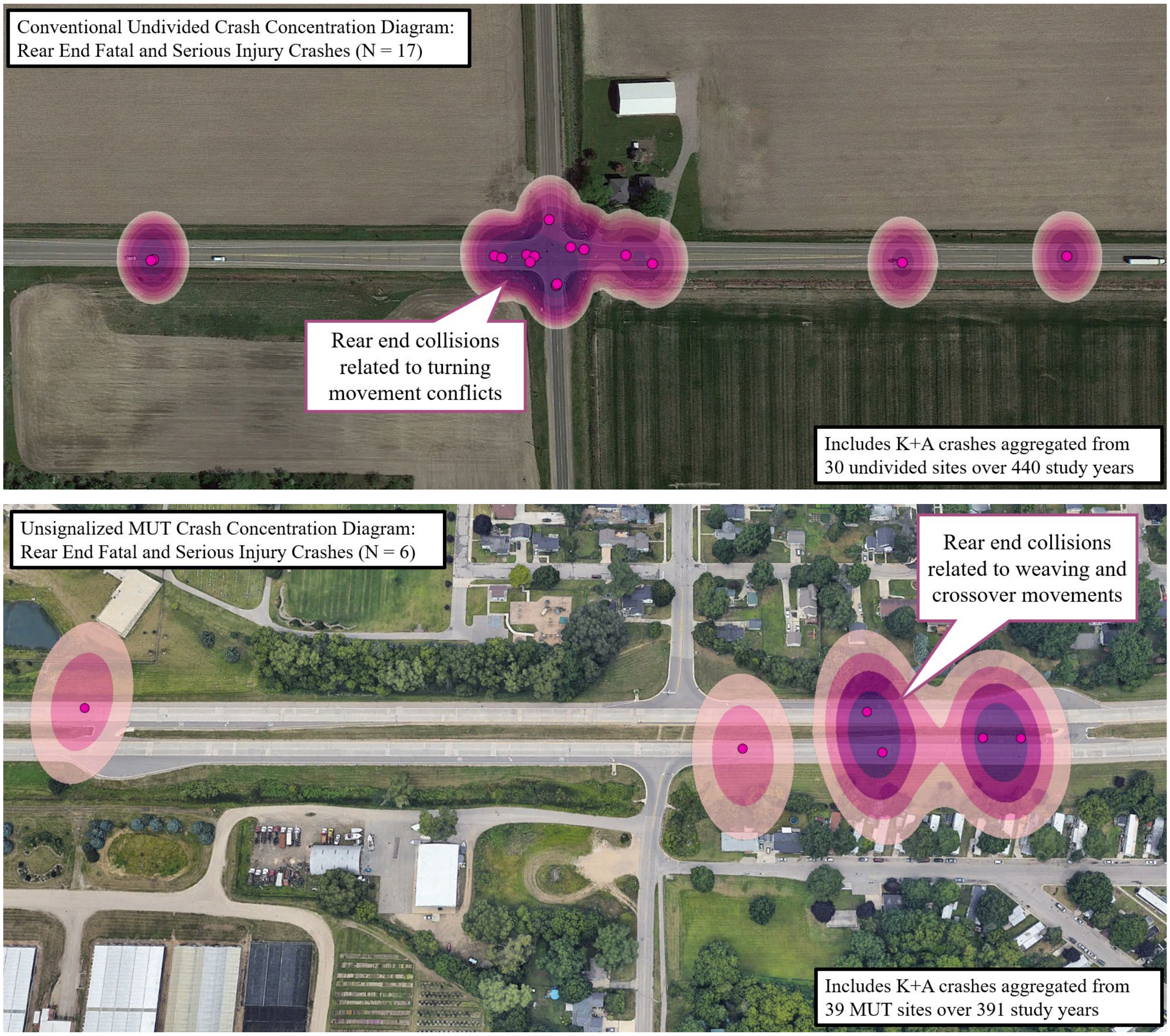


Figure 41. Rear End K+A Crash Conc. Diagrams – MUT and Conventional Undiv. Designs

The conventional undivided sites experienced a pattern of severe rear end collisions either within the intersection or along the major approaches near the intersection related to vehicles slowing or stopping to complete turning movements. Severe rear end collisions at the MUT sites occurred to conflicts related to vehicles completing weaving movements or using the directional crossovers. While this pattern represents a potential downside of the indirect left-turn movements employed as a part of MUT designs, the lower frequency of conflicts related to vehicles completing turning movements along the major approaches represents a major advantage of the MUT design. Severe rear end collisions were rare and random at the conventional divided sites (not shown, a total of eight occurred during the entire study period). A crash concentration diagram for sideswipe same K+A crashes at the MUT sites is shown in **Figure 42**.

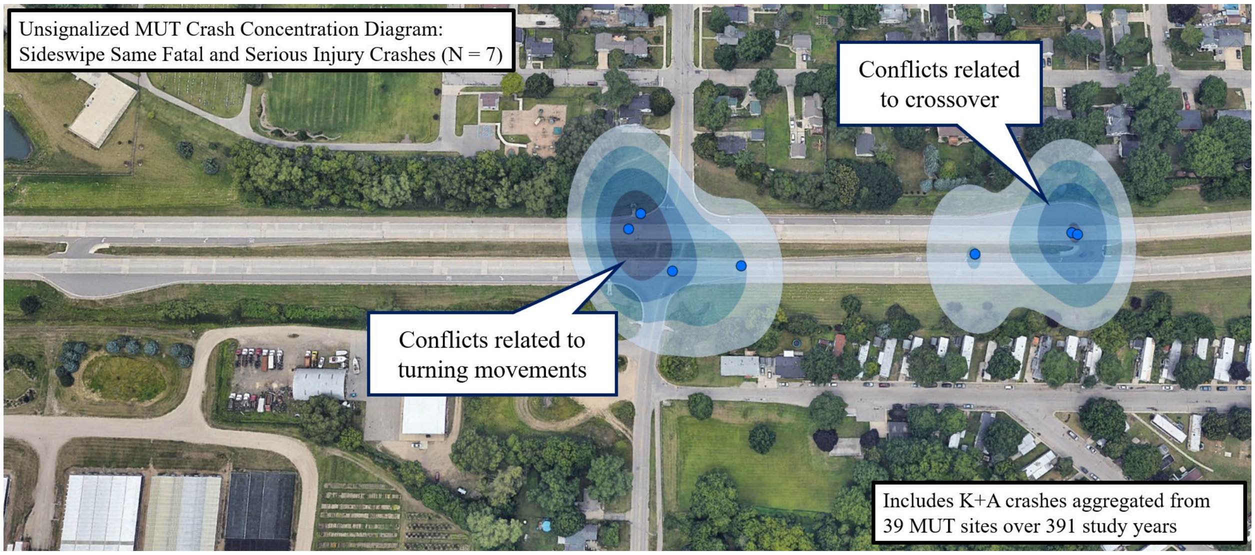


Figure 42. Sideswipe Same K+A Crash Concentration Diagrams – MUT and Conventional Undivided Sites

The MUT sites experienced a pattern of severe sideswipe same collisions which occur due to conflicts related to vehicles completing turning movements from the minor approaches as well as conflicts related to the directional crossovers. This pattern represents a potential disadvantage of the MUT design compared to the conventional designs where severe sideswipe same collisions were rare and random.

The review of severe crashes presented above as well as the analysis of traffic crash frequencies and aggregate crash rates presented in **Section 5.3** provide an overview of MUT safety performance and a comparison with similar conventional sites which allow direct left-turn movements. However, these findings should be interpreted with caution and modern analytical methods should be employed to determine if there are statistical differences in safety performance between the MUT and conventional designs.

5.4 Development of Safety Performance Functions

First, SPFs were developed to provide a general comparison of safety performance between the MUT sites and the conventional undivided and divided sites. Distinct SPFs were developed for fatal and injury (FI) and property damage only (PDO) crashes. **Table 11** provides a summary of the negative binomial model results specific to each of the three site types. It is important to note that for unsignalized intersections, none of the explanatory variables presented in **Table 6** were statistically significant and therefore the models presented in **Table 11** include only the natural logarithm of major and minor approach volume.

Table 11. Random Effects Negative Binomial Model Results – All Unsignalized Study Sites

All Conventional Undivided Sites (30 Sites, 440 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-9.125	2.429	-3.757	<0.001	-9.447	2.227	-4.255	<0.001
Major Approach Volume (*Ln of Vehicles per Day*)	0.775	0.271	2.860	0.004	0.867	0.250	3.462	<0.001
Minor Approach Volume (*Ln of Vehicles per Day*)	0.281	0.096	2.936	0.004	0.321	0.094	3.422	<0.001
Overdispersion Parameter	0.113	-	-	-	0.156	-	-	-

All Conventional Divided Sites (53 Sites, 597 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-9.131	1.842	-4.958	<0.001	-10.592	1.594	-6.647	<0.001
Major Approach Volume (*Ln of Vehicles per Day*)	0.706	0.175	4.041	<0.001	0.904	0.151	6.002	<0.001
Minor Approach Volume (*Ln of Vehicles per Day*)	0.344	0.074	4.675	<0.001	0.395	0.064	6.179	<0.001
Overdispersion Parameter	0.104	-	-	-	0.214	-	-	-

All MUT Sites (39 Sites, 391 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-10.274	3.188	-3.223	0.001	-11.320	2.595	-4.362	<0.001
Major Approach Volume (*Ln of Vehicles per Day*)	0.778	0.309	2.516	0.012	0.933	0.252	3.706	<0.001
Minor Approach Volume (*Ln of Vehicles per Day*)	0.320	0.094	3.393	0.001	0.486	0.080	6.091	<0.001
Overdispersion Parameter	0.091	-	-	-	0.283	-	-	-

The negative binomial model results presented in **Table 11** are also visualized in **Figures 43-46**. These figures show the annual FI and PDO crash frequencies observed at each site type versus major approach volume. Minor approach volumes are set to 1,000 vehicles per day. Distinct figures are shown to compare the MUT sites with the conventional undivided sites (**Figures 43 and 44**) and the MUT sites with the conventional divided sites (**Figures 45 and 46**).

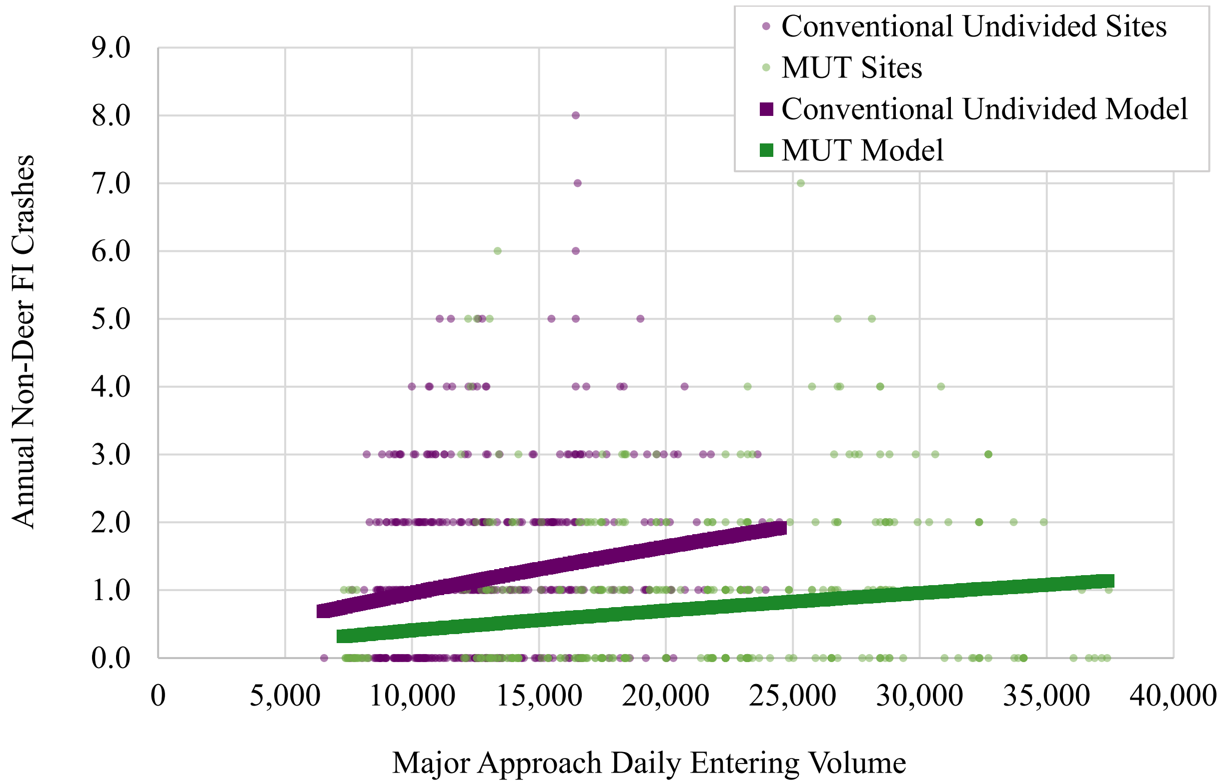


Figure 43. Annual FI Crashes vs. Major Appr. Vol. (Minor Appr. Vol. = 1,000 vpd): All Conventional Undiv. (30 Sites, 440 Years) and MUT Sites (39 Sites, 391 Years)

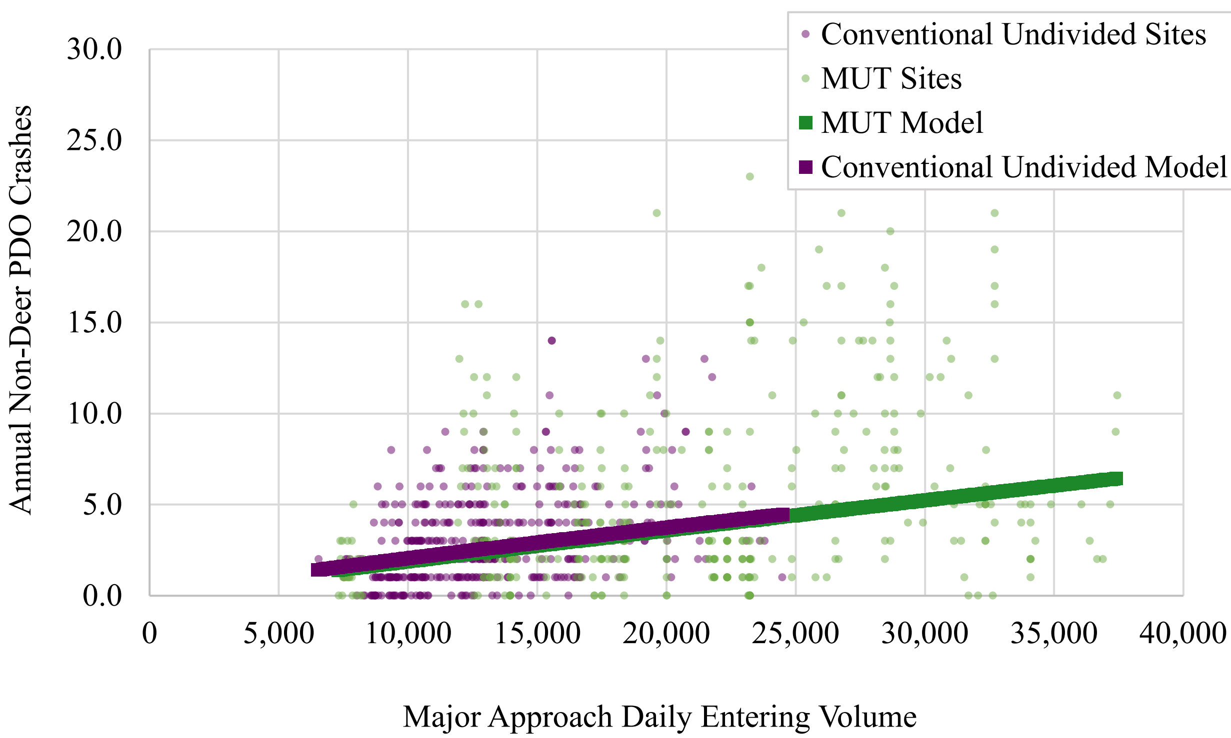


Figure 44. Annual PDO Crashes vs. Major Appr. Vol. (Minor Appr. Vol. = 1,000 vpd): All Conventional Undivided (30 Sites, 440 Years) and MUT Sites (39 Sites, 391 Years)

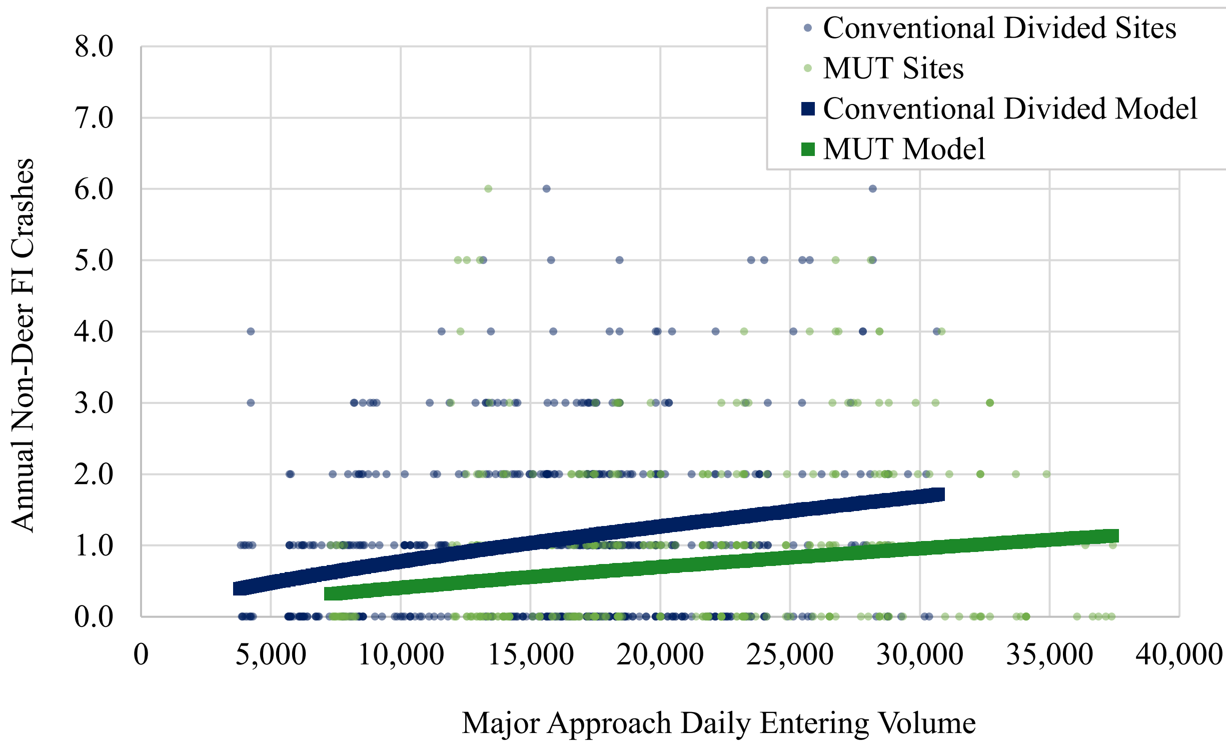


Figure 45. Annual FI Crashes vs. Major Appr. Vol. (Minor Appr. Vol. = 1,000 vpd): All Conventional Divided (53 Sites, 597 Years) and MUT Sites (39 Sites, 391 Years)

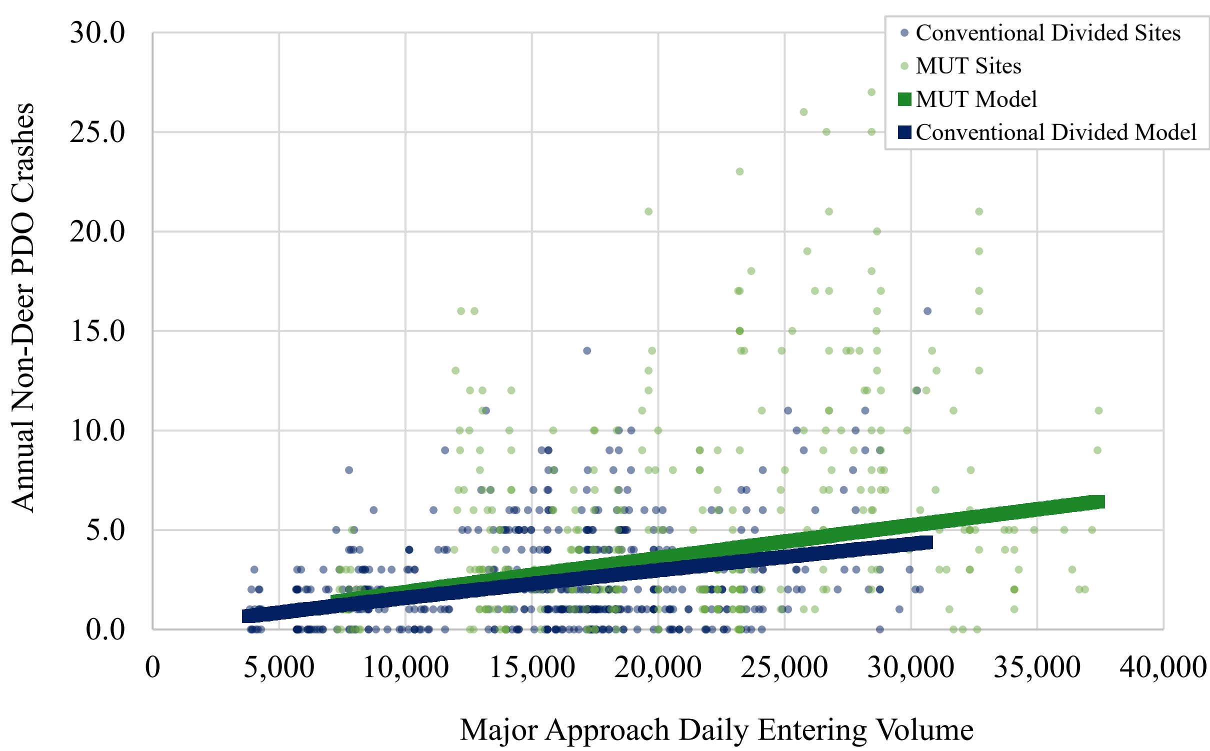


Figure 46. Annual PDO Crashes vs. Major Appr. Vol. (Minor Appr. Vol. = 1,000 vpd): All Conventional Divided (53 Sites, 597 Years) and MUT Sites (39 Sites, 391 Years)

Annual FI crash frequencies tended to be considerably smaller for the unsignalized MUT sites compared to the conventional undivided sites. PDO crash frequencies were similar for both site types, a finding which varies from the naïve results presented in **Section 5.2** where the aggregate PDO crash rate was 13 percent larger at the MUT sites. As shown in **Figure 44**, two MUT sites at the higher end of the volume range performed poorly with respect to PDO crashes, primarily driven by relatively large frequencies of rear end and sideswipe same collisions. This correlation in PDO crash counts at the same site over time was accommodated by the random effects framework, which provided improved insight compared to the naïve results presented in **Section 5.2.**

Annual FI crash frequencies also tended to be considerably smaller for the unsignalized MUT sites compared to the conventional divided sites. PDO crash frequencies tended to be greater at the conventional divided sites compared to the MUT sites. However, it is worth noting that this finding was diminished compared to the naïve results presented in **Section 5.2**, where the aggregate PDO crash rate was 63 percent larger at the MUT sites. As noted above, the correlation in PDO crash counts for the two MUT sites which performed poorly with respect to rear end and sideswipe same crashes was accommodated by the random effects framework.

Next, a series of additional negative binomial regression models were estimated to develop CMFs specific to the two conversion scenarios presented in **Section 1.4**. This included distinct models developed using the conventional undivided and divided reference site data (excluding the MUT sites with pre-conversion period data) in order to conduct the EB before-and-after analysis outlined in **Section 4.3**. Additionally, models were estimated to compare safety performance between the conventional undivided site condition versus the MUT site condition, as well as the conventional divided site condition versus the MUT site condition. These models were used as a part of the cross-sectional evaluation (also outlined in **Section 4.3**). Distinct SPFs were developed for fatal and injury (FI) and property damage only (PDO) crashes. The SPFs used to develop the CMFs specific to unsignalized MUT conversions are summarized in **Table 12**. The development of CMFs for unsignalized MUT conversions is summarized in **Section 5.5**.

Table 12. Random Effects Negative Binomial Model Results – Reference Sites and Cross-Sectional Models for Unsignalized Intersection CMF Development

Reference Sites for EB Method CMF Estimation								
Conventional Undivided Reference Sites (27 Sites, 432 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-9.132	2.555	-3.575	<0.001	-9.720	2.306	-4.214	<0.001
Major Approach Volume *(Ln of Vehicles per Day)*	0.767	0.280	2.745	0.006	0.890	0.253	3.516	<0.001
Minor Approach Volume *(Ln of Vehicles per Day)*	0.293	0.098	2.991	0.003	0.326	0.094	3.454	0.001
Overdispersion parameter	0.119	-	-	-	0.149	-	-	-
Conventional Divided Reference Sites (29 Sites, 461 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-5.889	1.669	-3.535	<0.001	-8.372	1.738	-4.818	<0.001
Major Approach Volume *(Ln of Vehicles per Day)*	0.412	0.163	2.534	0.012	0.679	0.169	4.010	<0.001
Minor Approach Volume *(Ln of Vehicles per Day)*	0.266	0.082	3.248	0.001	0.372	0.087	4.290	<0.001
Overdispersion parameter	0.007	-	-	-	0.186	-	-	-
Conventional and MUT Sites for Cross-Sectional CMF Estimation								
Conventional Undivided Sites and MUT Sites (66 Sites, 831 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-9.661	1.888	-5.117	<0.001	-10.228	1.656	-6.175	<0.001
Major Approach Volume *(Ln of Vehicles per Day)*	0.806	0.196	4.105	<0.001	0.853	0.170	5.010	<0.001
Minor Approach Volume *(Ln of Vehicles per Day)*	0.315	0.066	4.740	<0.001	0.444	0.060	7.384	<0.001
Binary Indicator Variable For MUT Site Condition	-0.826	0.149	-5.537	<0.001	0.014	0.131	0.109	0.913
Overdispersion parameter	0.184	-	-	-	0.241	-	-	-
Conventional Divided Sites and MUT Sites (68 Sites, 988 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-9.491	1.597	-5.945	<0.001	-11.038	1.430	-7.719	<0.001
Major Approach Volume *(Ln of Vehicles per Day)*	0.736	0.154	4.784	<0.001	0.916	0.138	6.632	<0.001
Minor Approach Volume *(Ln of Vehicles per Day)*	0.358	0.062	5.730	<0.001	0.441	0.057	7.730	<0.001
Binary Indicator Variable For MUT Site Condition	-0.730	0.109	-6.720	<0.001	0.163	0.081	2.004	0.045
Overdispersion parameter	0.177	-	-	-	0.259	-	-	-

5.5 Development of Crash Modification Factors

Each of the potential CMFs that were considered as a part of this study are presented in **Table 13.** This includes the CMFs developed via both the EB before-and-after and cross-sectional approaches outlined in **Section 4.3**. Distinct CMFs were developed for FI and PDO crashes. Unless denoted within the table, each CMF presented in **Table 13** was statistically significant at a 95 percent level of confidence.

Table 13. EB Method and Cross-Sectional CMFs for Unsignalized MUT Conversions

Unsignalized Conversion Type	Fatal and Injury Crashes				Property Damage Only			
	EB Method		Cross-Sectional		EB Method		Cross-Sectional	
	CMF	Std. Error	CMF	Std. Error	CMF	Std. Error	CMF	Std. Error
Undivided (Two-Lane Two-Way) to MUT	0.385	0.078	0.438	0.035	0.986*	0.096*	1.014*	0.175*
Divided (Four-Lane Boulevard) to MUT	0.686	0.059	0.482	0.030	1.325	0.059	1.177	0.156

**Not statistically significant at a 95 percent level of confidence*

5.5.1 CMFs for Converting Conventional Undivided Intersection to MUT Design

The CMFs specific to conventional undivided conversions developed via the EB and cross-sectional methods presented in **Table 13** were in general agreement. This included statistically significant reductions in FI crash frequency with no statistical difference in the frequency of PDO crashes. However, it is important to recognize that the EB method approach included only three sites which limits the practical significance of CMFs developed using such a limited sample. These findings do provide additional context and support for the CMFs developed using the cross-sectional approach.

Ultimately, the CMF for FI crashes (0.438) developed using the cross-sectional approach is recommended when considering future MUT conversions given that the CMF was statistically significant and is in general agreement with the EB method CMF developed using a limited sample of three sites. Given that both the EB method and cross-sectional PDO crash CMFs were not statistically significant, the data collected in Michigan evaluated as a part of this study do not support a CMF for PDO crashes specific to undivided conversions.

5.5.2 CMFs for Converting Conventional Divided Intersection to MUT Design

The FI CMF specific to conventional divided conversions developed via the EB method EB method (0.686) was more modest than the FI CMF estimated using the cross-sectional approach (0.482). Despite that fact that both CMFs were significantly different from zero, the use of the EB method FI CMF (0.686) is recommended when considering future MUT conversions due the potential concerns specific to cross-sectional studies [*27*]. Consistent with the aggregated crash rates presented in **Section 5.2**, both the EB method (1.325) and cross-sectional (1.177) CMFs for PDO crashes suggest higher PDO crash frequencies. Again, despite that fact that both CMFs were significantly different from zero, the use of the EB method PDO CMF (1.325) is recommended when considering future MUT conversions due the potential concerns specific to cross-sectional studies [*27*].

It is important to note that the CMFs for converting divided conventional intersections that was estimated using the cross-sectional approach (and consequently a larger sample of MUT sites) demonstrated more pronounced differences in crash frequency than the CMFs developed using the EB method (which used a more limited sample of 24 MUT sites possessing both pre- and post-conversion data available for analysis). This result was in part due to the fact select MUT sites that performed poorly received a larger emphasis in the EB method approach than in the cross-sectional approach. While two-thirds of the 24 conventional divided sites with both pre- and post-conversion data experienced a decrease in total crash frequency, two sites experienced a greater than 150.0 percent increase conversion (**Figure 47**).

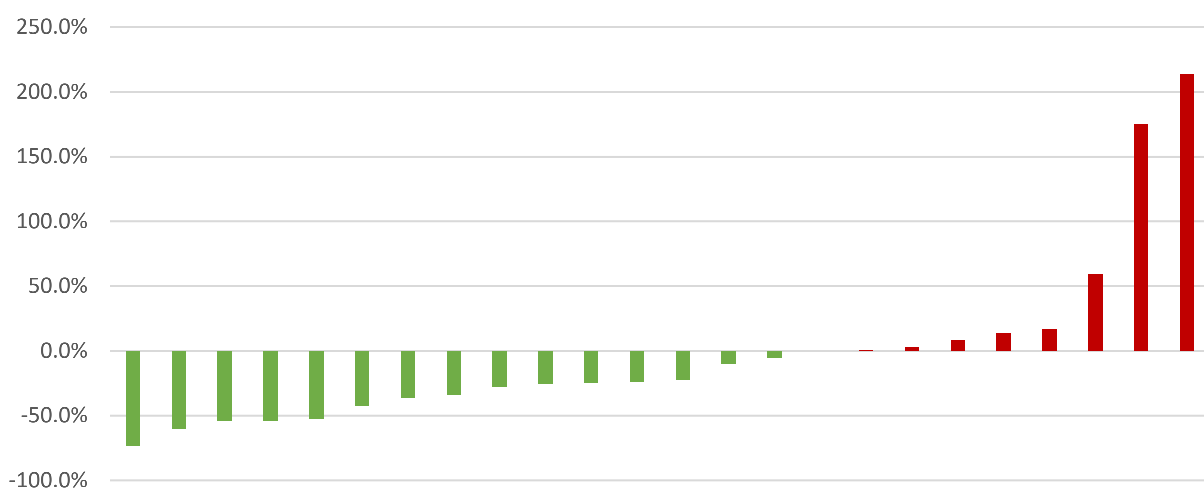


Figure 47. Percent Change in Total Crash Frequency after MUT Conversion: Conventional Divided to MUT Conversions Only (N = 24 Sites)

A more detailed examination of these two sites suggested that select minor approaches performed poorly with respect to rear end and sideswipe same crashes related to vehicles turning right to merge into traffic along the major approach. It is possible that a larger evaluation that includes data from multi-state sample of such conversions would converge between the CMFs developed using the EB-method and cross-sectional approaches for CMF (**Table 14)**. Such a study could also investigate if there are specific site characteristics associated with poorly performing minor approaches which could be mitigated by the inclusion of certain design elements.

5.5.3 Recommended CMFs for Unsignalized MUT Conversions

Ultimately, the CMFs presented in **Table 14** are recommended when considering future unsignalized MUT conversions.

Table 14. Recommended CMFs for Unsignalized Median U-Turn Conversions

Unsignalized Conversion Type	Fatal and Injury Crashes			Property Damage Only Crashes		
	CMF	Standard Error	Method	CMF	Standard Error	Method
Undivided (Two-Lane Two-Way) to MUT Design	0.438	0.035	Cross-Sectional	No Statistical Difference		
Divided (Four-Lane Boulevard) to MUT Design	0.686	0.059	EB Method	1.325	0.059	EB Method

The use of unsignalized MUT designs with a closed median opening provides superior FI safety performance compared to both conventional undivided and divided designs. In particular, the removal of the crossing conflict points (shown in **Figure 9**) at MUT designs essentially eliminates the pattern of severe head on left-turn and angle collisions occurring within conventional unsignalized intersections (shown in **Figures 39 and 40**). It is important to recognize that this evaluation does provide evidence that MUT conversions implemented along highways that already include a divided boulevard design are associated with a statistically significant increase in PDO crash frequency. Despite this concern, MUT conversions remain an effective alternative intersection design which can address potentially severe crash types in support of the USDOT's Safe System approach [*2*]. Roadway agencies should consider such conversions where operational analyses, local shareholder input, and other factors identify the implementation of an unsignalized MUT as a feasible design alternative.

6.0 SIGNALIZED MEDIAN U-TURN INTERSECTIONS

The 167 signalized intersections identified in **Section 3.1** (including 82 MUT sites and 85 reference sites) were evaluated consistent with the analytical methods outlined in **Section 4.0**. First, descriptive statistics are presented (**Section 6.1**) which summarize the traffic volume data, traffic crash data, and other intersection characteristics specific to both the MUT and conventional signalized intersections. Next, aggregate traffic crash frequencies and rates are provided in addition to distributions of crashes by type and severity (**Section 6.2**). A detailed analysis of crashes which resulted in fatal (K) and severe (A) injuries to either vehicle occupants or non-motorized road users is included to identify severe collision patterns (**Section 6.3**). This included a specific focus on collisions involving non-motorized road users. The development of the SPFs used in the evaluation are summarized (**Section 6.4**) and ultimately CMFs are presented (**Section 6.5**) for the two conversion scenarios outlined in **Section 1.5**.

6.1 Descriptive Statistics

The traffic volume data (or the number of entering vehicles per day along the major and minor approaches, traffic crash data (disaggregated by worst injury severity), and intersection data specific to the signalized MUT sites as well as the undivided and divided conventional sites are summarized in **Table 15**.

Table 15. Summary of Traffic Volume, Traffic Crash, and Intersection Characteristics

	Conventional Undivided Sites (N=73)			Conventional Divided Sites (N=16)			All Median U-Turn Sites (N=82)		
Characteristic	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Major App. Vehicles per Day	15,230	30,546	52,746	5,673	14,033	24,347	10,405	43,416	87,798
Minor App. Vehicles per Day	2,853	15,934	38,075	2,828	6,174	20,626	2,280	13,125	36,806
Annual K+A Crashes*	0.00	0.53	5.00	0.00	0.27	3.00	0.00	0.54	5.00
Annual K+A+B+C Crashes	0.00	10.41	35.00	0.00	2.37	12.00	0.00	8.17	35.00
Annual PDO Crashes	4.00	37.83	125.00	0.00	6.49	25.00	0.00	28.07	99.00
Annual Total Crashes	7.00	48.23	154.00	0.00	8.86	36.00	0.00	36.24	127.00
Annual Non-Motorized Crashes	0.00	0.63	5.00	0.00	0.08	1.00	0.00	0.55	7.00
Major App. Posted Speed Limit	30.0	44.5	55.0	40.0	50.3	55.0	35.0	48.7	55.0
Minor App. Posted Speed Limit	25.0	41.6	55.0	30.0	44.4	55.0	25.0	40.6	55.0
Major App. Principal Arterial	0.00	0.88	1.00	0.00	0.75	1.00	0.00	0.98	1.00
Major App. Minor Arterial	0.00	0.12	1.00	0.00	0.25	1.00	0.00	0.02	1.00
Minor App. Minor Arterial	0.00	0.32	1.00	0.00	0.00	0.00	0.00	0.26	1.00
Minor App. Major Collector	0.00	0.63	1.00	0.00	0.75	1.00	0.00	0.59	1.00
Minor App. Minor Collector	0.00	0.05	1.00	0.00	0.25	1.00	0.00	0.16	1.00
Major Approach Lanes	2.00	4.11	6.00	4.00	4.00	4.00	4.00	6.00	8.00
Minor Approach Lanes	2.00	3.21	4.00	2.00	2.25	4.00	2.00	3.15	6.00
Left-Turn Lanes	2.00	4.05	8.00	2.00	3.31	4.00	na	na	na
All Right Turn Lanes	0.00	2.26	4.00	0.00	1.44	3.00	na	na	na
Major Appr. Right Turn Lanes	na	na	na	na	na	na	0.00	1.63	2.00
Minor Appr. Right Turn Lanes	na	na	na	na	na	na	0.00	1.38	2.00

Table 15 (cont'd)

Characteristic	Conventional Undivided Sites (N=73)			Conventional Divided Sites (N=16)			All Median U-Turn Sites (N=82)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Lighting Present	0.00	0.63	1.00	0.00	0.44	1.00	0.00	0.66	1.00
Skew	0.0	3.4	55.0	0.0	10.6	45.0	0.0	6.8	55.0
Driveways	1.0	15.2	39.0	0.0	5.1	13.0	0.0	8.7	23.0
Minor Intersections	0.0	1.7	6.0	0.0	0.6	2.0	0.0	1.7	9.0
Median Openings or Crossovers	na	na	na	0.0	1.3	4.0	2.0	3.7	6.0
Median Width	na	na	na	15.0	22.1	30.0	15.0	52.30	150.0
Distance to Main Crossovers	na	na	na	na	na	na	300.0	626.5	795.0
Crossover Storage Lane Length	na	na	na	na	na	na	220.0	527.2	1,400.0
Weave Area Length	na	na	na	na	na	na	0.0	147.7	395.0
Truck Loon Present at Main Crossovers	na	na	na	na	na	na	0.00	0.29	2.00
Driveway or Intersection Directly Aligned with Crossover	na	na	na	na	na	na	0.00	0.46	2.00
Number of Interior Crossovers	na	na	na	na	na	na	0.00	0.24	2.00
Number of Main Crossovers which are Signal Controlled	na	na	na	na	na	na	0.00	1.26	2.00
Average Number of Storage Lanes at Main Crossovers	na	na	na	na	na	na	1.00	1.09	2.00

**Note that fatal (K) and serious injury (A) crashes were manually reviewed as a part of a distinct process*

Major approach volumes at the MUT sites ranged from 10,405 to 87,798 vehicles per day with an average of approximately 43,416 vehicles per day. Signalized MUTs tended to serve larger major approach volumes than either the conventional undivided (mean of 30,546 vehicles per day) and conventional divided (mean of 14,033 vehicles per day) sites included in the study. While minor approach volumes were in general agreement across the signalized MUT and conventional undivided sites, the maximum minor approach volume at the conventional divided sites was limited to 20,626 vehicles per day. Despite the efforts to identify reference sites that possessed geometric and other design characteristics which were similar to the pre-conversion MUT sites, there is lack of available conventional sites with volumes to match the upper end of the range of approach volumes served by signalized MUTs. This is due the widespread adoption of the MUT design along arterial highways practiced by both MDOT and local roadway agencies in Michigan. In order to help address this concern, a subset of MUTs were selected from the 82 available for analysis when comparing the MUT design to conventional intersections in order to ensure a fair comparison between site conditions.

Annual average crash K+A crash frequencies at the signalized MUT (0.54) and conventional undivided sites (0.53) were similar. Both annual average FI and PDO crash frequencies are larger at the conventional undivided sites than the MUT sites. While annual average K+A crash frequencies are considerably smaller at the conventional divided sites, this is in part due to the lower maximum traffic volumes served by the study sites.

Major approach posted speed limits ranged between 30 and 55 miles per hour. Posted speed limits along the minor approaches ranged from located streets posted at 25 miles per hour up to 55 miles per hour high speed arterials. The major approaches of study sites are predominately comprised of principal arterial routes for all three site conditions. The minor approaches include a mix of minor arterials, collectors, and local roadways.

The number of major approach lanes ranged between two and six at conventional undivided intersections, with the number of minor approach lanes ranging between two and four. The conventional divided sites included only sites with four major approach lanes and the number of minor approach lanes ranged between two and four. The number of major approach lanes at signalized MUTs ranged between four and eight, with the number of minor approach lanes ranging between two and six. While there were various configurations of exclusive left-turn lanes present at the conventional sites, the undivided sites tended to incorporate more exclusive left-turn lanes (mean of 4.05) than the divided sites (3.31). Conventional undivided sites also tended to incorporate more exclusive right-turn lanes (mean of 2.26) than the conventional (1.44) sites. A more detailed count of exclusive right-turn lanes was conducted at the signalized MUT intersections where distinct counts of major and minor approach right-turn lanes were collected. Signalized MUT major approaches tended to have a higher average number of exclusive right-turn lanes (1.63) than minor approaches (1.38).

Lighting was present more often at the MUT (66 percent) and conventional undivided (63 percent) sites than the conventional divided (44 percent) sites. Skew angles tended to be higher at the conventional divided sites (mean of 10.60 degrees) than the conventional undivided (3.40 degrees) sites than the undivided sites (6.80 degrees). Driveway counts within the intersection influence area were highest at the conventional undivided sites (mean of 15.2) than the conventional divided (5.1) and MUT sites (8.7). MUT and conventional undivided site influence areas included a similar number of minor intersections (mean of 1.7). Conventional divided sites tended to include fewer minor intersections within the influence area (0.6). These differences were also considered as part of selecting the subset MUTs to compare with conventional designs.

Median openings at the conventional divided sites ranged from zero to four with an average of 1.3. Intuitively, the average number of directional crossovers was larger at the MUT sites (3.7) given that each site includes a minimum of two directional crossovers. The total number of directional crossovers included within the signalized MUT influence areas ranged from two (or only the required main directional crossovers on each side) to six (a full system of directional crossovers which includes the two required main crossovers, two interior crossovers adjacent to the main intersection, and two crossovers located outside of the main crossovers). The number of interior crossovers ranged between zero and two with a mean of 0.24.

The distance to main crossover ranged from 300 to 795 feet with an average of 626.5 feet (in general agreement with Michigan's design guidance of 600 to 700 feet [*31*]). Main crossover storage lane lengths ranged between 220 feet and 1,400 feet (including select cases where the storage lane began upstream of the main intersection). Weave area lengths ranged from zero feet (where the storage lane begins upstream of the main intersection) up to 395 feet. Truck loons were present at approximately 15 percent of main crossovers and an average of 23 percent of the directional crossovers included a driveway or intersection in direct alignment. Approximately 63 percent of main crossovers at signalized MUTs in the study were signalized. The majority of main crossovers in the study include one storage lane with a maximum of two in select locations.

6.2 Traditional Safety Performance Metrics

The total frequency of crashes, annual average, and crash rate per one million entering vehicles for the 82 signalized MUT sites is shown in **Table 16** disaggregated by police-reported crash type and worst injury in the crash.

Table 16. Crash Frequency, Annual Average, and Rate – All Signalized MUTs (N=82)

Police-Reported Crash Type	Frequency	Annual Average	Crash Rate	Percent
Single Vehicle	2,702	2.12	0.103	5.9%
Head On	163	0.13	0.006	0.4%
Head On Left-Turn	313	0.25	0.012	0.7%
Angle	8,540	6.70	0.326	18.5%
Rear End	25,801	20.25	0.986	55.9%
Sideswipe Same	6,531	5.13	0.250	14.1%
Sideswipe Opposite	384	0.30	0.015	0.8%
Other	1,734	1.36	0.066	3.8%
Total	**46,168**	**36.24**	**1.764**	**100.0%**
Worst Injury in Crash	**Frequency**	**Annual Average**	**Crash Rate**	**Percent**
K (Fatal)	94	0.07	0.004	0.2%
A (Serious Injury)	599	0.47	0.023	1.3%
B (Minor Injury)	2,120	1.66	0.081	4.6%
C (Possible Injury)	7,597	5.96	0.290	16.5%
PDO (No Injury)	35,758	28.07	1.367	77.5%
Total	**46,168**	**36.24**	**1.764**	**100.0%**

The majority of traffic crashes occurring within the influence area of signalized MUTs were rear end collisions (56 percent), followed by angle (19 percent), and sideswipe same (14 percent) collisions. A total of 693 fatal and serious injury crashes occurred at the signalized MUTs during the study period, representing 1.5 percent of all crashes. PDO crashes represented approximately 78 percent of all traffic crashes.

Table 17 provides a comparison between the crash rates observed at the MUT and conventional site types. Given that the conventional sites available for study were limited to sites which serve lower approach volumes than the MUT sites (**Table 15**), it was necessary to select a subset of MUT sites to provide a fair comparison with conventional sites. Two distinct subgroups of MUT sites were identified to compare with all conventional undivided and divided sites to ensure the range of approach volumes was in general agreement. A total of 45 MUT sites were selected to compare with the 73 conventional undivided sites by removing MUT sites which serve greater than 85,000 total vehicles per day as well as sites which served major approach volumes of less than 15,000 vehicles per day and more than 53,000 vehicles per day. A total of 21 MUT sites were selected to compare with the 16 conventional divided sites by removing MUT sites which served more than 45,000 total entering vehicles per day, more than 35,000 entering vehicles along the major approach, as well as sites which incorporated 15 or more driveways.

Table 17. Crash Rates per 1M Entering Veh. – Signalized MUTs vs. Conventional Designs

Police-Reported Crash Type	Conventional Undivided vs. MUT Sites			Conventional Divided vs. MUT Sites		
	Undivided (N=73)	MUT (N=45)	Percent Difference	Divided (N=16)	MUT (N=21)	Percent Difference
Single Vehicle	0.095	0.116	21.8%	0.132	0.140	5.9%
Head On	0.029	0.006	-79.7%	0.009	0.004	-51.7%
Head On Left-Turn	0.219	0.014	-93.4%	0.096	0.008	-92.1%
Angle	0.680	0.354	-47.9%	0.323	0.290	-10.1%
Rear End	1.300	0.950	-26.9%	0.491	0.791	61.1%
Sideswipe Same	0.332	0.206	-37.9%	0.086	0.147	70.2%
Sideswipe Opposite	0.055	0.015	-73.4%	0.017	0.009	-47.2%
Other	0.102	0.072	-30.0%	0.046	0.056	22.0%
Total	**2.813**	**1.732**	**-38.4%**	**1.201**	**1.445**	**20.3%**
Worst Injury in Crash	**Conventional Undivided vs. MUT Sites**			**Conventional Divided vs. MUT Sites**		
	Undivided (N=73)	**MUT (N=45)**	**Percent Difference**	**Divided (N=16)**	**MUT (N=21)**	**Percent Difference**
Fatal	0.003	0.004	41.7%	0.004	0.002	-61.5%
Serious Injury	0.028	0.028	1.1%	0.032	0.028	-13.4%
Minor Injury	0.130	0.082	-36.6%	0.078	0.068	-13.7%
Possible Injury	0.446	0.276	-38.2%	0.206	0.224	8.8%
PDO (No Injury)	2.206	1.342	-39.2%	0.880	1.124	27.7%
Total	**2.813**	**1.732**	**-38.4%**	**1.201**	**1.445**	**20.3%**

Table 17 presents some considerable differences in aggregate average traffic crash rates at the MUT sites compared to both the conventional undivided and divided sites. The rate of all crash types aside from single vehicle collisions were lower at the signalized MUT sites compared to the conventional undivided sites. While the rate of fatal crashes was higher (42 percent) at the MUT sites than the conventional undivided sites, the rate of FI (K+A+B+C) crashes was considerably lower at the MUT sites (36 percent). The in-depth evaluation severe K+A collisions presented in **Section 6.3** provides additional context related to the higher rate of fatal collisions. PDO and total crash rates were both lower at the MUT sites (39 and 38 percent, respectively).

The total rate of crashes was higher at the signalized MUT (1.445) sites than the conventional divided sites (1.201). This larger total crash rate was primarily driven by larger rates property damage only rear end and sideswipe same collisions. Notably, the rate of fatal (61 percent), serious injury (13 percent), and minor injury (14 percent) collisions was lower at the MUT sites than the conventional divided sites. These differences were primarily driven by lower rates of head on (52 percent), head on left-turn (92 percent), and sideswipe same collisions (47 percent). Due to the rate of possible injury crashes being larger at the MUT sites, fatal and all injury (K+A+B+C) crash rates were nearly equal between the two site types. The in-depth evaluation severe K+A collisions presented in **Section 6.3** provides additional context related to the low rates of K+A crashes occurring at the signalized MUT sites. As previously noted, these aggregate crash rates should be interpreted with caution and the application of modern analytical approaches are required (**Sections 6.4 and 6.5**) to determine if there is a statistical difference in the FI or PDO crash frequencies associated with the MUT design.

Traffic crash rates for seven sites with both pre-and post-conversion data are included in **Table 18** to supplement the cross-sectional comparison presented in **Table 17**. It is important to note that **Table 18** includes select sites which were not included in the larger study (and are not included in the data provided in **Tables 5 and 15)**. Additionally, these sites include a mix of both divided and undivided major approach configurations. Traffic crash data were collected via a spatial analysis which was similar to the approach summarized in **Section 3.4**, however, the total influence area distance along the approaches with directional crossovers was allowed to vary for each site such that at least 150’ of influence area was included beyond the edge of the crossover. The total influence area distance along approaches without crossovers (and remained undivided) were set to 350 feet.

Table 18. Traffic Crash Rates for Sites with Pre-and Post-Conversion Data (N=7)

Intersection Data				K+A Crashes			K+A+B+C Crashes			PDO Crashes		
Location	Pre-Conversion Condition	Pre-Conversion Years	Post-Conversion Years	Pre-Conversion Rate	Post-Conversion Rate	Percent Change	Pre-Conversion Rate	Post-Conversion Rate	Percent Change	Pre-Conversion Rate	Post-Conversion Rate	Percent Change
Rochester and Wattles	Undivided	6	8	0.013	0.005	-57.5%	0.451	0.268	-40.5%	2.531	1.479	-41.6%
Crooks and South Boulevard	Undivided	2	12	0.000	0.019	na	0.272	0.272	0.1%	2.400	1.586	-33.9%
Crooks and Auburn	Undivided	2	12	0.000	0.005	na	0.760	0.364	-52.0%	3.078	2.213	-28.1%
M-24 and Silverbell	Divided	12	3	0.023	0.017	-25.3%	0.312	0.506	62.3%	2.337	2.886	23.5%
Highland and Grand River	Undivided	2	11	0.000	0.026	na	0.347	0.211	-39.2%	1.780	1.990	11.8%
Highland and Byron	Undivided	2	11	0.000	0.030	na	0.475	0.325	-31.6%	1.848	1.483	-19.8%
Pickard and Leaton	Undivided	11	4	0.051	0.035	-31.9%	0.289	0.384	33.2%	0.943	1.188	26.0%
All Sites with Pre- and Post-Conversion Data		**37**	**61**	**0.024**	**0.016**	**-31.7%**	**0.364**	**0.313**	**-13.9%**	**1.669**	**1.492**	**-10.6%**

The aggregate rate of fatal and serious injury crashes (32 percent), fatal and all injury crashes (14 percent) and total crashes (11 percent) were lower after the conversion to the signalized MUT design. While the divided conversion at M-24 and Silverbell has experienced lower rates of K+A crashes after conversion, there have been increases in both fatal and all injury and total crash rates. This is consistent with the findings presented in **Table 17** where the rate of K+A crashes was lower at the signalized MUT sites compared to the conventional divided sites, but possible injury and property damage only crash rates were larger. While the traffic crash rates presented in **Table 18** help to provide additional context specific to the safety performance of impacts of signalized MUT conversions, this limited sample should be interpreted with caution and the cross-sectional evaluation summarized in **Sections 6.4 and 6.5** was used to determine if there is a statistical difference in the FI or PDO crash frequencies associated with the MUT design.

6.3 Fatal and Serious Injury Crash Patterns

The additional manual review of K+A crash report forms (outlined in **Section 3.4**) allowed for a more in-depth evaluation these severe collisions in order to identify common circumstances. A summary of the annual average number of K+A crashes by crash type, location, and category is provided in **Table 19** for each site type. Subsequently, a series of crash concentration diagrams are presented for specific crash types that identify common locations for K+A crashes.

Table 19. Annual Average K+A Crashes by Type, Location, and Category – Signalized MUT vs. Conventional Designs

Crash Type	Median U-Turn		Undivided		Divided	
	Average	Percent	Average	Percent	Average	Percent
Single Vehicle	0.05	9.1%	0.02	4.7%	0.03	10.1%
Head On	0.01	2.2%	0.02	4.4%	0.00	1.4%
Head-On Left-Turn	0.00	0.7%	0.13	24.8%	0.09	31.9%
Angle	0.23	41.6%	0.15	28.2%	0.09	33.3%
Rear End	0.12	21.6%	0.07	13.2%	0.04	13.0%
Sideswipe Same	0.03	4.6%	0.01	1.7%	0.00	1.4%
Sideswipe Opposite	0.00	0.6%	0.01	1.4%	0.00	0.0%
Other	0.01	1.0%	0.01	1.5%	0.00	0.0%
Car-Pedestrian	0.08	13.9%	0.07	14.2%	0.01	4.3%
Car-Bike	0.03	4.8%	0.03	5.9%	0.01	4.3%
Total	**0.54**	**100.0%**	**0.53**	**100.0%**	**0.27**	**100.0%**
Crash Location	**Median U-Turn**		**Undivided**		**Divided**	
	Average	**Percent**	**Average**	**Percent**	**Average**	**Percent**
Major Approach	0.18	32.2%	0.28	53.0%	0.05	20.3%
Minor Approach	0.05	10.0%	0.05	9.6%	0.02	7.2%
Within Intersection	0.26	47.2%	0.20	37.3%	0.20	72.5%
Crossovers	0.06	10.7%	na	na	0.00	0.0%
Total	**0.54**	**100.0%**	**0.53**	**100.0%**	**0.27**	**100.0%**
Crash Category	**Median U-Turn**		**Undivided**		**Divided**	
	Average	**Percent**	**Average**	**Percent**	**Average**	**Percent**
Wrong Way	0.00	0.9%	na	na	0.00	0.0%
Lane Departure	0.05	8.5%	0.05	9.0%	0.03	11.6%
Disregard Traffic Control	0.23	41.8%	0.06	11.7%	0.11	40.6%
Failed to Yield	0.03	5.3%	0.23	43.2%	0.08	29.0%
Speed Too Fast	0.12	21.2%	0.07	12.8%	0.04	13.0%
Crossing not at Crosswalk	0.04	7.2%	0.06	11.0%	0.01	2.9%
Crossing during don't Walk	0.02	4.2%	0.02	4.2%	0.01	2.9%
Other	0.06	10.8%	0.04	8.1%	0.00	0.0%
Total	**0.54**	**100.0%**	**0.53**	**100.0%**	**0.27**	**100.0%**

The signalized MUT and conventional undivided sites experienced similar annual average frequencies of K+A collisions. The conventional divided sites experienced lower annual average frequencies of K+A collisions due to the fact these sites served lower approach volumes. **Table 19** demonstrates several key differences with respect to the patterns of severe collisions by crash type between the signalized MUT and conventional sites. Head on left-turn collisions represented approximately 25 percent of severe collisions at conventional undivided sites and approximately 32 percent at conventional divided sites. This pattern of severe crashes was essentially eliminated at the signalized MUT sites. While both the conventional undivided (28 percent) and divided sites (33 percent) experienced a regular pattern of angle collisions, the signalized MUT sites experienced both the highest annual average of severe angle collisions (0.23 per year) as well as largest share of angle collisions of all crashes (42 percent). Similar trends can also be observed for rear end and sideswipe same collisions.

While the total number of annual severe pedestrian and bicycle crashes is similar for both the signalized MUT and conventional undivided sites is similar (an average of 0.11 and 0.10 total non-motorized crashes annually, respectively), subsequent analyses will demonstrate that there are important differences in the circumstances that drive pedestrian and bicycle crashes between the site two site types. The number of severe pedestrian and bicycle collisions at the conventional divided sites was relatively limited due to the fact these sites are located in areas with lower non-motorized demand. A subsequent detailed review of severe crashes involving non-motorized road users presented in **Section 6.3.1** will focus on the differences between signalized MUT and conventional undivided intersections.

The location of all K+A crashes are shown in **Figure 48, 49, and 50** for each of the three intersection types. The precise location data obtained from the crash report form review was used to map each collision to an example intersection into order to visualize the relative crash location within the example intersection's influence area. The kernel density tool in ArcGIS was subsequently used to identify common patterns of severe crashes which occurred at each of the three site types over the entire study period (which are used in the subsequent discussion).

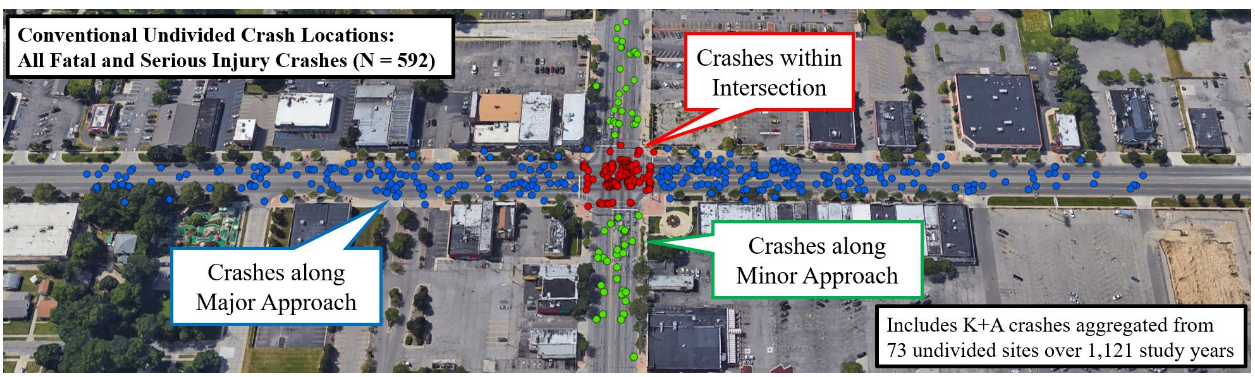


Figure 48. K+A Crash Locations for All 73 Conventional Undivided Sites

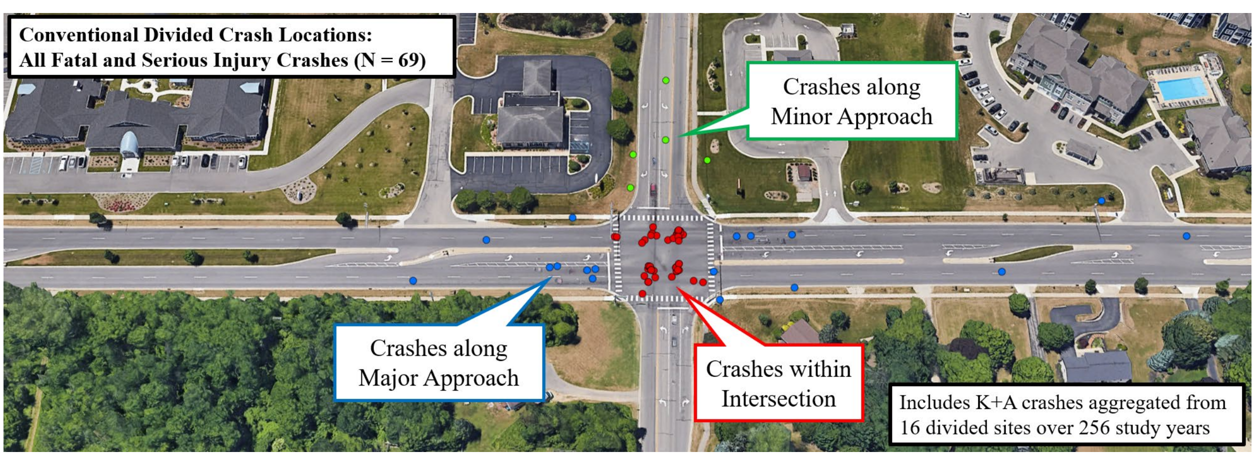


Figure 49. K+A Injury Crash Locations for All 16 Conventional Divided Sites

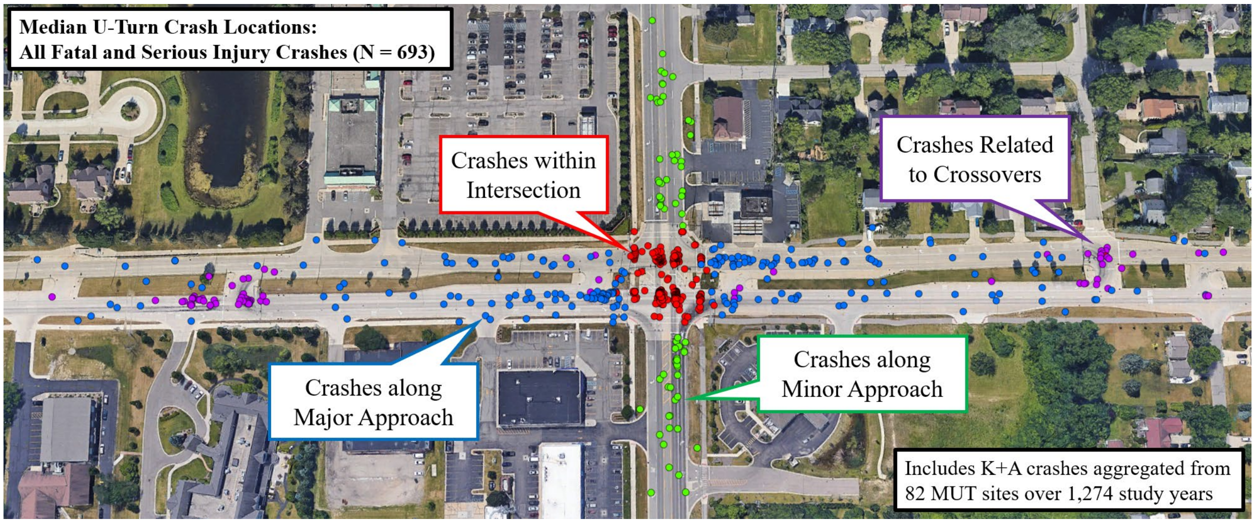


Figure 50. Fatal and Serious Injury Crash Locations for All 82 Signalized MUT Sites

The majority (53 percent) of severe collisions at the conventional undivided sites occur along the major approaches (**Figure 51**). The remaining 37 percent occur within the intersection and along the minor approaches (10 percent). The crash concentration diagram shown in **Figure 51** demonstrates the importance of including the areas in between the crossover and intersection area as part of the safety performance influence area as discussed in **Section 3.4**.

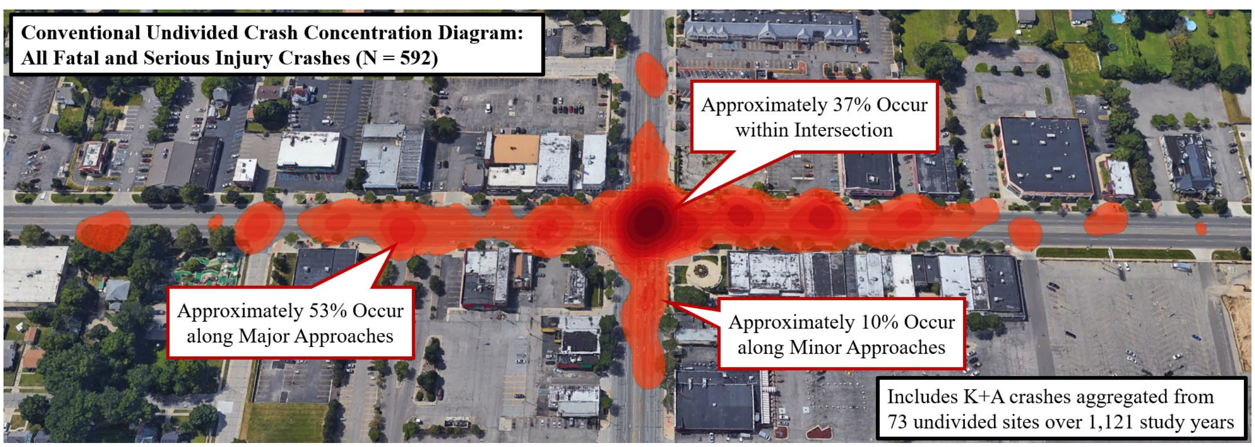


Figure 51. K+A Crash Concentration Diagram for All 82 Signalized MUT Sites

The majority (70 percent) of severe collisions at the conventional divided sites occur within the intersection (**Figure 52**). The remaining 23 percent occur within the intersection and along the minor approaches (7 percent). While the traffic volumes served by the major approaches of the 16 conventional divided sites were lower than the conventional undivided sites (**Table 16**), the shift away from collisions along the major approaches highlights importance of considering the pre-conversion condition during CMF development.

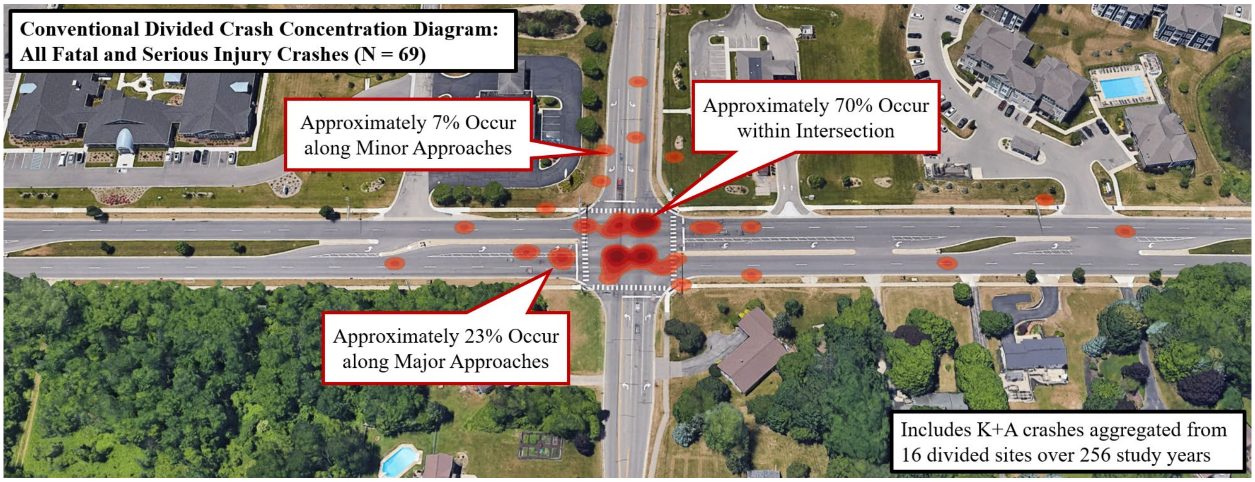


Figure 52. Fatal and Serious Injury Crash Locations for All 16 Divided Conventional Sites

Approximately 47 percent of severe collisions at the signalized MUT sites occur within the intersection (**Figure 53**). Approximately 32 percent of severe collisions occur along the major approaches and 10 percent occur along the minor approaches. The signalized MUT intersections also experienced a pattern of severe collisions at the directional crossovers (11 percent).

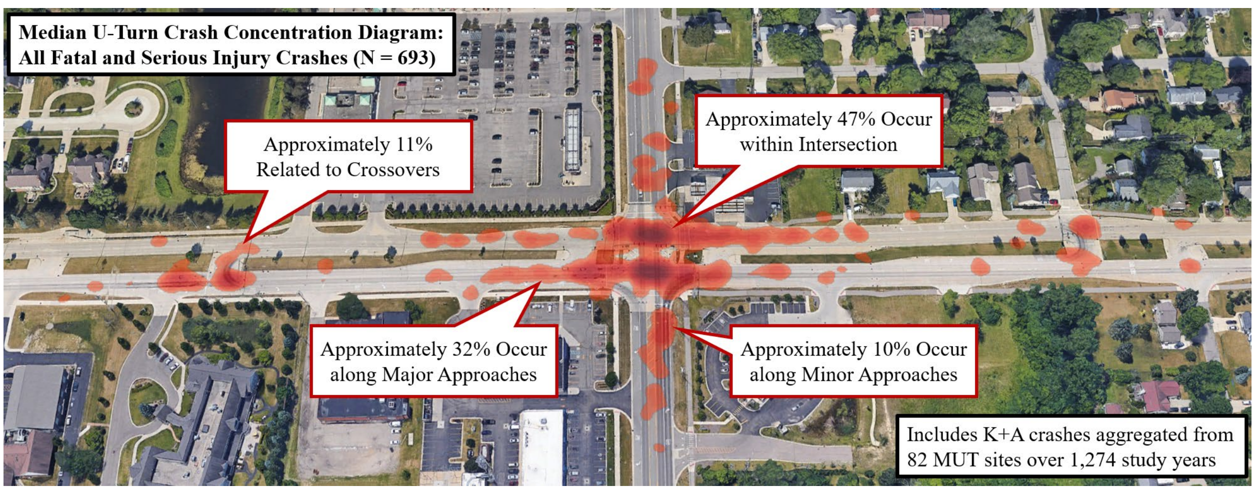


Figure 53. K+A Crash Concentration Diagrams for All 82 Signalized MUT Sites

The crash concentration diagram presented in **Figure 51** demonstrates the importance of including a larger influence area around the directional crossovers as discussed in **Section 3.4**. The crash concentration diagram shown in **Figure 54** demonstrates that severe single vehicle collisions occur throughout the influence area of both the conventional and MUT designs and are primarily related to lane departure events (the conventional sites are not shown to a limited number of single vehicle collisions occurring during the study period). Consistent with the crash rates presented in **Section 6.2,** the MUT sites experienced higher average frequencies of severe single vehicle collisions than the conventional undivided sites.

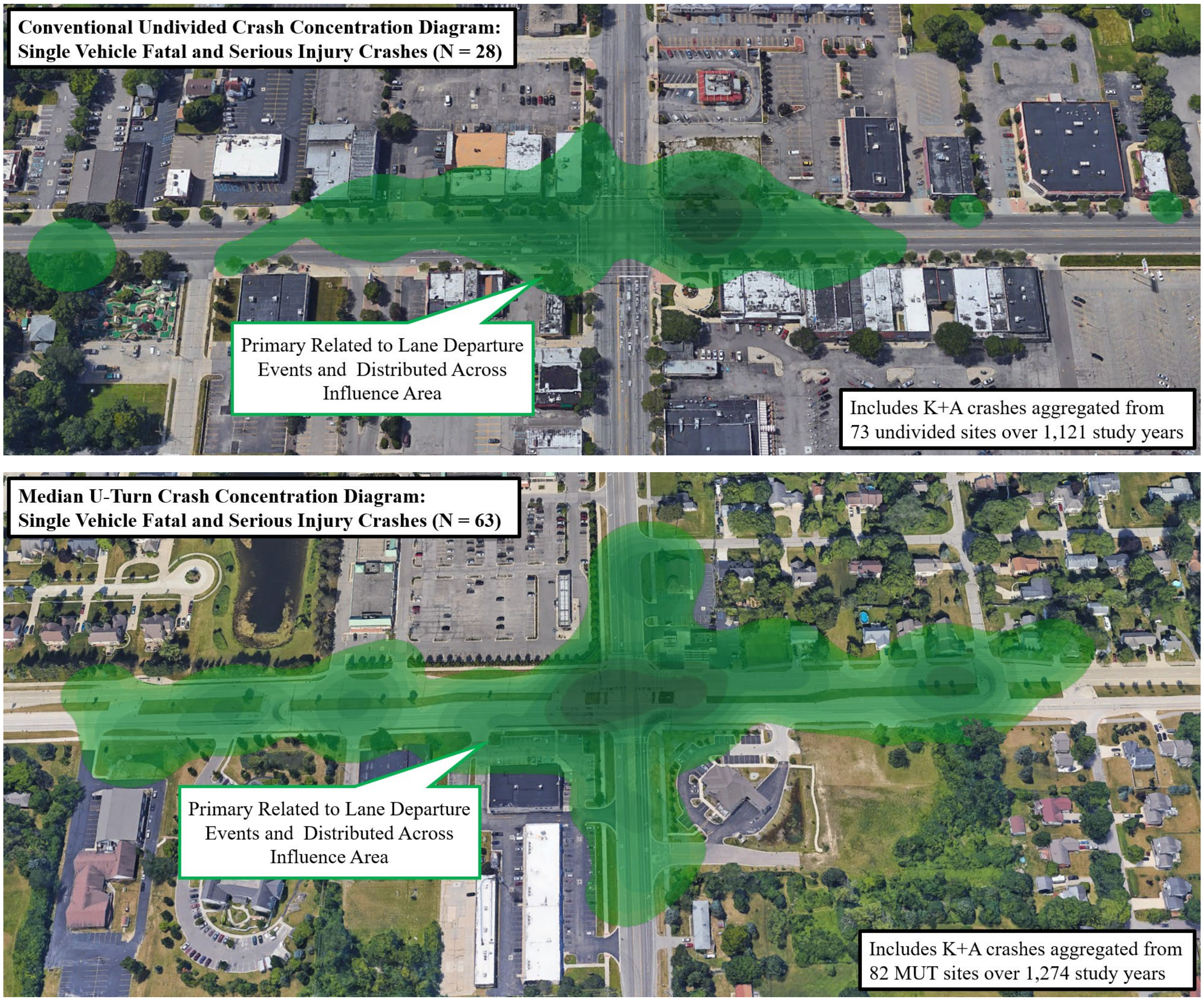


Figure 54. Single Veh. K+A Crash Conc. Diagrams – MUT vs. Conventional Undiv. Sites

Severe head on and sideswipe opposite crashes occurred across the conventional undivided influence area and are primarily related to lane departure events (**Figure 55**).

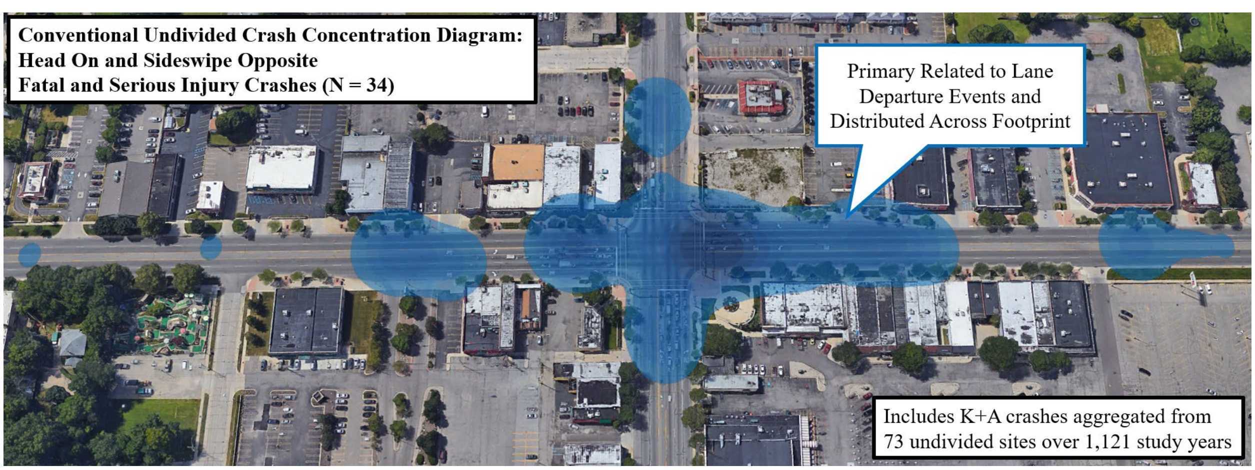


Figure 55. Head-On and Sideswipe Opposite K+A Crash Concentration Diagram for All 73

Conventional Undivided Sites

A limited number of severe head on, head on-left turn, and sideswipe opposite crashes occurred across signalized MUT influence areas (**Figure 56**), primarily related to either wrong way or lane departure events. It should also be noted that only one head on left-turn collision occurred at the 82 signalized MUTs during the study period, indicating that severe collisions due to illegal left-turn movements are exceedingly rare.

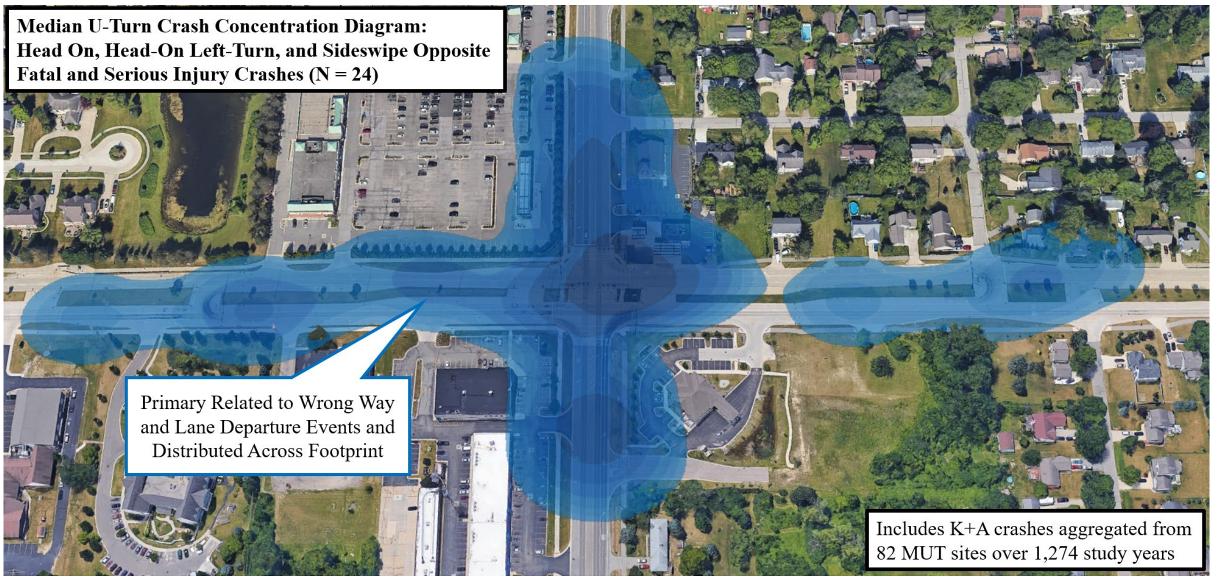


Figure 56. Head On, Head On Left-Turn and Sideswipe Opposite K+A Crash Concentration Diagram for All 82 MUT Sites

An annual average of 0.13 severe head on left-turn collisions occurred at the conventional undivided sites (**Figure 57**), primarily located within the intersection related to left-turn movements from the major approaches.

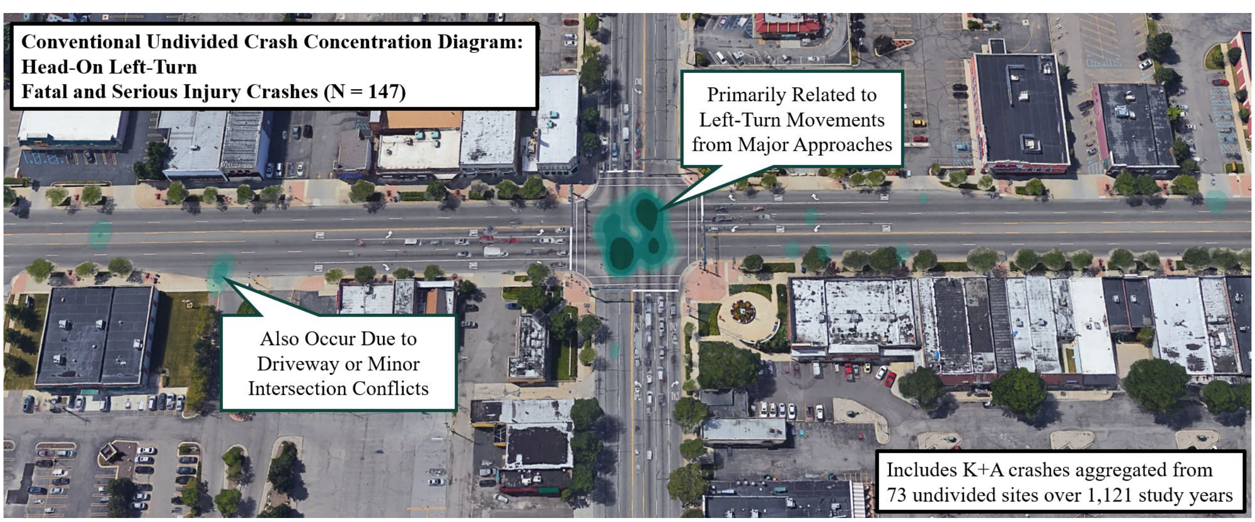


Figure 57. Head-On Left-Turn K+A Crash Concentration Diagram for All 73

Conventional Undivided Sites

An annual average of 0.09 severe head on left-turn collisions occurred at the conventional divided sites (**Figure 58**), primarily located within the intersection related to left-turn movements from the major approaches.

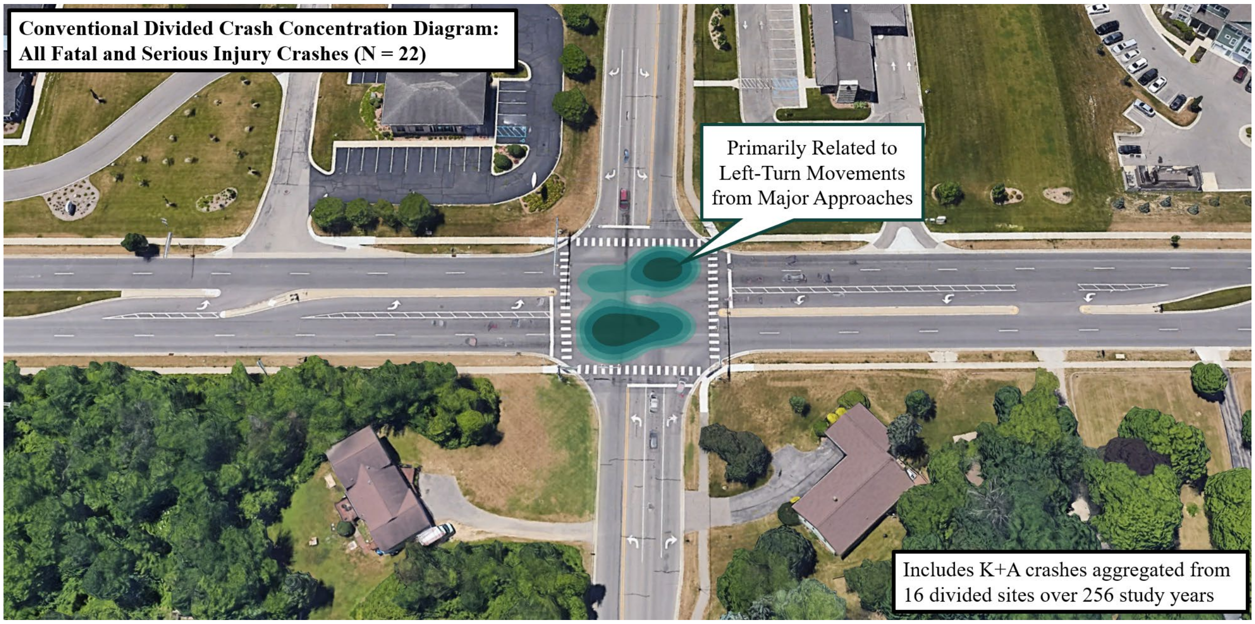


Figure 58. Head On Left-Turn K+A Crash Conc. Diagram for All 16 Con. Divided Sites

Given that head on left-turn crashes occurring with the intersection at the signalized MUT sites was exceedingly rare, this represents one of the major advantages of the indirect left-turn movement design compared to the conventional sites which allow direct left-turns.

An annual average of 0.15 severe angle collisions occurred at the conventional undivided sites (**Figure 59**), primarily related to drivers disregarding the traffic signal. These collisions also occurred due to conflicts from drivers exiting minor intersections or driveways.

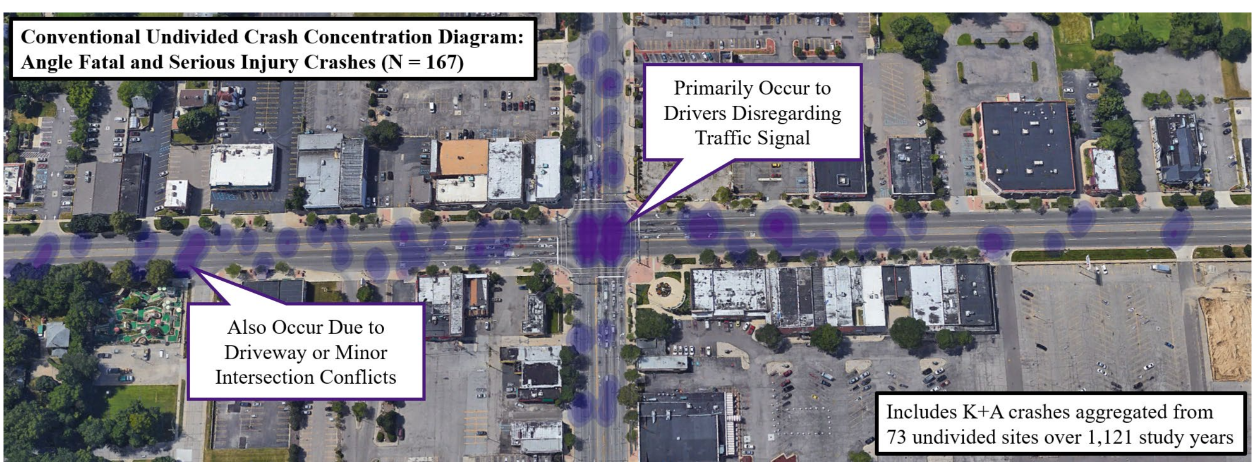


Figure 59. Angle K+A Crash Conc. Diagram for All 73 Conventional Undivided Sites

An annual average of 0.09 severe angle collisions occurred at the conventional divided sites (**Figure 60**), primarily related to drivers disregarding the traffic signal. The pattern of angle collisions relate driveways was not present at the conventional divided sites due to the lower access point densities within the influence areas as well as the access management benefits of the boulevard design. While the traffic volumes served by the major approaches of the 16 conventional divided sites were lower than the conventional undivided sites (**Table 16**), the shift away from pattern of access point-related severe collisions highlights the importance of considering the pre-conversion condition during CMF development.

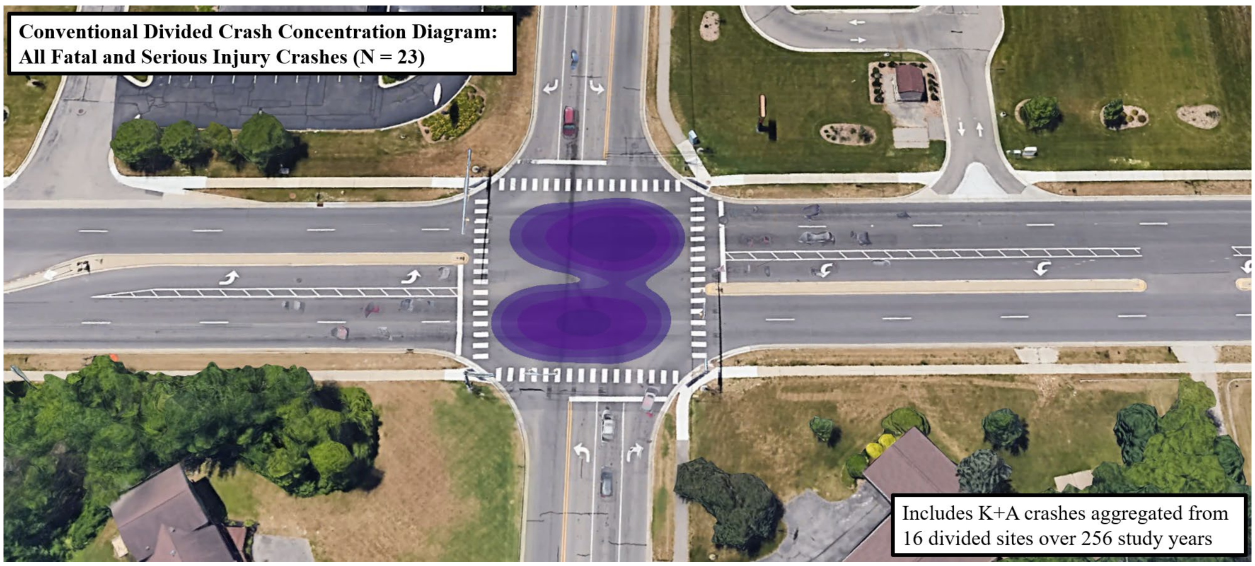


Figure 60. Angle K+A Crash Conc. Diagram for All 73 Conventional Undivided Sites

An annual average of 0.23 severe angle collisions occurred at the signalized MUT sites (**Figure 61**), primarily related to drivers disregarding the traffic signal.

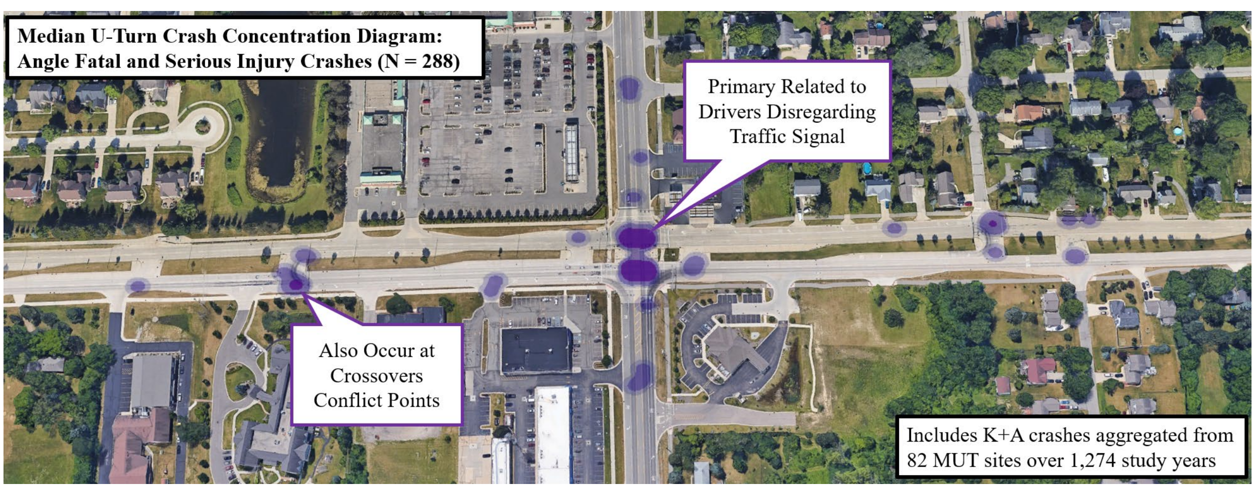


Figure 61. Angle K+A Crash Concentration Diagrams – MUT vs. Conventional Designs

Figure 61 also demonstrates the pattern of angle collisions involving conflicts at the directional crossovers present at the signalized MUT sites. While the overall rates of police-report angle type crashes of all severities were lower at the MUT sites than the conventional sites (**Section 6.2**), the effective design of signalized MUTs should seek potential opportunities to address these patterns of severe angle crashes. Design treatments intended reduce red-light-running behavior, including upgrades to traffic control devices (such as the use of reflective backplates on signal heads [*62*]) or signal timing strategies intended to improve compliance with the main intersection traffic signal should be a priority. Crossover design should focus on reducing conflicts related to drivers either disregarding traffic control (either a signal or stop sign) or failing to select an appropriate gap. This is particularly relevant for signalized MUTs that include signalized crossovers which control the flow of traffic, the location of queues, and the availability of gaps.

An annual average of 0.07 severe rear end collisions occurred at the conventional undivided sites and an annual average of 0.12 occurred at the MUT sites (**Figure 62**), primarily related to drivers being unable to stop before the queue upstream of the traffic signal.

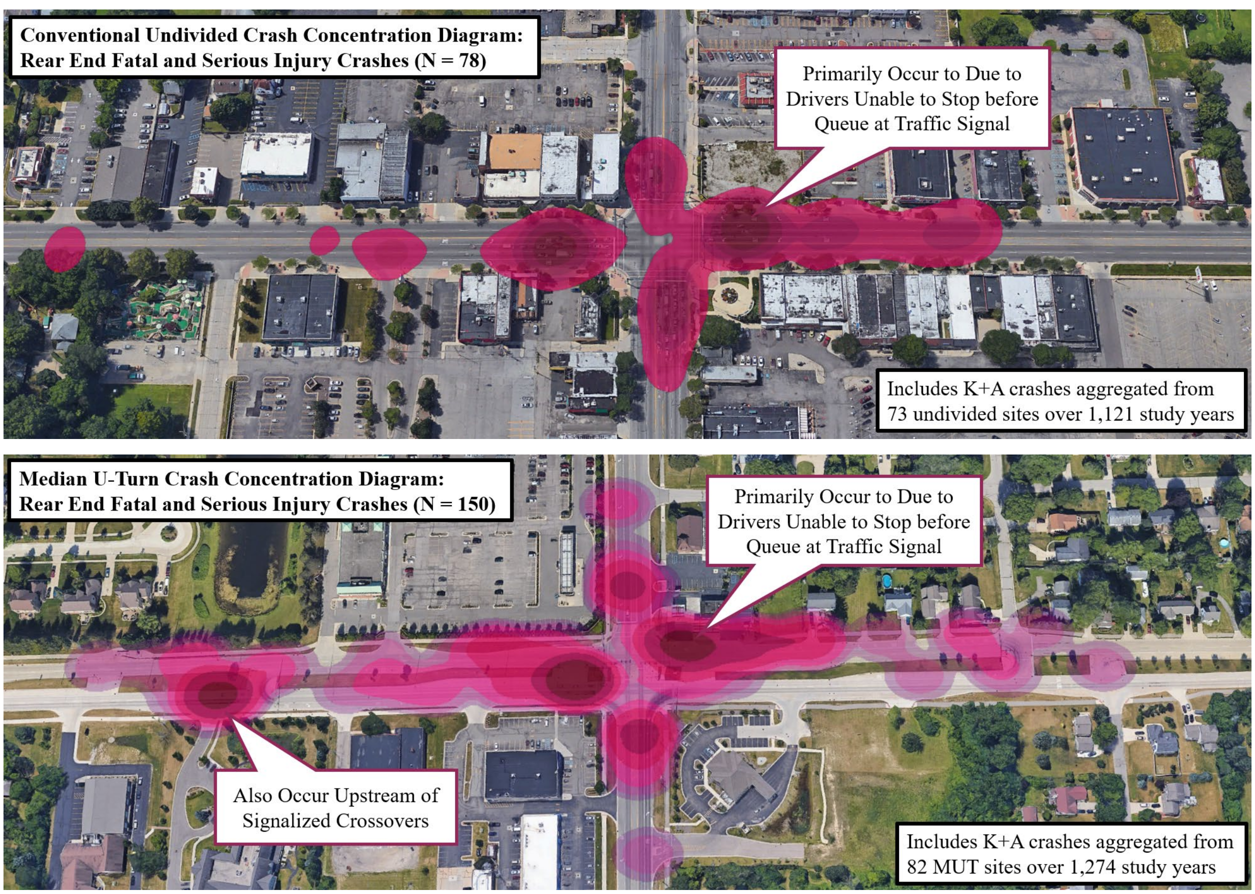


Figure 62. Rear End K+A Crash Conc. Diagrams – MUT vs. Conventional Undivided Sites

An annual average of 0.03 severe sideswipe same collisions occurred at the signalized MUT sites (**Figure 63**), primarily related to turning movement conflicts within the intersection as well as conflicts as the directional crossovers. Given that severe sideswipe same collisions were relatively rare at the conventional sites, this represents a potential drawback specific to MUTs.

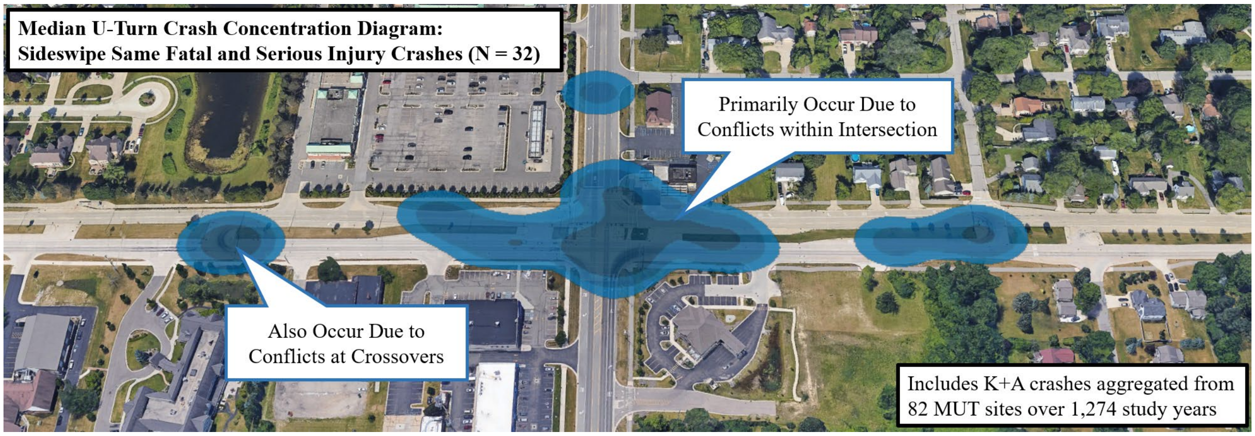


Figure 63. Sideswipe Same K+A Crash Concentration Diagram for All 82 MUT Design

6.3.1 Pedestrian and Bicycle Severe Crash Patterns

An additional detailed review of severe crashes involving non-motorized road users was conducted that focused on the differences between signalized MUT and conventional undivided intersections. **Table 20** summarizes the annual average frequencies of severe crashes involving pedestrians and bicyclists by crash category and location.

Table 20. Pedestrian and Bicycle K+A Crash Type, Location, and Category – MUT vs. Conventional Designs

Crash Category	Median U-Turn		Undivided		Divided	
	Average	Percent	Average	Percent	Average	Percent
Crossing during Don't Walk	0.02	22.5%	0.02	21.0%	0.01	33.3%
Crossing not at Crosswalk	0.04	38.8%	0.06	54.6%	0.01	33.3%
Disregard Traffic Control	0.01	12.4%	0.00	2.5%	0.00	0.0%
Failed to Yield	0.01	14.0%	0.01	10.9%	0.01	33.3%
Other	0.01	12.4%	0.01	10.9%	0.00	0.0%
Total	**0.10**	**100.0%**	**0.11**	**100.0%**	**0.02**	**100.0%**
Crash Location	**Median U-Turn**		**Undivided**		**Divided**	
	Average	**Percent**	**Average**	**Percent**	**Average**	**Percent**
Major Approach	0.04	40.3%	0.06	59.7%	0.00	16.7%
Minor Approach	0.01	8.5%	0.01	7.6%	0.01	33.3%
Within Crosswalk	0.05	48.8%	0.03	32.8%	0.01	50.0%
Crossovers	0.00	2.3%	na	na	0.00	0.0%
Total	**0.10**	**100.0%**	**0.11**	**100.0%**	**0.02**	**100.0%**

While the total number of annual severe pedestrian and bicycle crashes is similar for both the signalized MUT and conventional undivided sites is similar (an average of 0.11 and 0.10 total non-motorized crashes annually, respectively), there are important differences in the location of severe collisions involving non-motorized road users (**Figure 64**).

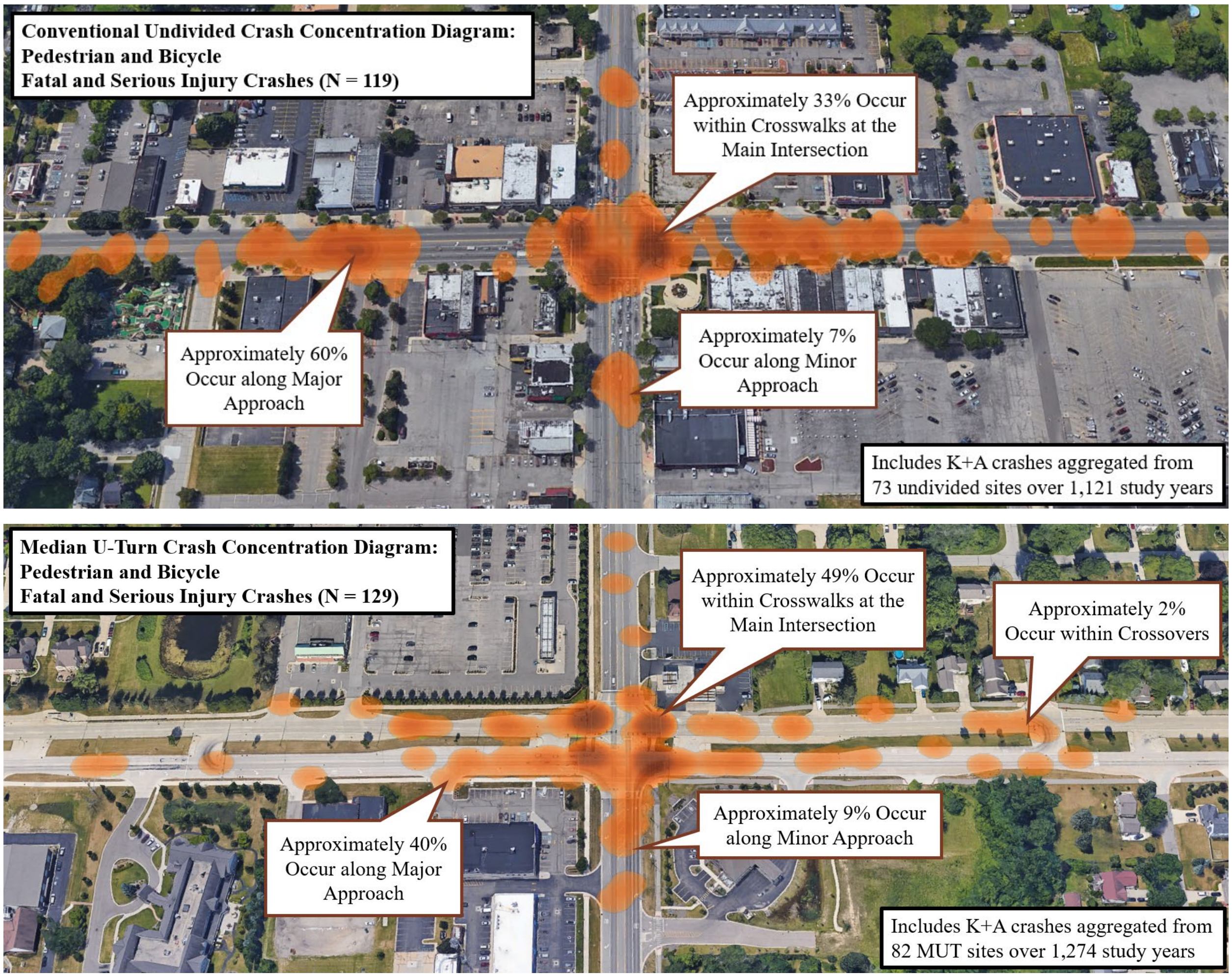


Figure 64. Pedestrian and Bicycle K+A Crash Concentration Diagrams – MUT vs. Conventional Undivided Design

The majority of severe pedestrian and bicycle collisions occurred along the major approaches of the conventional undivided sites (60 percent). This was driven largely by collisions that occurred due to non-motorized road users attempting to cross the major approaches away from the marked crosswalk available at the main intersection. A larger proportion of severe non-motorized collisions occurred within the intersection at the signalized MUT sites (49 percent), due to larger proportions of severe collisions involving crossing movements attempted during "Don't Walk" signal phases (23 percent), drivers failing to yield at crosswalks (14 percent), and drivers disregarding the signal at the main intersection (12 percent). Crash concentration diagrams for severe non-motorized collisions that occurred to pedestrians and bicyclists attempting to complete crossing movements during the "Don't Walk" signal phase are shown in **Figure 65**.

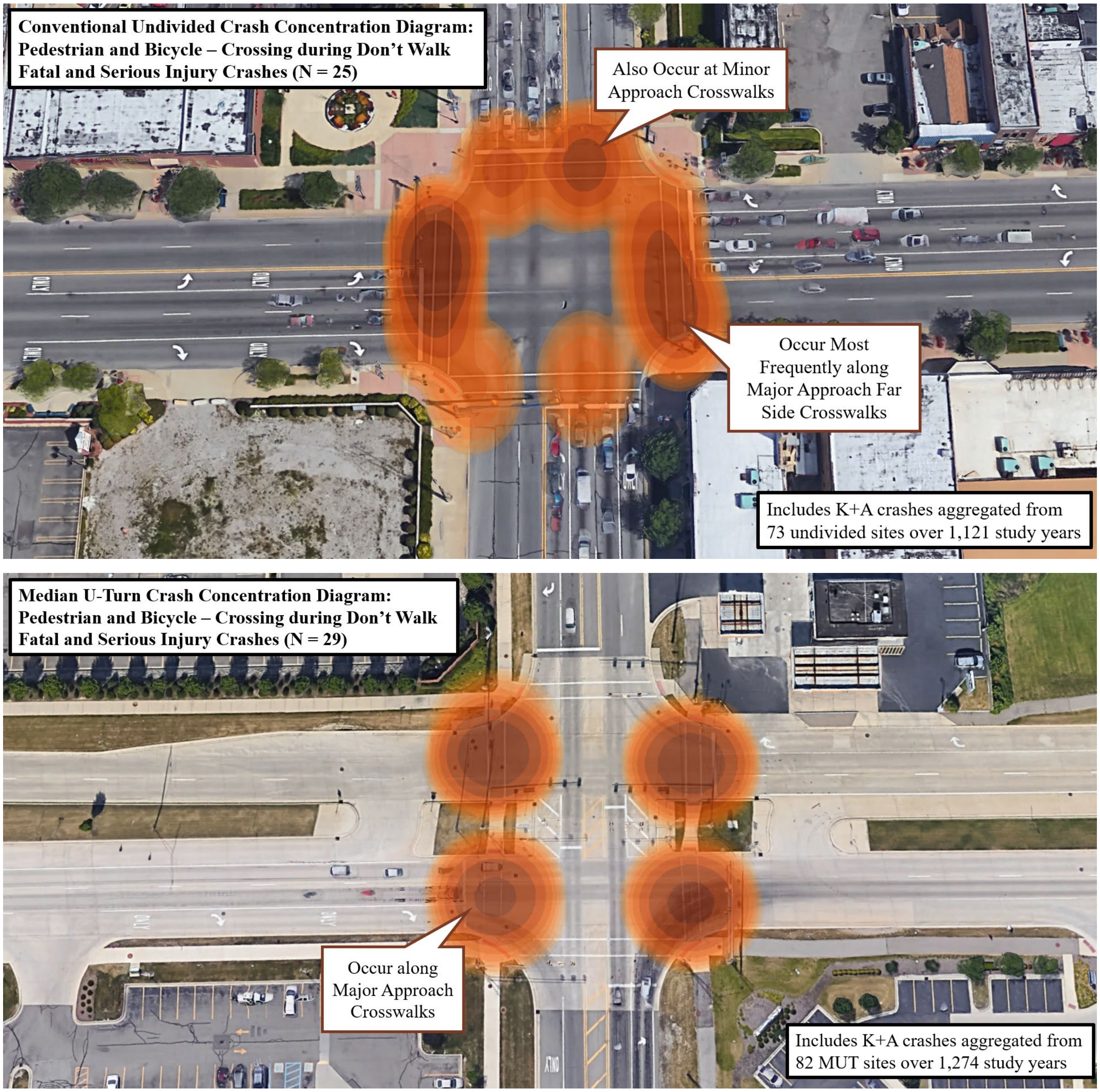


Figure 65. Pedestrian and Bicycle (Crossing during Don't Walk Phase) K+A Crash Concentration Diagrams – MUT vs. Conventional Undivided Design

These collisions occurred along marked crosswalks present at both the major and minor approaches of conventional undivided intersections, most commonly along the far side crosswalk. A distinctly different pattern can be observed for the signalized MUT sites where all 29 severe non-motorized collisions that occurred during the "Don't Walk" phase were located along the major approach crosswalks. While signal timing plans were not incorporated within this evaluation, this finding is likely driven by the large proportion of green time splits commonly provided to the major approaches at signalized MUTs. Therefore, non-motorized road users attempting to cross the minor approaches are provided with ample “Walk” phasing. Conversely, non-motorized road users attempting to cross the major approaches are provided with “Walk” phases which are less frequent and may only allow for crossing one side of the divided boulevard. Signal timing strategies for MUT designs should be investigated which provide a balance between operational efficiency and sufficient “Walk” intervals to minimize the pattern of severe collisions involving non-motorized road users attempting to cross during “Don’t Walk” phases along the major approach crosswalks.

Crash concentration diagrams for severe non-motorized collisions that occurred due to pedestrians and bicyclists attempting to complete crossing movements not at a crosswalk signal phase are shown in **Figure 66**.

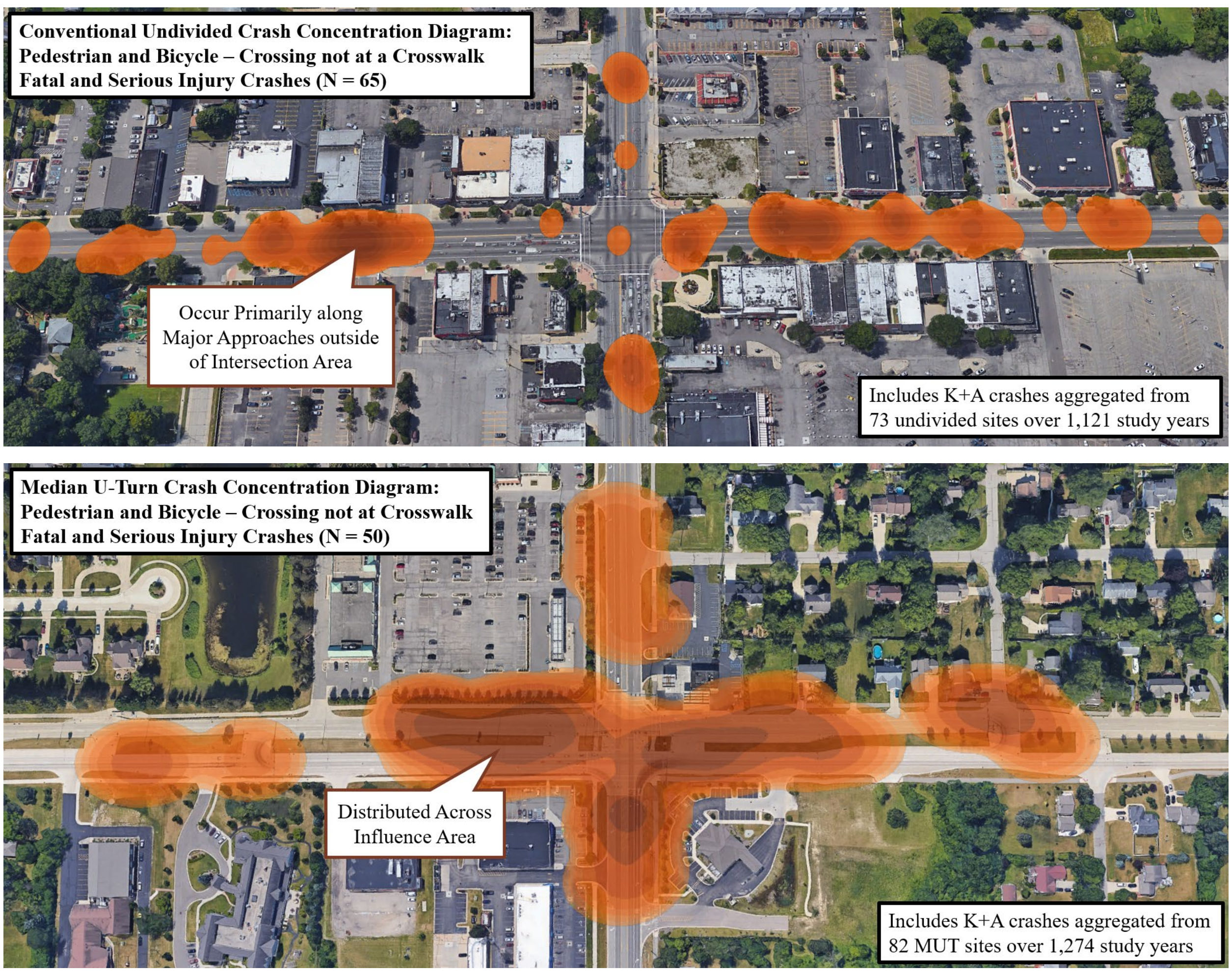


Figure 66. Pedestrian and Bicycle (Crossing not at a Crosswalk) K+A Crash Concentration Diagrams – MUT vs. Conventional Undivided Design

As previously noted, the conventional undivided sites experienced a larger proportion and annual average frequency of severe collisions that occurred due to non-motorized road users attempting to cross away from the marked crosswalks at the intersection than the signalized MUT sites. These collisions tended to occur farther away from the main intersection at the conventional undivided sites than at the MUT sites where such collisions occurred mostly in the area adjacent to the main intersection. Design treatments for signalized MUTs that discourage crossing movements in these areas as well as signal timing strategies which allow for additional opportunities to cross at the major approach crosswalks may help to address these patterns.

Crash concentration diagrams for severe non-motorized collisions that occurred due to drivers failing to yield to pedestrians and bicyclists in the crosswalk or drivers disregarding the traffic signal are shown in **Figure 67**.

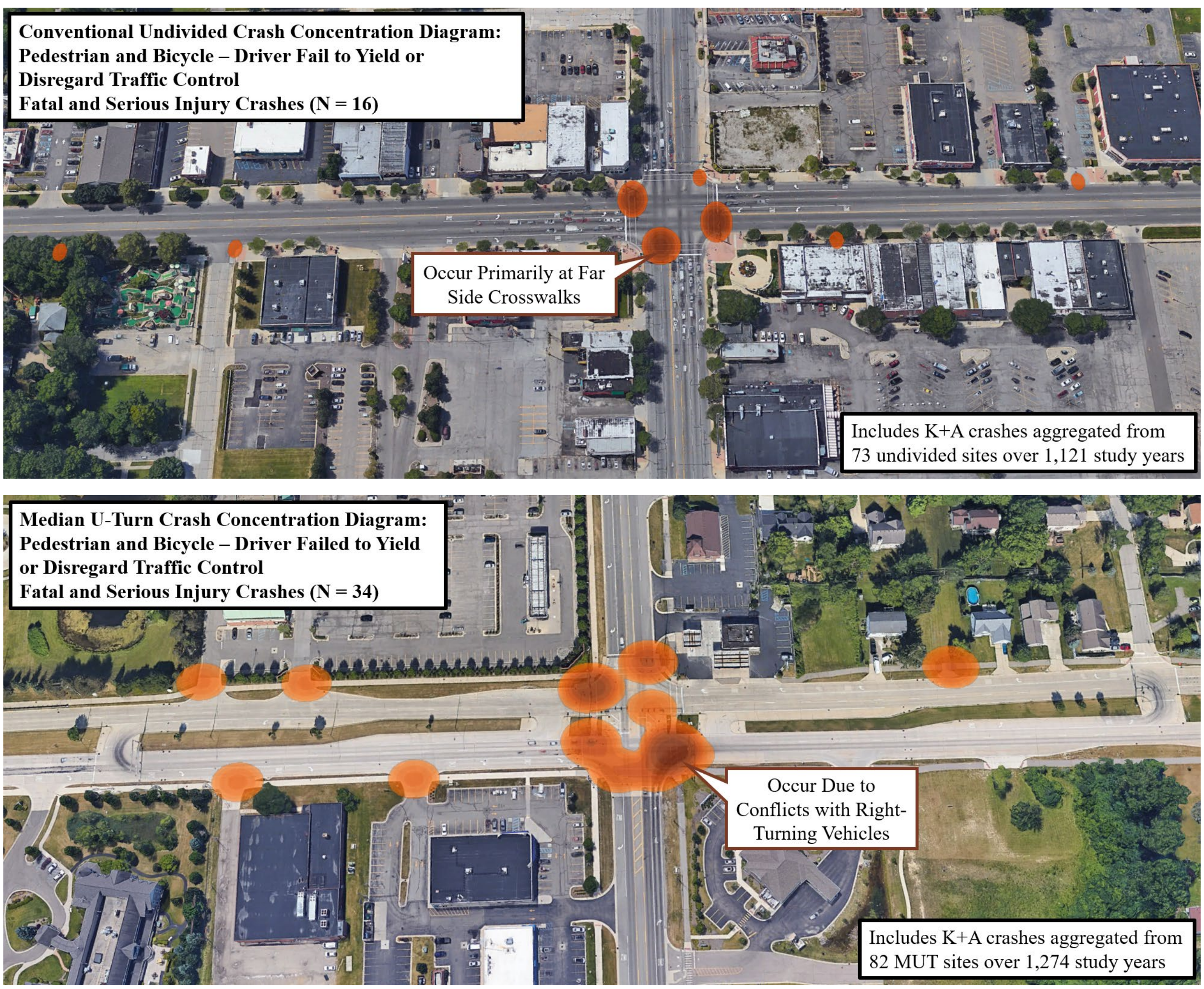


Figure 67. Pedestrian and Bicycle (Driver Failed to Yield or Disregarded Traffic Control) K+A Crash Concentration Diagrams – MUT vs. Conventional Undivided Design

While such severe collisions involving non-motorized road users were present at the conventional undivided sites, the increased number of right-turn conflicts driven by the indirect left-turn movements at the MUT sites resulted in a more distinct pattern. The crash concentration diagram presented in **Figure 67** identifies conflicts related to drivers from the minor approaches completing right-turn movements at the main intersection at a potential concern for the signalized MUT sites.

Ultimately, it is important to recognize that pedestrian and bicycle demand data (including the number of crossing movements) was not included within this study. Therefore, this limits the evaluation of severe collisions involving non-motorized road users to the review of common crash patterns presented in **Figures 64-67**. Future research should include pedestrian and bicycle demand data to determine if there are statistical differences in non-motorized safety performance.

6.4 Development of Safety Performance Functions

First, SPFs were developed specific to all 82 signalized MUT sites included in the study, summarized in **Table 21** and visualized by major approach volume in **Figures 68-73**. These models help to identify MUT-specific design features which impact safety performance. Distinct SPFs were developed for fatal and injury (FI) and property damage only (PDO) crashes.

Table 21. Negative Binomial Model Results – Signalized MUT Sites (82 Sites, 1,274 Years

Parameter	Fatal and Injury Crashes				Property Damage Only Crashes			
	Est.	Std. Error	z value	Sig.	Est.	Std. Error	z value	Sig.
Intercept	-7.211	1.0761	-6.701	<0.001	-6.859	0.905	-7.581	<0.001
Major Approach Volume (*Ln of Vehicles per Day*)	0.520	0.084	6.192	<0.001	0.522	0.071	7.395	<0.001
Minor Approach Volume (*Ln of Vehicles per Day*)	0.332	0.071	4.679	<0.001	0.414	0.060	6.843	<0.001
Average Distance to Main Crossovers Greater Than 600' *(Baseline is Less than 600')*	-0.164	0.082	-1.997	0.046	-0.266	0.072	-3.711	<0.001
Average Weave Area Length Less Than 200' *(Baseline is Greater than 200')*	0.232	0.090	2.582	0.010	0.169	0.078	2.181	0.029
Number of Main Crossovers which are Signal Controlled	0.139	0.051	2.742	0.006	0.140	0.044	3.224	0.001
Average Number of Storage Lanes at Main Crossovers	0.308	0.139	2.214	0.027	0.500	0.121	4.122	<0.001
Overdispersion Parameter	0.108	-	-	-	0.093	-	-	-

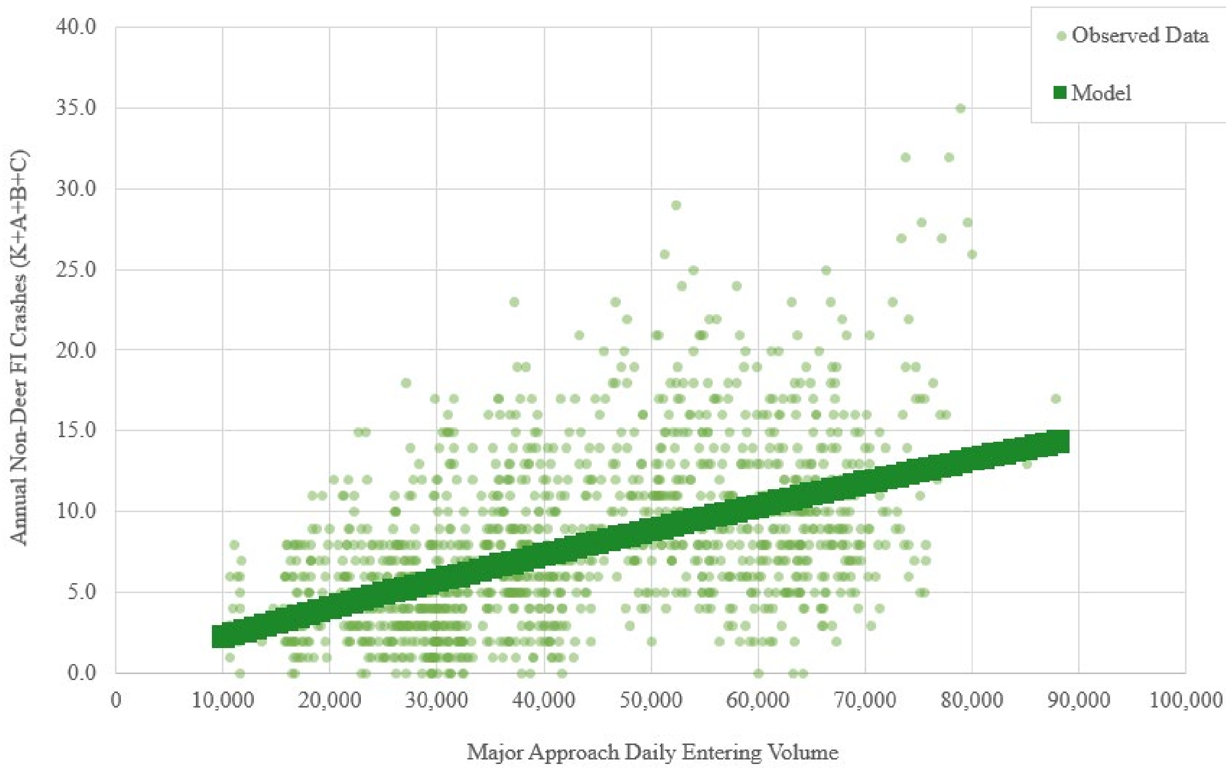


Figure 68. Annual FI Crashes vs. Major Approach Volume (All Other Factors = Average Values): All Signalized MUT Sites (82 Sites, 1,274 Years of Data)

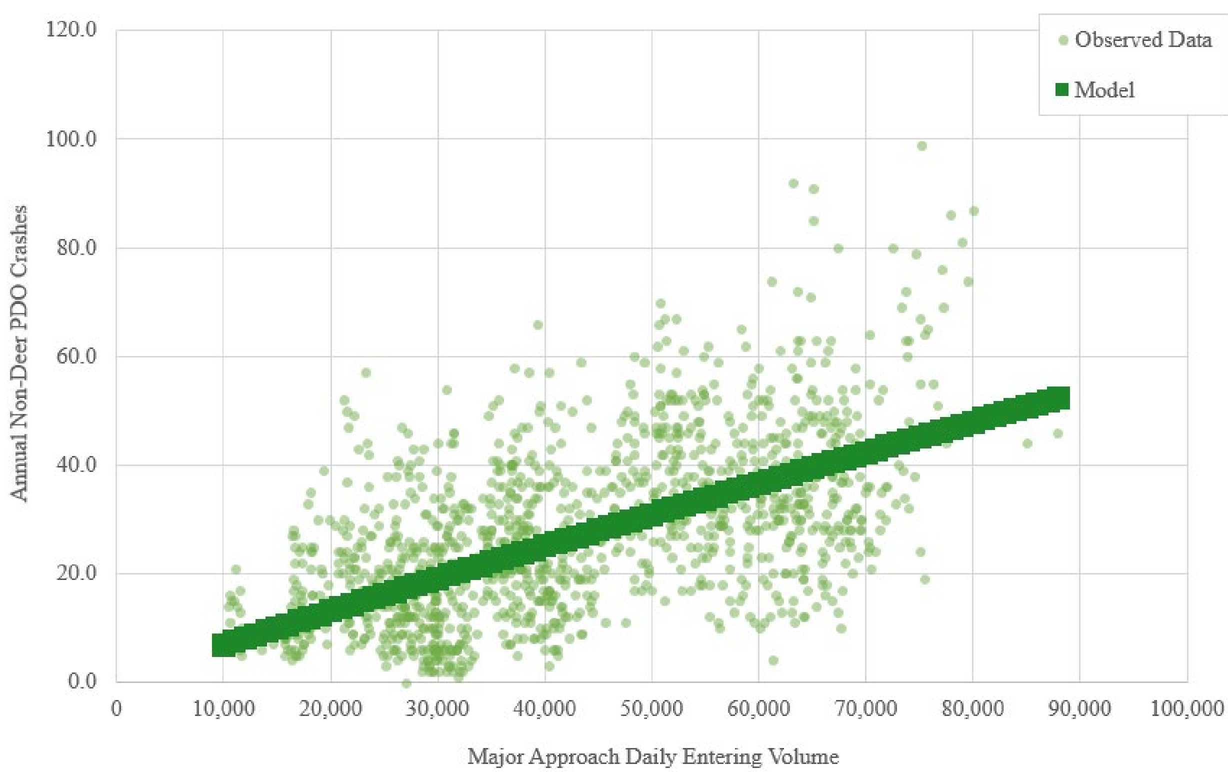


Figure 69. Annual PDO Crashes vs. Major Approach Volume (All Other Factors = Average Values): All Signalized MUT Sites (82 Sites, 1,274 Years of Data)

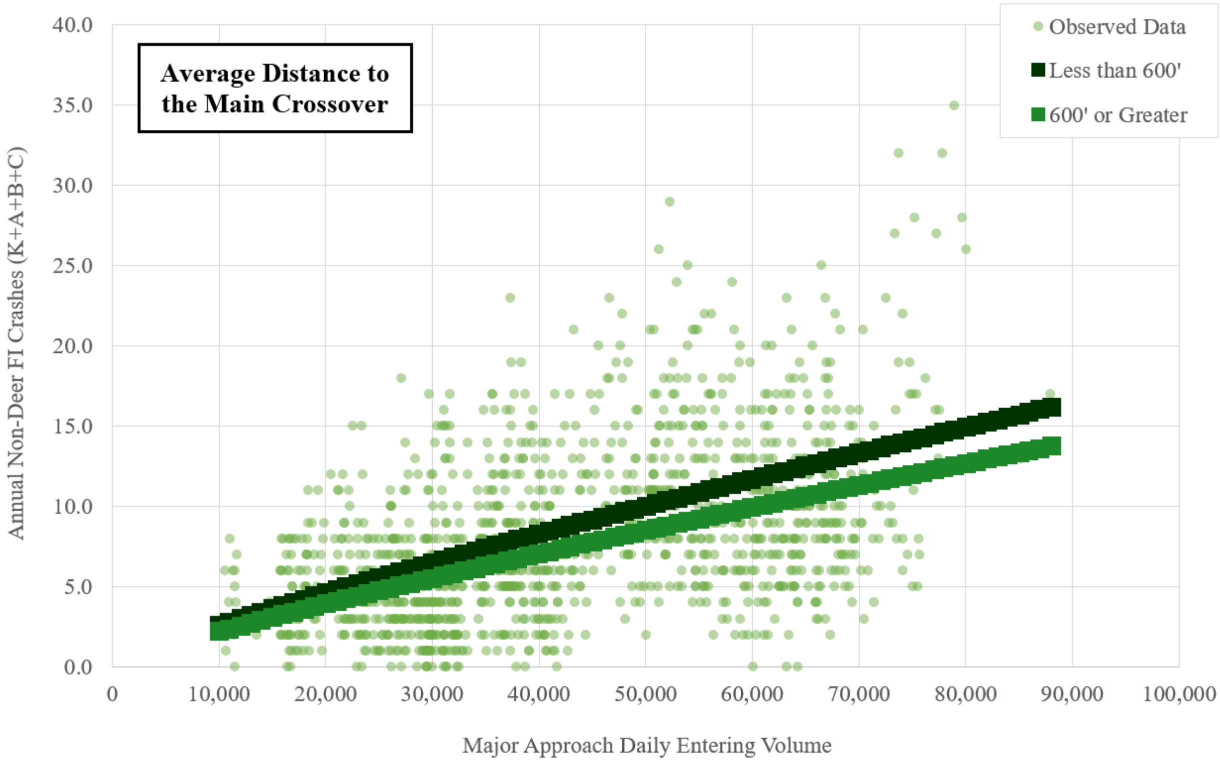


Figure 70. Annual FI Crashes vs. Major Appr. Vol. by Avg. Distance to Main Crossover (All Other Factors = Average Values): All Signalized MUT Sites (82 Sites, 1,274 Years)

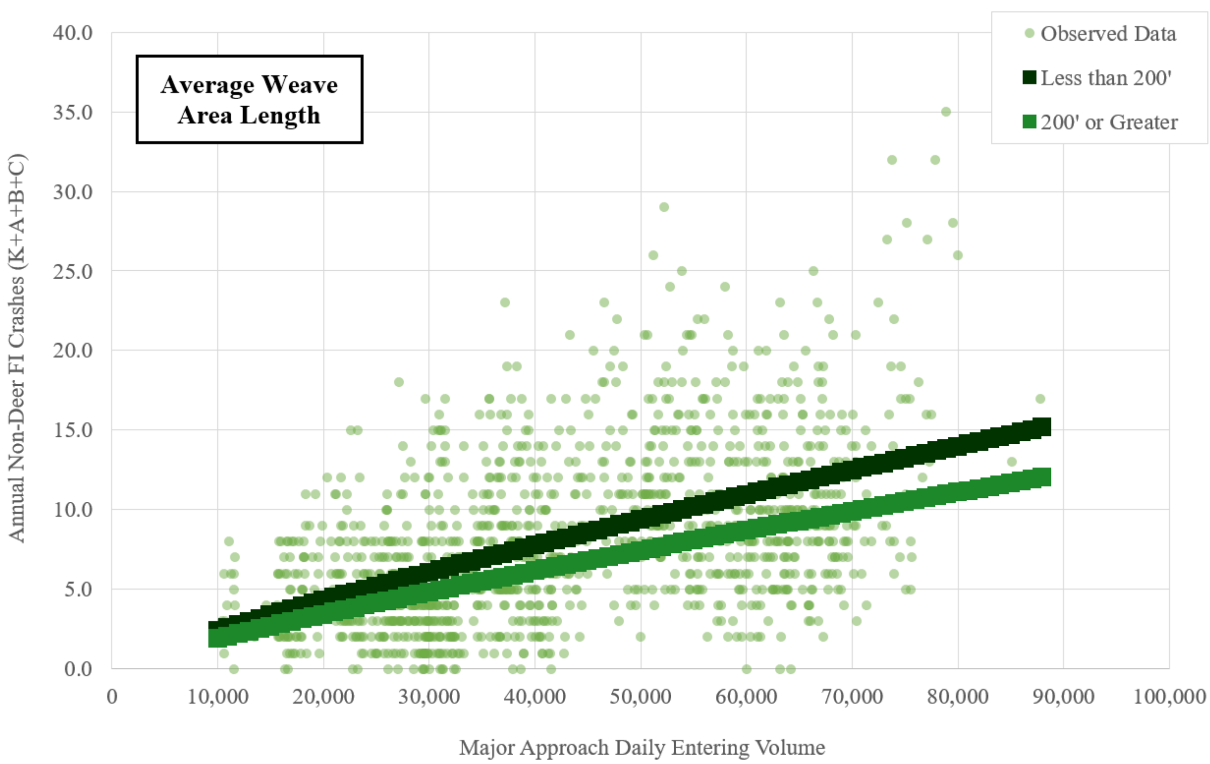


Figure 71. Annual FI Crashes vs. Major Appr. Vol.by Avg. Weave Area Length (All Other Factors = Average Values): All Signalized MUT Sites (82 Sites, 1,274 Years of Data)

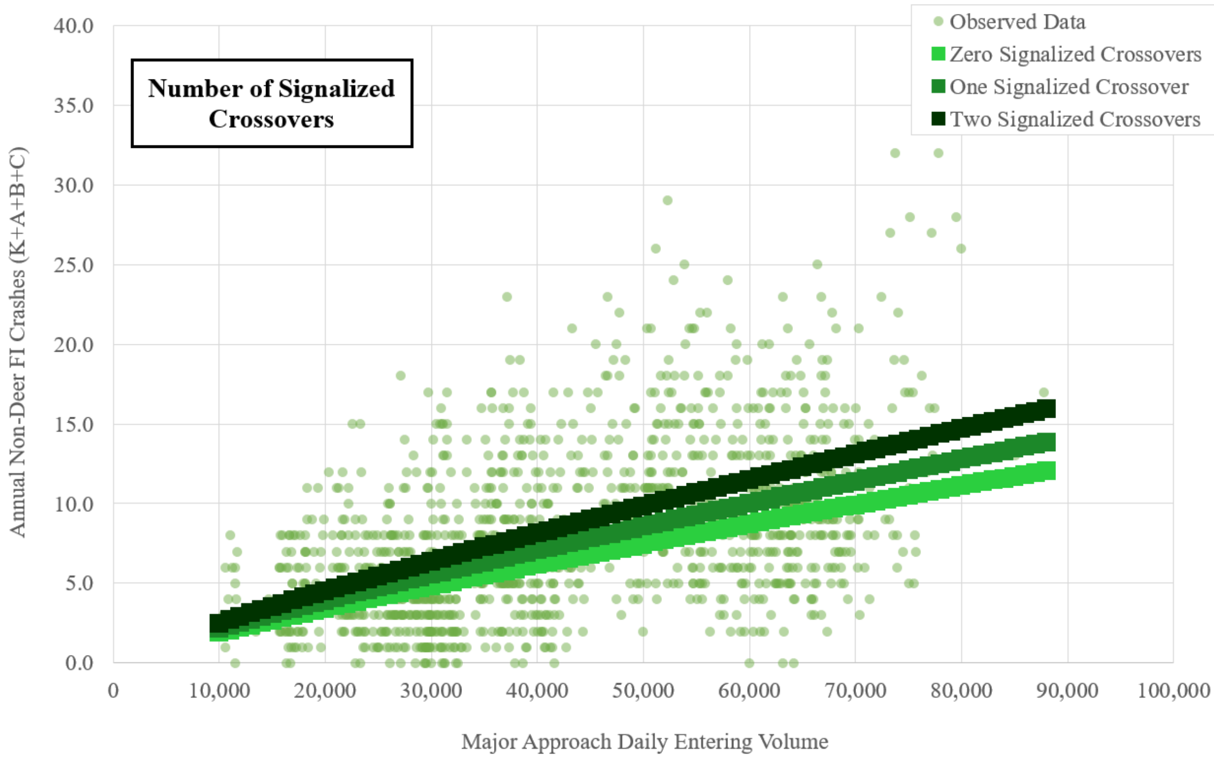


Figure 72. Annual FI Crashes vs. Major Appr. Vol. by Number of Signalized Crossovers (All Other Factors = Avg. Values): All Signalized MUT Sites (82 Sites, 1,274 Years of Data)

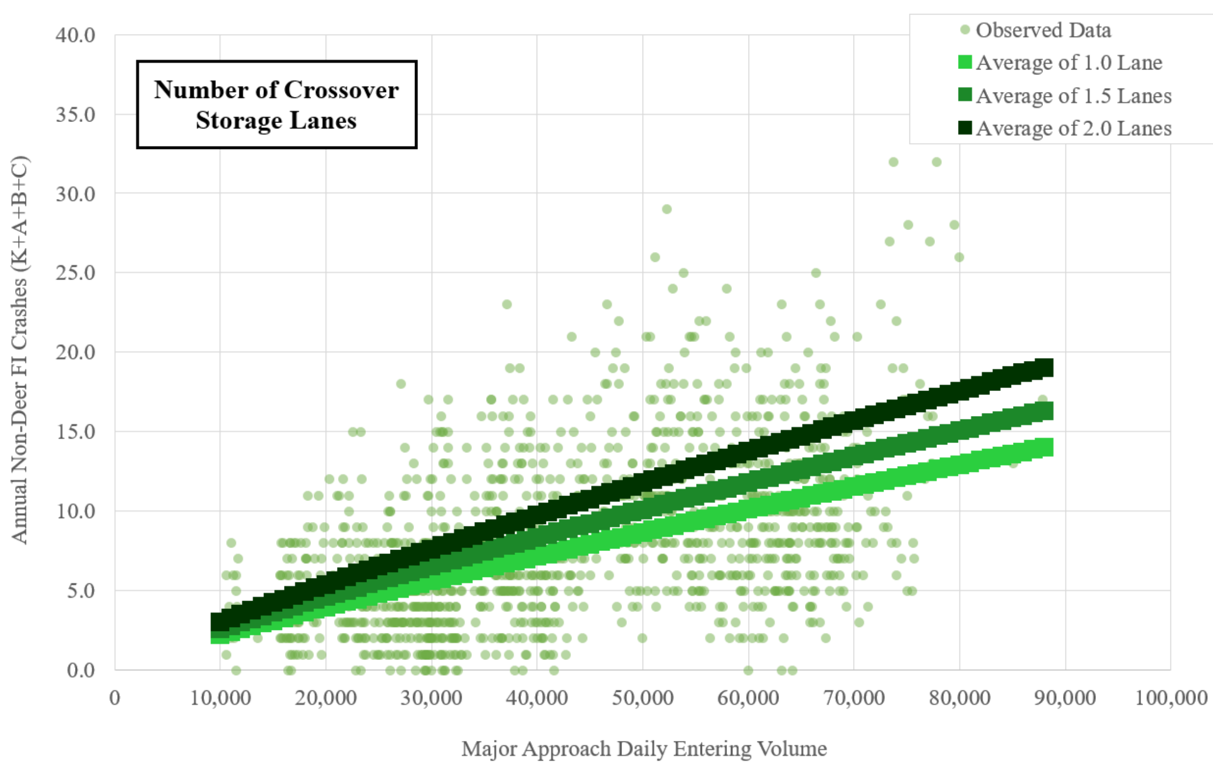


Figure 73. Annual FI Crashes vs. Major Appr. Vol. by Avg. Number of Storage Lanes (All Other Factors = Average Values): All Signalized MUT Sites (82 Sites, 1,274 Years)

Both FI and PDO crash frequencies at signalized MUT intersections were more sensitive to major approach volume than minor approach volumes. Signalized MUTs which included an average distance to the crossover of more than 600 feet were associated with lower frequencies of FI and PDO collisions (**Table 21** and **Figure 70**). This finding supports MDOT's design guidance of 600 to 700 feet [*31*]. Signalized MUTs which include average weave area lengths of less than 200 feet were associated with higher frequencies of FI and PDO collisions (**Table 21 and Figure 71**). Therefore, the design of directional crossovers at signalized MUTs should attempt to ensure at least 200 feet of weave area length is included to minimize these impacts. Both the signalization of the directional crossovers as well as the inclusion of multiple storage lanes were associated with higher frequencies of FI and PDO collisions (**Table 21 and Figures 72-73**). These design features may be necessary to support the operational performance of signalized MUTs with relatively high U-turn demand at the directional crossovers (including both indirect left-turn movements as well as vehicles using the crossovers to access adjacent developments). However, it is also important to recognize that these features also result in reduced safety performance.

Next, a series of additional negative binomial regression models were estimated to develop CMFs specific to the two conversion scenarios presented in **Section 1.5**. Models were estimated to compare safety performance between the conventional undivided site condition versus the MUT site condition, as well as the conventional divided site condition versus the MUT site condition. These models were used as a part of the cross-sectional evaluation (**Section 4.3**). Distinct SPFs were developed for fatal and injury (FI) and property damage only (PDO) crashes. The SPFs used to develop the CMFs specific to signalized MUT conversions are summarized in **Table 22**. The development of CMFs for signalized MUT conversions is summarized in **Section 6.5**.

Table 22. Negative Binomial Model Results for Cross-Sectional Approach

Conventional Undivided Sites (73 Sites, 1,121 Years of Data) and Sample of MUT Sites (45 Sites, 682 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-7.668	1.102	-6.975	<0.001	-6.152	1.113	-5.526	<0.001
Major Approach Volume (*Ln of Vehicles per Day*)	0.559	0.102	5.472	<0.001	0.422	0.102	4.321	<0.001
Minor Approach Volume (*Ln of Vehicles per Day*)	0.438	0.0552	7.933	<0.001	0.534	0.059	9.013	<0.001
Binary Indicator Variable For MUT Site Condition *(1 = MUT Design)*	-0.421	0.064	-6.601	<0.001	-0.380	0.067	-5.680	<0.001
Overdispersion parameter	0.109	-	-	-	0.144	-	-	-

Table 22 (cont'd)

Conventional Divided Sites (16 Sites, 256 Years of Data) and Sample of MUT Sites (21 Sites, 315 Years of Data)								
Parameter	**Fatal and Injury Crashes**				**Property Damage Only Crashes**			
	Est.	**Std. Error**	**z value**	**Sig.**	**Est.**	**Std. Error**	**z value**	**Sig.**
Intercept	-2.550	1.075	-2.371	0.018	-4.058	0.983	-4.127	<0.001
Minor Approach Volume (*Ln of Vehicles per Day*)	0.431	0.121	3.570	<0.001	0.735	0.110	6.67	<0.001
Binary Indicator Variable For MUT Site Condition *(1 = MUT Design)*	0.350	0.119	2.934	0.003	0.487	0.111	4.393	<0.001
Overdispersion parameter	0.150	-	-	-	0.138	-	-	-

Annual crash frequencies experienced at all 73 conventional undivided intersections and the sample of 45 MUT sites are shown in **Figures 74** (FI crashes) and **Figure 75** (PDO crashes) versus major approach volume. The model results from **Table 22** are also shown where minor approach volumes are set to the average value. The sample of MUT sites experienced fewer FI (34.4 percent) and PDO (31.6 percent) crashes than the conventional undivided sites. These findings were consistent with the crash rates presented in **Section 6.2**. While the sample of MUT sites experienced greater fatal and serious injury (K+A) aggregate crash rates (**Table 1**) than the conventional undivided sites, a model developed using K+A crashes only included results which showed that the binary indicator for site condition was not statistically significant.

Annual crash frequencies experienced at all 16 conventional divided intersections and the sample of 21 MUT sites are shown in **Figures 76** (FI crashes) and **Figure 77** (PDO crashes) versus minor approach volume. Crash frequencies were not sensitive to the major approach volumes given that the sample of MUT sites and conventional divided sites included relatively low variations in major approach volumes. Instead, there was a statistically significant relationship between crash frequency and minor approach volumes (representing the frequency of conflicts with vehicles traveling along the major approaches). The sample of MUT sites experienced more FI (42.0 percent) and PDO (62.7 percent) crashes than the divided sites. Given that only minor approach volumes were included in the conventional divided cross-sectional models as well as the fact that the correlation in FI crash counts for poorly performing signalized MUTs was accommodated by the random effects framework, there are differences between the model results presented in **Table 22** and the aggregate crash rates presented in **Section 6.2**.

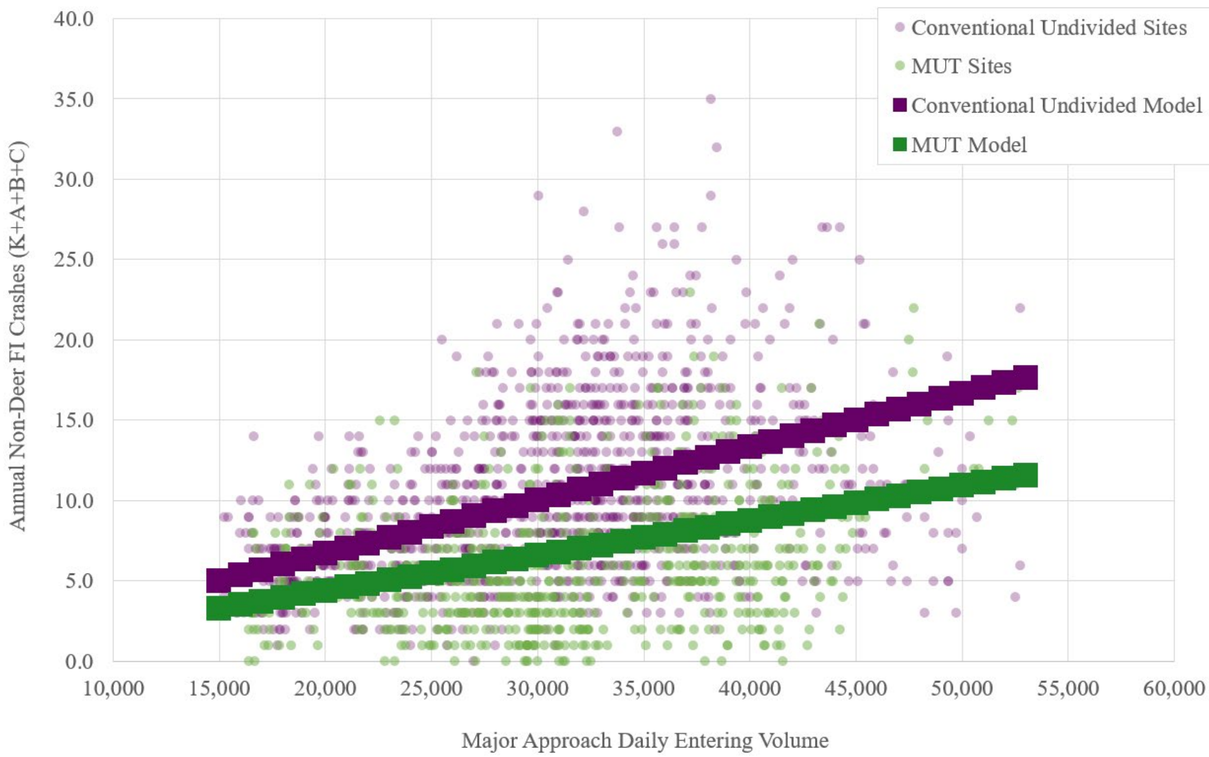


Figure 74. Annual FI Crashes vs. Major Appr. Vol.(Minor Appr. Vol. = Average Value): All Conventional Undiv. (73 Sites, 1,121 Years) and MUT Sites (45 Sites, 682 Years)

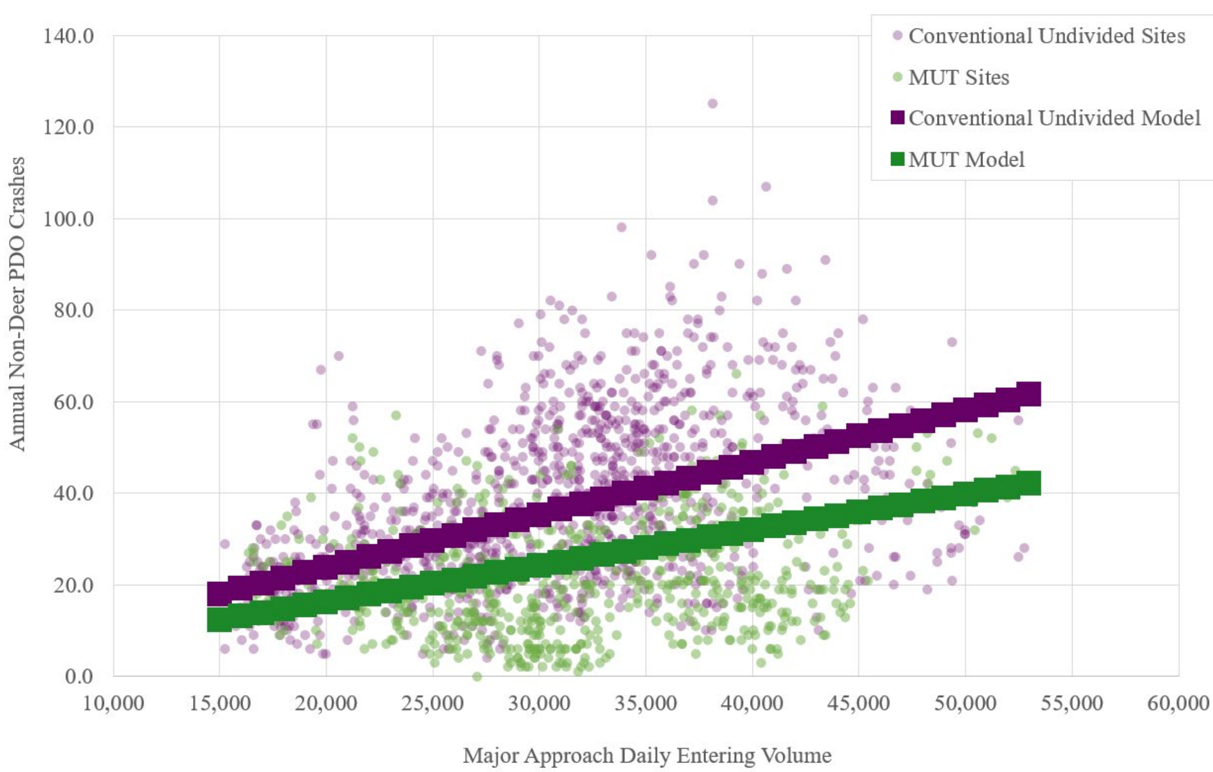


Figure 75. Annual PDO Crashes vs. Major Appr. Vol. (Minor Appr. Vol. = Average Value): All Conventional Undiv. (73 Sites, 1,121 Years) and MUT Sites (45 Sites, 682 Years)

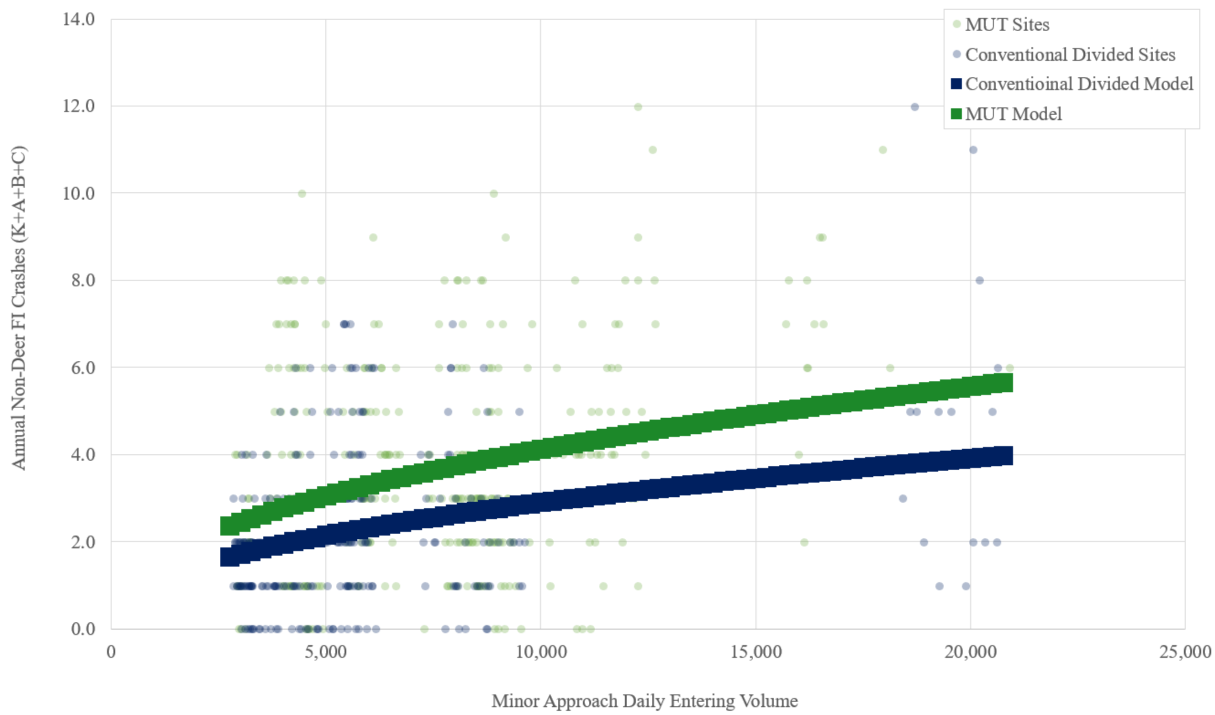


Figure 76. Annual FI Crashes vs. Minor Approach Volume: All Conventional Divided (16 Sites, 256 Years of Data) and MUT Sites (21 Sites, 315 Years of Data)

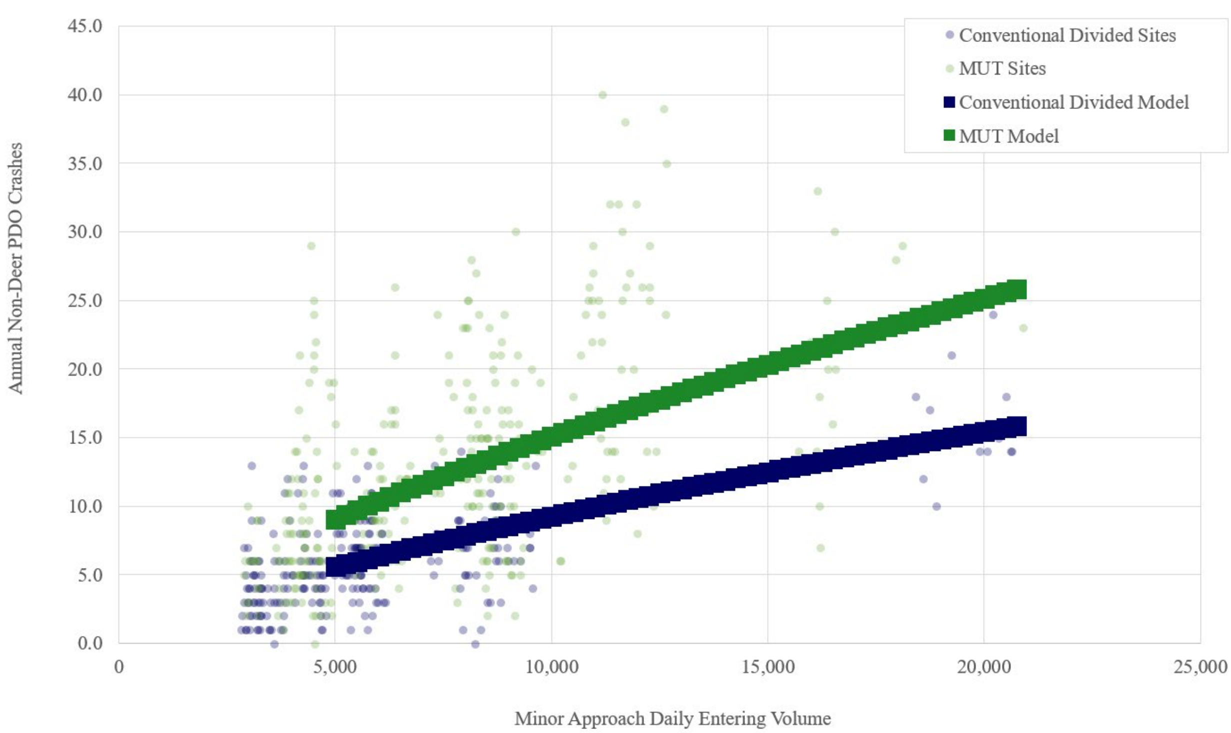


Figure 77. Annual PDO Crashes vs. Minor Approach Volume: All Conventional Divided (16 Sites, 256 Years of Data) and MUT Sites (21 Sites, 315 Years of Data)

6.5 Development of Crash Modification Factors

Table 23 provides a summary of the CMFs for signalized MUT conversions considered as a part of this evaluation. Distinct CMFs were developed for FI and PDO crashes. The CMFs presented in **Table 23** were statistically significant at a 95 percent level of confidence.

Table 23. Recommended FI and PDO CMFs for Signalized MUT Conversions

Signalized Conversion Type	Fatal and Injury Crashes (K+A+B+C)		Property Damage Only Crashes	
	CMF	Std. Error	CMF	Std. Error
Signalized Intersection with Undivided Approaches to Signalized MUT	0.656	0.041	0.684	0.046
Signalized Intersection with Divided Major Approaches to Signalized MUT	Additional research is required to develop CMFs specific to converting conventional intersections with existing divided major approaches. However, there is evidence that signalized MUTs may offer reductions in fatal (K), serious injury (A) and minor (B) injury crash rates with offsetting increases in possible (C) injury and property damage only crash rates.			

The signalized MUT design provides lower frequencies of FI and PDO crashes (**Table 23**) compared to the conventional undivided sites, driven by lower rates of all multiple-vehicle collision types (**Table 17**). It is important to note that these findings are in general agreement with the prior work summarized in **Section 2.2**. While future work should include investigating fatal and severe injury (K+A) safety performance over a larger, multi-state sample of MUT and reference sites, the review of severe collisions outlined in **Section 6.3** provides additional context for the larger fatal crash rates observed at the MUT sites (**Table 17**). This includes the important differences in the pattern of severe angle crashes related to drivers disregarding the traffic signal at the main intersection as well as severe collisions involving non-motorized road users.

Despite the fact that the cross-sectional models presented in **Table 22** suggest that both FI (42.0 percent) and PDO (62.7 percent) crash frequencies were higher at the MUT sites compared to the conventional divided sites, these values are not recommended as CMFs given that the conventional reference sites may not adequately represent a fair comparison to the MUT sites (even after selecting a subset of MUT sites that serve lower traffic volumes and incorporate lower access point densities). The analysis of aggregate traffic crash rates included in **Section 6.2** does provide evidence that signalized MUTs may provide superior performance in terms of severe injury collisions (K+A+B) with potential tradeoffs in possible (C) injury and PDO collisions.

7.0 CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

Given the adoption of the Safe System approach within the USDOT's *National Roadway Safety Strategy* that emphasizes prioritizing safety treatments which help to eliminate fatalities and serious injuries [*2*], it is important to identify and employ countermeasures that have the potential to address the more than 10,000 intersection-related fatalities that occur annually in the United States [*10*]. The use of reduced left-turn conflict intersections [*3*], including MUT designs, have been identified by the FHWA as a proven countermeasure shown to decrease the risk of potentially severe crash types by implementing indirect left-turn movements and reducing conflict points [*3*]. This study included the evaluation of historical traffic crash data at both signalized and unsignalized intersections in Michigan which have been converted to a median U-turn design to quantify safety performance and develop analytical tools for practitioners considering future conversions. Reference sites at locations which maintain a conventional design with both undivided and divided major approaches were also identified to compare performance between traditional designs (which allow direct left-turn movements) and the median U-turn design. A summary if the key findings (**Section 7.1**), recommendations for roadway agencies (**Section 7.2**), as well as study limitations and suggestions for future work (**Section 7.3**) is provided below.

7.1 Summary of Findings

While detailed discussion of the results can be found in **Section 5.0** (unsignalized MUTs) and **Section 6.0** (signalized MUTs), a summary of the major findings is provided below:

- Unsignalized MUT designs with a closed median opening provides superior FI safety performance compared to both conventional undivided and divided designs.
  - However, this evaluation does provide evidence that MUT conversions implemented along highways that already include a divided boulevard are associated with a statistically significant increase in PDO crash frequency.
  - In particular, the removal of the crossing conflict points at MUT designs essentially eliminates the pattern of severe head on left-turn and angle collisions occurring within conventional unsignalized intersections.
- Signalized MUT designs provide superior FI and PDO safety performance compared to the conventional undivided design, driven by lower rates of all multiple-vehicle collision types.
  - However, fatal crash rates were larger at the signalized MUT sites than the

conventional undivided sites. The patterns of severe angle collisions that occurred due to drivers disregarding traffic signals at the main intersection as well as non-motorized crashes occurring within the crosswalks may have contributed to these results.

- Despite the fact that both FI and PDO crash frequencies were higher at the MUT sites compared to the conventional divided sites, CMFs for divided conversions are not included as the available conventional reference sites may not adequately represent a fair comparison with the MUT sites available for study in Michigan due to the relatively low maximum approach volumes served by these sites.
  - This study does provide evidence that signalized MUTs may provide superior performance over conventional divided designs in terms of severe injury collisions (K+A+B) with potential tradeoffs in possible (C) injury and PDO collisions.
- The CMFs that are recommended when considering either unsignalized or signalized MUT conversions are presented in **Table 24**.

Table 24. Recommended CMFs for Median U-Turn Conversions

Unsignalized Conversions						
Unsignalized Conversion Type	Fatal and Injury Crashes			Property Damage Only Crashes		
	CMF	Standard Error	Method	CMF	Standard Error	Method
Undivided (Two-Lane Two-Way) to MUT Design	0.438	0.035	Cross-Sectional	No Statistical Difference		
Divided (Four-Lane Boulevard) to MUT Design	0.686	0.059	EB Method	1.325	0.059	EB Method

Signalized Conversions				
Signalized Conversion Type	Fatal and Injury Crashes (K+A+B+C)		Property Damage Only Crashes	
	CMF	Std. Error	CMF	Std. Error
Signalized Intersection with Undivided Approaches to Signalized MUT	0.656	0.041	0.684	0.046
Signalized Intersection with Divided Major Approaches to Signalized MUT	Additional research is required to develop CMFs specific to converting conventional intersections with existing divided major approaches. However, there is evidence that signalized MUTs may offer reductions in fatal (K), serious injury (A) and minor (B) injury crash rates with offsetting increases in possible (C) injury and property damage only crash rates.			

7.2 Recommendations

A series of recommendations were developed specific to the planning, design, and maintenance of MUT intersections. These are summarized below, including recommendations specific to unsignalized (**Section 7.2.1**) and signalized (**Section 7.2.2**) MUT applications.

7.2.1 Unsignalized MUT Intersections

The conversion of unsignalized conventional intersections (i.e., where direct left-turn movements are allowed) to an unsignalized MUT design may be considered as a viable countermeasure for the reduction of fatal and injury (KABC) crashes. Additional considerations specific to unsignalized MUTs include:

- During implementation decisions, consideration must also be given to the traffic operational impacts that would result from such a conversion.
- The MUT design should attempt to mitigate potential rear end and sideswipe same crashes that often increase on the minor approach after implementation of the MUT. This could include ensuring that adequate intersection sight distance is available for drivers approaching the stop-controlled minor approaches.
- For existing intersections that are *undivided*, consideration must also be given to the right-of-way availability and costs associated with the widening of the major roadway to accommodate the U-turns.
- For existing intersections that are *divided*, right-of-way is less likely to be impacted, assuming that the existing median is of sufficient length and width to accommodate the U-turns. Furthermore, while lower rates of fatal and injury crashes are expected post-conversion, the safety benefits may be offset by a higher occurrence of property damage collisions.

7.2.2 Signalized MUT Intersections

The conversion of signalized conventional intersections with undivided approaches to a signalized MUT design may be considered as a viable countermeasure for the reduction of both fatal and injury (KABC) as well as property damage only crashes. There is evidence that signalized MUTs may provide superior performance over conventional divided designs in terms of severe injury collisions (K+A+B) with potential tradeoffs in possible (C) injury and PDO collisions.

Additional considerations specific to signalized MUTs include:

- During implementation decisions, consideration must also be given to the traffic operational impacts that would result from such a conversion, particularly the tradeoff between a reduction in delay for the through movements versus increases in delay for the left-turn movements.
- The MUT design should attempt to mitigate potential severe angle collisions that occur after implementation of the MUT due to drivers disregarding traffic signals at the main intersection. This could include upgrades to traffic control devices (such as the use of reflective backplates on signal heads) or signal timing strategies intended to improve compliance with the main intersection traffic signal.
- Signal timing strategies should be investigated which provide a balance between operational efficiency and sufficient "Walk" intervals to minimize the pattern of severe collisions involving non-motorized road users attempting to cross during "Don't Walk" phases along the major approach crosswalks.
- Design treatments for corridors which include signalized MUTs that discourage crossing movements away from marked crosswalks (such as providing a barrier within the median) may help to address severe crash patterns involving pedestrians attempting two-stage crossings outside of the crosswalk area.
- For existing intersections that are *undivided*, consideration must also be given to the right-of-way availability and costs associated with the widening of the major roadway to accommodate the U-turns.
- For existing intersections that are *divided*, right-of-way is less likely to be impacted, assuming that the existing median is of sufficient length and width to accommodate the U-turns.
- Given that both FI and PDO crashes were shown to decrease when the average distance to the main crossovers was greater than 600 feet, this supports the continued use of MDOT's design guidance of locating the directional crossovers 600 to 700 feet from main intersection as a part of signalized MUT designs when feasible [*31*].
    - This does not imply that MUT designs should not be considered when site constraints require placing the directional crossovers less than 600 feet away from the intersection. Instead, the analytical tools provided in **Section 6.4** should be used

to provide a fair estimate of safety performance.

- Given that signalized MUTs which include average weave area lengths of less than 200 feet were associated with higher frequencies of FI and PDO collisions, the design of directional crossovers at signalized MUTs should attempt to ensure at least 200 feet of weave area length is included to minimize these impacts.
  - This does not imply that MUT designs should not be considered when site constraints require weave area lengths of less than 200 feet. Instead, the analytical tools provided in **Section 6.4** should be used to provide a fair estimate of safety performance.
- Given that both the signalization of the directional crossovers as well as the inclusion of multiple storage lanes were associated with higher frequencies of FI and PDO collisions, important to recognize that these features also result in reduced safety performance.
  - This does not imply that MUT designs should not be considered when U-turn demands dictate that these design features may be necessary to support the operational performance of signalized MUTs with relatively high U-turn demand at the directional crossovers (including both indirect left-turn movements as well as vehicles using the crossovers to access adjacent developments). Instead, the analytical tools provided in **Section 6.4** should be used to provide a fair estimate of safety performance.

7.3 Limitations and Future Work

While the results of this work included the development of appropriate analytical tools for roadway agencies to make data-driven design decisions related to both unsignalized and signalized MUTs, there are several limitations present that should be addressed as a part of future search which incorporates a larger, multi-state sample of MUT and reference sites. Many of these limitations are in part due to the longstanding practice by both MDOT and local highway agencies to implement MUT designs along arterial corridors, limiting the availability to collect intersection data across all potential study conditions. The important limitations present within this evaluation and suggestions for future work include the following:

- Given that this work focused on MUTs with divided major approaches, future work should evaluate the performance of configurations where the major and minor approaches are divided as well as cases where only the minor approach is divided.

- The relatively small sample sizes of MUT sites with pre-conversion data limited the use of the EB before-and-after approach and cross-sectional methods were used to develop several of the CMFs included in this study.
    - However, a before-and-after approach is preferred in cases where sufficient pre- and post-conversion period data is available for analysis as the difference in safety performance observed via cross-sectional studies can be due to either known or unknown factors, including the countermeasure under evaluation [*27*].
    - Future work should attempt incorporate a large sample of sites with pre-conversion period data which benefit CMF estimation for all four conversion types considered in the study.
- The sample size of unsignalized MUT sites was relatively limited, and no relationship was able to be established between crash frequency and any site characteristics outside of entering approach volumes.
    - It is worth noting that that the direction of the parameter estimates of many additional explanatory variables were intuitive and therefore a larger study may potentially allow for the estimation of statistically significant relationships between these characteristics and unsignalized MUT intersection safety performance.
- Despite the efforts to identify reference sites that possessed geometric and other design characteristics which were similar to the pre-conversion MUT sites, there is lack of available conventional sites with volumes to match the upper end of the range of major approach volumes served by MUTs. The major and minor approach volumes ideally should be in general agreement between the MUT and reference sites.
    - This was a critical limitation for developing a CMF specific to converting a conventional signalized intersection with divided major approaches to a MUT design. Future work should include reference sites from jurisdictions outside of Michigan that commonly employ conventional intersections along divided urban and suburban arterials.
- The relatively long study period (2004 to 2019) was necessary to maximize the number of sites with pre- and post-conversion data. However, this does represent a potential concern for unobserved factors to influence the results of the analysis.

- The safety performance evaluation included in this study is based on data from a single state. Future work should include sites located across multiple states to improve the transferability of these results to other jurisdictions.
- Pedestrian and bicycle demand data (including the number of crossing movements) was not included within this study. Therefore, this limits the evaluation of severe collisions involving non-motorized road users to the review of common crash patterns presented in **Section 6.3.1**. Future research should include pedestrian and bicycle demand data to determine if there are statistical differences in non-motorized safety performance.

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APPENDIX

SAFETY PERFORMANCE OF MEDIAN U-TURN INTERSECTIONS EXECUTIVE SUMMARY

The use of alternative intersection designs can provide both safety and operational benefits for road users at potentially lower costs when implemented in the appropriate setting. The Federal Highway Administration has previously recognized a subset of alternative intersections designs broadly referred to as "reduced left-turn conflict intersections" as a proven safety countermeasure that have been shown to decrease the risk of potentially severe crash types by reducing conflict points through the use of indirect left-turn movements. Median U-turn intersections (also referred to as "Michigan lefts" or "boulevard turnarounds") are one such alterative design that accommodates indirect left-turn movements via directional U-turn crossovers located within the median along one or both of the intersecting roadways (**Figure 78**).

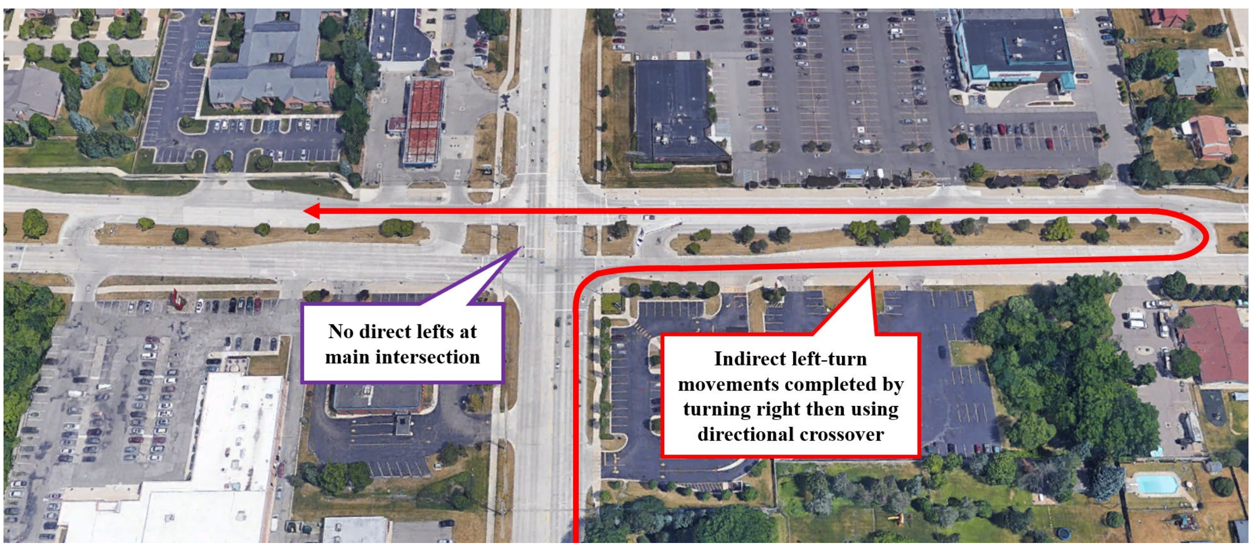

Figure 78. Example of Median U-Turn Intersection in Michigan

Michigan has long been a pioneer in the implementation of median U-turns along urban and suburban divided boulevards, with initial installations dating back several decades. Additionally, various indirect left-turn configurations have been implemented along rural highways and frontage roads for urban freeways. Other states have also implemented MUTs or related reduced left-turn conflict intersections in a variety of configurations.

Knowledge Gaps and Study Objectives

While prior work has consistently demonstrated that median U-turn intersection designs represent an effective countermeasure that can improve operational performance and reduce the frequency of severe crash types when implemented in the appropriate context, much of the extant research is outdated and several important areas of investigation remain unexplored. This includes defining the appropriate crash influence area, the impacts of pre-conversion characteristics, impacts to pedestrian and bicycle collisions, and evaluating crashes pre/post conversion (e.g., longitudinal panel data) compared to a purely cross-sectional evaluation. To address these and other knowledge gaps, research was performed to quantify the safety performance characteristics and develop analytical tools related to the utilization of median U-turn intersections.

Data Collection

Historical traffic volume data, traffic crash data, and other intersection characteristics were collected for signalized and unsignalized intersections in Michigan where left-turns are accommodated by a median U-turn design. To allow for comparison of the performance between the median U-turn and traditional designs, data were also collected for a sample of reference intersections (divided and undivided) where conventional direct left-turn movements were maintained. A novel approach was developed to define the safety performance influence area of a median U-turn intersection, which subsequently improved the method of identifying and collecting target crash data (**Figures 79 and 80**).

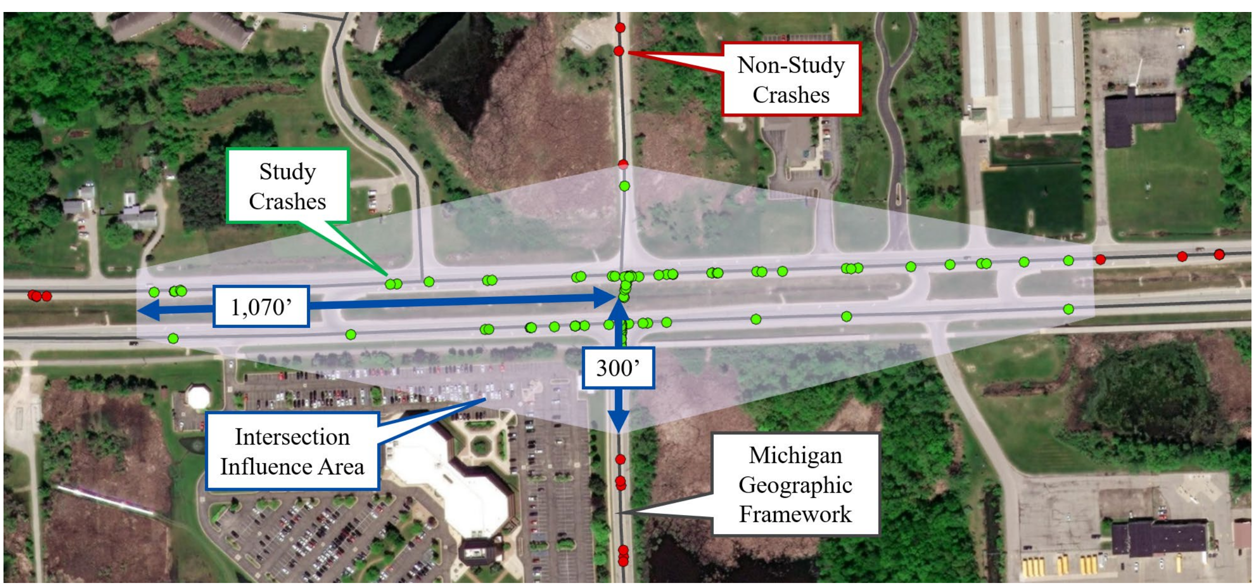

Figure 79. Crash Data Collection Process and Influence Area – Unsignalized Intersections

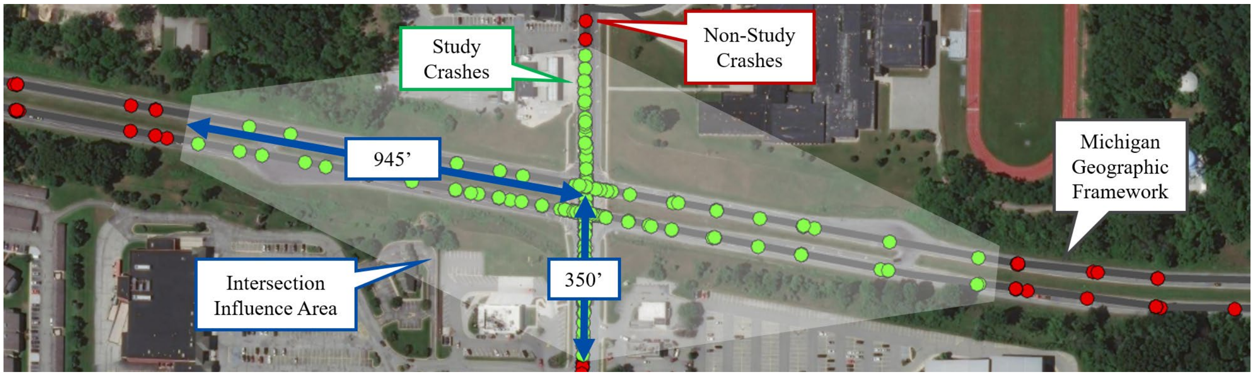

Figure 80. Crash Data Collection Process and Influence Area – Signalized Intersections

Analytical Methods

Utilizing the traffic crash data, a series of analyses were performed to identify the differences between conventional and median U-turn intersections, and to also identify the differences in safety performance between various median U-turn design characteristics. The analyses compared crash rates, types, severity distributions, and severe injury collision patterns, and included development of a series of safety performance functions and crash modification factors. Crash modification factors were developed via both Empirical Bayes before-and-after as well as a cross-sectional approaches. The results were then generalized into a series of recommendations for roadway agencies considering future implementation of median U-turn intersections, including specific design recommendations intended to improve safety performance for all road users.

Findings

Ultimately, it was concluded that median U-turn designs represent an effective safety countermeasure to target the reduction of severe crash types for both unsignalized and signalized intersections. While there are some potential tradeoffs with respect to non-injury crash frequencies for specific pre-conversion configurations, the use of these indirect left-turn intersection designs is consistent with the Safe System approach adopted by the United States Department of Transportation within the National Roadway Safety Strategy that emphasizes prioritizing safety treatments which help to eliminate fatalities and serious injuries.

Unsignalized median U-turn intersections offer superior fatal and injury crash performance compared to conventional unsignalized intersections. The removal of the crossing conflict points at unsignalized median U-turn designs (which include a closed median at the intersection) essentially eliminates the pattern of severe head on left-turn and angle collisions occurring within conventional intersections. However, it is important to recognize that non-injury crashes were shown to increase when converting a conventional unsignalized intersection to a median U-turn at locations with an existing median on the major roadway. The recommended crash modification factors for considering future unsignalized MUT conversions are shown in **Table 25**.

Table 25. Recommended CMFs for Unsignalized Median U-Turn Conversions

Unsignalized Conversion Type	Fatal and Injury Crashes			Property Damage Only Crashes		
	CMF	Standard Error	Method	CMF	Standard Error	Method
Undivided (Two-Lane Two-Way) to MUT Design	0.438	0.035	Cross-Sectional	No Statistical Difference		
Divided (Four-Lane Boulevard) to MUT Design	0.686	0.059	EB Method	1.325	0.059	EB Method

Signalized median U-turn intersections offer superior safety performance for both injury and non-injury crashes compared to conventional signalized intersections along undivided roadways, driven by lower rates of all multiple-vehicle collision types. It is important to recognize that signalized MUTs experienced a consistent pattern of angle collisions occurring within the intersection due to drivers disregarding the traffic signal. While the annual average number of severe pedestrian and bicycle crashes is similar for both the signalized MUT and conventional undivided sites is similar, there are important differences in the circumstances that drive pedestrian and bicycle crashes between the site two site types. This includes the pattern of collisions involving non-motorized road users crossing major approaches at MUTs during the "Don't Walk" phase.

The comparison of median U-turns locations to conventional divided signalized intersections was limited by a lack of reference sites with comparable traffic volumes. This study does provide evidence that signalized MUTs may provide superior performance over conventional divided designs in terms of severe injury collisions (K+A+B) with potential tradeoffs in possible (C) injury and PDO collisions. The recommended crash modification factors for considering future signalized MUT conversions are shown in **Table 26**.

Table 26. Recommended FI and PDO CMFs for Signalized MUT Conversions

Signalized Conversion Type	Fatal and Injury Crashes (K+A+B+C)		Property Damage Only Crashes	
	CMF	Std. Error	CMF	Std. Error
Signalized Intersection with Undivided Approaches to Signalized MUT	0.656	0.041	0.684	0.046
Signalized Intersection with Divided Major Approaches to Signalized MUT	Additional research is required to develop CMFs specific to converting conventional intersections with existing divided major approaches. However, there is evidence that signalized MUTs may offer reductions in fatal (K), serious injury (A) and minor (B) injury crash rates with offsetting increases in possible (C) injury and property damage only crash rates.			

Finally, several design features of signalized median U-turn intersections were identified as having a significant impact on safety performance, including the distance to crossovers from the main intersection, the length of weaving areas, the number of signalized crossovers, and the number of storage lanes. Analytical tools were provided for practitioners to consider the potential safety performance impacts of these design features when evaluating future MUT installations.

Recommendations

A series of recommendations were developed specific to the planning, design, and maintenance of both unsignalized and signalized MUT intersections.

Unsignalized MUT Intersections

The conversion of unsignalized conventional intersections (i.e., where direct left-turn movements are allowed) to an unsignalized MUT design may be considered as a viable countermeasure for the reduction of fatal and injury (KABC) crashes. Additional considerations specific to unsignalized MUTs include:

- During implementation decisions, consideration must also be given to the traffic operational impacts that would result from such a conversion.
- The MUT design should attempt to mitigate potential rear end and sideswipe same crashes that often increase on the minor approach after implementation of the MUT. This could include ensuring that adequate intersection sight distance is available for drivers approaching the stop-controlled minor approaches.
- For existing intersections that are *undivided*, consideration must also be given to the right-

of-way availability and costs associated with the widening of the major roadway to accommodate the U-turns.

- For existing intersections that are *divided*, right-of-way is less likely to be impacted, assuming that the existing median is of sufficient length and width. Furthermore, while lower rates of fatal and injury crashes are expected post-conversion, the safety benefits may be offset by a higher occurrence of property damage collisions.

Signalized MUT Intersections

The conversion of signalized conventional intersections with undivided approaches to a signalized MUT design may be considered as a viable countermeasure for the reduction of both fatal and injury (KABC) as well as property damage only crashes. There is evidence that signalized MUTs may provide superior performance over conventional divided designs in terms of severe injury collisions (K+A+B) with potential tradeoffs in possible (C) injury and PDO collisions. Additional considerations specific to signalized MUTs include:

- During implementation decisions, consideration must also be given to the operational impacts that would result from conversion, particularly the tradeoff between a reduction in delay for the through movements versus increases in delay for the left-turn movements.
- The MUT design should attempt to mitigate potential severe angle collisions that occur after implementation of the MUT due to drivers disregarding traffic signals at the main intersection. This could include upgrades to traffic control devices (such as the use of reflective backplates on signal heads) or signal timing strategies intended to improve compliance with the main intersection traffic signal.
- Signal timing strategies should be investigated which provide a balance between operational efficiency and sufficient "Walk" intervals to minimize the pattern of severe collisions involving non-motorized road users attempting to cross during "Don't Walk" phases along the major approach crosswalks.
- Design treatments for corridors which include signalized MUTs that discourage crossing movements away from marked crosswalks (such as providing a barrier within the median) may help to address severe crash patterns involving pedestrians attempting two-stage crossings outside of the crosswalk area.
- For existing intersections that are *undivided*, consideration must also be given to the right-

of-way availability and costs associated with the widening of the major roadway.

- For existing intersections that are *divided*, right-of-way is less likely to be impacted, assuming that the existing median is of sufficient length and width.
- Roadway agencies should consider the safety performance impacts of the MUT-specific features were shown to impact safety performance (including the distance to crossovers from the main intersection, the length of weaving areas, the number of signalized crossovers, and the number of storage lanes) when evaluating future designs.

Limitations and Future Work

While the results of this work included the development of appropriate analytical tools for roadway agencies to make data-driven design decisions related to both unsignalized and signalized MUTs, there are several limitations present that should be addressed as a part of future search which incorporates a larger, multi-state sample of MUT and reference sites. Many of these limitations are in part due to the longstanding practice by both MDOT and local highway agencies to implement MUT designs along arterial corridors, limiting the availability to collect intersection data across all potential study conditions. The important limitations present within this evaluation and suggestions for future work include the following:

- Given that this work focused on MUTs with divided major approaches, future work should evaluate the performance of configurations where the major and minor approaches are divided as well as cases where only the minor approach is divided.
- The relatively small sample sizes of MUT sites with pre-conversion data limited the use of the EB before-and-after approach and cross-sectional methods were used to develop several of the CMFs included in this study.
- The relatively long study period (2004 to 2019) was necessary to maximize the number of sites with pre- and post-conversion data. However, this does represent a potential concern for unobserved factors to influence the results of the analysis.
- Pedestrian and bicycle demand data (including the number of crossing movements) was not included within this study. Therefore, this limits the evaluation of severe collisions involving non-motorized road users to the review of common crash patterns. Future research should include pedestrian and bicycle demand data to determine if there are statistical differences in non-motorized safety performance.