Quantitative Safety Information on Access Points at Either End of a U-turn Crossover

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Quantitative Safety Information on Access Points at Either End of a U-turn Crossover

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16. Abstract
This study used data from 132 MUTs (264 U-turns) from the State of Michigan to investigate the safety aspects of access control at the U-turn crossovers. Some of the U-turns were access controlled, while others had access. Crash prediction models were estimated utilizing mixed-effects negative binomial regression. The models produced useful results but also had some counterintuitive results. The project team used their best judgment to develop recommended CMFs for selected features of the U-turns. Here is an overview of some of the key findings from the study:

- While the count of access points in the merging directions (where U-turning vehicles merge with oncoming through traffic) were associated with higher crash likelihoods 4.45 percent, 6.94 percent, and 8.67 percent for total, fatal and injury (FI), and property damage only (PDO) crashes, respectively, compared to no access points in merging direction. that in diverging direction (where U-turning vehicles leave the mainline to enter the U-turn segment) was associated with higher likelihood by 5.53 percent for only PDO crashes, compared to no access points.
- Among the different access point types, counts of side streets were associated with higher crash likelihoods by 10.77 percent, 6.05 percent, and 9.96 percent for total, FI, and PDO crashes, respectively, compared to no access points of these types.
- The variable representing whether there was an access point close to the U-turn crossover that allowed vehicle to make a left directly from the U-turn lane was found to be associated with greater likelihoods by 12.99 percent and 25.73 percent for total and FI crashes, respectively, compared to no such access points.
- Increasing U-turn radius was associated with slightly lower likelihood, by only 0.52 percent for total crashes, for each unit (ft) increase of U-turn radius.
- Increase in the number of through lanes at U-turns in the diverging direction was associated with a lower crash likelihood by 12.04 percent for FI crashes only.
- Based on the recommended CMFs, U-turns lanes without left turns as well as higher number of through lanes in diverging directions could be suggested to improve the safety performance.

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EXECUTIVE SUMMARY

The overall purpose of this project is to help NCDOT make optimum decisions on whether to provide / not provide control of access near U-turn crossovers. Following a comprehensive review of the literature, the project team investigated different ways of conducting the research to address the overall purpose. The cross-sectional regression-based approach using data from U-turn crossovers with and without control of access was identified to be the most effective way to address the objectives. With most U-turns in North Carolina being access-controlled, the project team was able to find locations in Michigan where some U-turns were access-controlled while others allowed access.

An inventory identified 370 U-turn segments. These sites had different control types (traffic signal, stop sign, and yield sign) at the U-turn crossovers. These U-turn crossovers are a part of alternative designs, including median U-turn (MUT) intersections, reduced conflict intersections (RCIs), indirect left and cross (ILAC) intersections, and other configurations. Given that the primary objective of this study was to evaluate the safety impact of access points near U-turn segments and consider the functional differences between MUTs and other intersection types (e.g., RCI that redirect both through and left-turn movements), the analysis was limited to MUT sites (152 sites) to ensure consistency and comparability among sites included. Out of the identified 152 MUT sites, 20 sites were excluded due to missing traffic volume data on either the major or minor roads, an essential input for assessing safety performance. The final dataset included 132 MUT sites (equivalent to 264 U-turns) with complete geometric and traffic data for further analysis.

Mixed-effects negative binomial regression modeling was used to relate crash frequency (for total, fatal and injury, and PDO crashes) with site characteristics of the U-turns, including information about access management. The models produced useful results as well as counterintuitive results, and the project team used their judgment in recommending CMFs for specific features of the U-turns. Note that the average crash frequencies for all sites are 5.7 crashes per year, 1.1 crashes per year, and 4.6 crashes per year, for total, FI, and PDO crashes, respectively. Here is an overview of some of the key findings from the study:

1. While the count of access points in the merging directions was associated with higher crash likelihoods for total, FI, and PDO crashes, compared to no access points in the merging direction, that in diverging direction (where U-turning vehicles leave the mainline to enter the U-turn segment) were associated with a higher likelihood for only PDO crashes, compared to no access points in diverging direction. It should be noted that drivers are prohibited from turning directly from a driveway into the U-turn crossover by pavement markings at the U-turn storage lanes. However, some may disregard this, especially where the next U-turn crossover is much farther away.
2. Among the different access point types, while counts of side streets were associated with higher crash likelihoods, that for access points with low turnover rate were associated

with lower likelihoods, consistently for all severities, compared to no access points of these types.

3. U-turns where left turns are allowed directly from the U-turn lanes were found to be associated with greater crash likelihoods compared to scenarios where no left turns are allowed directly for total and FI crashes, but no such effect was observed for PDO crashes
4. Increasing the U-turn radius was associated with slightly lower likelihood of total crashes.
5. A higher number of through lanes at U-turns in the diverging direction was associated with a lower crash likelihood for FI crashes.

Crash modification factors and/or crash modification functions were recommended for the following parameters. The findings of these parameters are summarized in Table 1.

- Number of access points in the merging direction,
- Number of access points in the diverging direction,
- Number of side streets,
- Allowing left turns from the U-turn lane,
- Increase in the radius of U-turns,
- Increase in the number of through lanes in the diverging direction.

Based on the recommended CMFs, U-turns crossovers without left turns as well as higher number of through lanes in diverging directions could be suggested to improve the safety performance.

Table 1. Summary of effects of independent variables on crash likelihoods

Parameter	Total Crashes	FI Crashes	PDO Crashes
Each 1 (one) increase in number of access points in the merging direction	Higher (4.5%)	Higher (6.9%)	Higher (8.7%)
Each 1 (one) increase in number of access points in the diverging direction	No change (0%)*	No change (0%)*	Higher (5.3%)
Each 1 (one) increase in number of side streets	Higher (10.8%)	Higher (6.1%)	Higher (10.0%)
Allowing left turns from the U-turn lanes, compared to no left turns from the U-turn lanes.	Higher 13.0%)	Higher (25.7%)	No change (0%)*
Each 1 (one) ft increase in the radius of U-turns	Lower (0.5%)	No change (0%)*	No change (0%)*
Each 1 (one) increase in number of through lanes in the diverging direction	No change (0%)*	Higher (12.0%)	No change (0%)*

** Depicts statistically insignificant effects*

The last section of the report also identified some promising avenues for future research.

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Chapter 1. Introduction

1.1 Background

The North Carolina Department of Transportation (NCDOT) has installed many U-turn crossovers on arterial roads in recent years. Usually, these crossovers are part of a reduced conflict intersection (RCI), median U-turn (MUT) intersection, or other alternative designs. The NCDOT Roadway Design Manual calls for full control of access on U-turn bulbs' origin and terminal ends. Safety problems may occur when side streets (or driveways) and U-turn crossovers are located at the same location. Though most of the U-turn crossovers in North Carolina (NC) have included control of access on the bulb-out (terminal) side, and many have included control of access on the origin side, purchasing this control of access is expensive, and sometimes it means moving or closing an existing driveway or acquiring an entire property.

With the price of real estate increasing quickly in the metro areas of NC, these purchases can add significantly to project costs, sometimes endangering the viability of projects or meaning that fewer other projects can be constructed. In addition, it is difficult to make the public relations case for a project being good for business when it involves having to take properties, remove driveways, or move driveways that are not in the direct path of the construction. NCDOT's CLEAR (Communicate Lessons, Exchange Advice, Record) program has suggested examining the practice of including full control of access at U-turn crossovers.

1.2 Research Objective and Scope

The current literature on the impact of access points at the end of a U-turn crossover in alternative intersections is limited. In addition, different policies have been adopted by State DOTs in the US. For example, while most U-turn crossovers have full control of access on the bulb-out side in NC, in Michigan (MI), there are many U-turn crossovers (also called Michigan lefts) with no access control to driveways and side streets.

The central questions this proposed study seeks to answer (whether a full control access is required at the end of a U-turn crossover to secure safety, and what the impact of adjacent driveways on safety is at U-turn crossovers) have not previously been resolved comprehensively. In addition, there are also important research questions to answer, such as, (a) is a bulb-out always required to ensure safety in U-turn crossovers, and (b) whether moving a bulb-out from its ideal location (typically 600-800 ft from the middle intersection) to another location is required to miss an access point (such as a driveway or a side street).

Having reliable crash modification factors (CMFs) and a subsequent set of considerations for U-turn crossovers with/without access control would allow NCDOT to make informed decisions on whether to provide access control near a U-turn crossover and where the cost of doing so is not justified.

The overall purpose of this project is to help NCDOT make optimum decisions on whether to provide control of access near U-turn crossovers. To achieve this purpose, the objectives of this research are:

- To develop CMFs for U-turn crossovers with or without access control, and
- To develop a set of considerations to include in the Roadway Design Manual addressing this issue.

1.3 Report Organization

The next chapter of the report provides a summary of previous research. This is followed by an overview of the research methodology. Then, we discuss the data collection and the results of the analysis. Lastly, the report provides the conclusions and future research.

1.4 Abbreviations List

The following abbreviations are utilized throughout the report:

- **AADT:** Annual Average Daily Traffic
- **ADT:** Average Daily Traffic
- **CMF:** Crash Modification Factor
- **DOT:** Department of Transportation
- **EB:** Empirical Bayes
- **FHWA:** Federal Highway Administration
- **FI:** Fatal and Injury crashes
- **IPM:** Improved Prediction Method
- **LTR:** Low turnover rate
- **HTR:** High turnover rate
- **MUT:** Median U-turn
- **NCDOT:** North Carolina Department of Transportation
- **NCHRP:** National Cooperative Highway Research Program
- **RCI:** Reduced Conflict Intersection
- **Redirect L&T Intersection:** Redirect Left and Through from a minor road
- **Reverse RCI:** Reversed Reduced Conflict Intersection
- **SPF**: Safety Performance Function
- **TRB:** Transportation Research Board
- **TRR:** Transportation Research Record
- **TWSC:** Two-Way Stop Controlled Intersections

1.5 Key Terms

1. **Alternative Intersection:** A type of intersection where one or more traffic flows are rerouted from a typical signalized conventional intersection. This modification aims to eliminate or minimize conflict points and to enhance both the functionality of traffic signals and the safety of pedestrians at these signalized intersections (Hughes et al., 2010).
2. **Crash Modification Factors**: A crash modification factor (CMF) is determined through crash analyses associated with a specific countermeasure implemented at a location, comparing crashes before and after the modification. The CMF is a multiplicative factor that indicates the proportion of crashes that would be expected after implementing countermeasures. This factor is utilized to predict the anticipated number of crashes upon applying a similar modification to another road or intersection. This factor enables traffic engineers to evaluate the potential effectiveness of a particular countermeasure at a specific site (Ulak et al., 2020).
3. **Safety Performance Function**: A safety performance function (SPF) is a predictive model for crashes that utilizes the statistical analysis of crash data to forecast crash frequencies. They utilize various traffic and geometry-related variables like AADT, median width, and length. They form the basis of safety analysis based on the application of crash modification factors and crash factors (Ulak et al., 2020).
4. **Full Control Access:** This is a type of access control where prioritization is given to through traffic by allowing access through selected public roads via ramps while restricting grade crossings and direct private driveway connections.
5. **No Control Access:** This is a type of access control where access connections, which may be at-grade or grade-separated, are provided for public roads and private driveways.
6. **EB Before-After Method:** This is a safety evaluation method that takes into account before- and after-period traffic conditions of a crash countermeasure through the utilization of a calibration factor for SPF or a locally developed SPF (Hauer, 1997).
7. **Improved Prediction Method:** This is a four-step approach of safety assessment by taking into consideration traffic conditions before and after the installation of a crash counter measure when there is no SPF (Hauer, 1997).

Chapter 2. Review of Literature

This literature review report is made up of subsections that summarize research on access management at U-turn crossovers, including the development of CMFs and SPFs for various alternative designs involving U-turn crossovers (such as MUT, RCI, reverse RCI, redirect left and through from a minor (Redirect L&T), and thru-cuts). This comprehensive review aims to provide readers with a thorough grasp of existing literature concerning the safety performance of U-turn crossovers across different intersection designs, the influence of access control at these points, and the necessary steps required to advance the implementation of access management strategies at U-turn crossovers.

The literature review consists of published reports from FHWA and NCHRP, scientific articles, and documents from the state DOTs. This section of the literature review comprises two main categories: 1) studies done on access management at U-turn crossovers of signalized intersections, and 2) studies done on the safety performance of RCIs and MUTs. As presented in **Error! Reference source not found.**, the research team found 19 publications related to the access management of U-turn crossovers at signalized intersections, and the safety performance of the MUTs and the RCIs to find possible answers to the questions provided in the introduction of this report.

Table 2.1. Total number of reviewed publications

Category	Number of Publications
Access management at U-turn crossovers of signalized intersections	7
Safety performance of U-turn crossovers in alternative intersections, such as RCIs and MUTs	12
Total	**19**

2.1 Access Management at U-turn Crossovers of Signalized Intersections

Access management significantly influences how well arterial roads perform in balancing the movement of traffic and the accessibility of adjacent properties. Improvements in access control have been shown to not only bolster safety and capacity but also that roads lacking proper access control tend to have inferior safety and operational performance compared to those with more improved access management. As transportation infrastructure ages, the need for improved access becomes more pronounced due to heightened demand.

The FHWA signalized intersections informational guide (Chandler et al., 2013) provided strategies to enhance access management around intersections, within a 250-foot range upstream or downstream, which included alterations in infrastructure, design, or signage. These changes aim to limit or consolidate driveways, create dedicated turning lanes, or regulate and reposition turning movements. Driveways offering full access should preferably be situated outside the operational zones of two nearby signal-controlled intersections. Some of the key considerations when assessing driveway placement, as proposed by the FHWA signalized intersections informational guide (Chandler et al., 2013) include:

- The volume and nature of traffic utilizing the access or driveway
- Possible conflicts with adjacent driveways
- Existing crash types and severity in the vicinity, and
- Traffic volume on the main road

It is crucial to emphasize that the elimination of driveways should not solely rely on general guidelines but should instead undergo engineering evaluation, accounting for broader system impacts. Closing driveways without considering these effects may merely shift the issue to another location. Additionally, as a rule of thumb, the operational area around an intersection holds greater significance along corridors with higher speeds (posted at 45 mph or more) primarily focused on facilitating traffic flow (Chandler et al., 2013). There will be a high possibility of angular collisions in situations where driveways and accesses are haphazardly placed, emphasizing the paramount importance of safety considerations.

Lu et al. (2001) assessed the safety effects of either making direct left turns or making right turns followed by U-turns for left-turning vehicles at driveways/side streets. The analysis of safety aspects focused on traffic conflict data, while separate reports were created for crash data and operational analyses. Ten (10) specific locations were chosen for data collection, which was conducted using video cameras. Nine (9) distinct types of conflicts linked to left turn movements were considered, and the average number of conflicts and conflicts per thousand vehicles involved were calculated from the gathered data. The average hourly conflicts for direct left turns were 6.35, while for right turns followed by U-turns, it was 4.2. Notably, these differences were more pronounced during peak traffic periods. When considering conflicts per thousand vehicles involved, the averages were 30.2 for direct left turns and 18.7 for right turns, followed by U-turns. Furthermore, a comparison was made before and after implementing a median closure, allowing only right turns followed by U-turns at a specific site. Results indicated a nearly 50% reduction in the total average hourly conflicts by replacing direct left turns with right turns followed by U-turns. Additionally, the severity of conflicts during the post-implementation period was significantly lower than before.

Blaschke et al. (2022), in their NCHRP Report No. 977, provided guidance and techniques regarding access management in the vicinity of interchanges, terminal intersection key factors, corridor characteristics, and assessment methodology. However, the development of empirical SPFs and CMFs was not feasible because of the small sample size of case studies. Based on crash trends observed, it was found that rear-end and angle crashes are among the most common crash types in the vicinity of interchanges (at driveway locations and median openings). Most crashes were also found to be property damage only (PDO) or possible injury. Several sites were also involved with pedestrian and bicycle crashes, especially at driveways between the terminal intersection and the next intersection away from the interchange.

In another similar recent study, Dixon et al. (2020), in their NCHRP Report No. 929, conducted a study to more accurately measure the performance of unsignalized median openings in terms of their operation and safety located close to both the downstream and upstream of intersections with one or more turning bays. The report identified parameters impacting the safety of median openings near intersections based on data collected in five states: Arizona, Kansas, Missouri, Pennsylvania, and Texas. According to the results, the number of driveways and side streets, U-turn type, and the number of arterial traffic lanes could impact the minimum required spacing between a median opening and the intersection.

Dixon et al. (2020) highlighted that the best approach to resolve the challenge of a continuous raised median is to introduce mid-block median openings, which will enable U-turn crossovers and metered left turns at very strategic spots. However, inasmuch as U-turn crossovers can resolve these challenges, they may also pose some safety threats, such as safe access to these corridors within the enclave of the median opening to road users of adjacent properties. There is less flexibility for emergency vehicles in accessing adjacent properties to the opposite direction of travel lanes (Dixon et al., 2020). There will also be a need for the construction of an additional pavement (loon) to accommodate heavy vehicles that may experience difficulty when using unsignalized U-turn crossovers to avoid direct conflicts with opposing vehicles and create enough space for turning (Lu et al., 2001). This may create controversies with adjacent property owners who may be required to sell their properties to make room for turning space.

On the other hand, Potts et al. (2004) argued that loon operations did not have any relatable specific problems in their evaluation of several unsignalized median openings with loons. They highlighted that while directional midblock median opening with left turn lanes and loons had a relatively higher average median-opening crash rate than directional midblock median opening with left turns, crashes at the openings of the former did not involve trucks and were not caused because of the use of the loons (this was determined after reviewing the crash narratives and details). Based on the study of Potts et al. (2004), even though the sample size utilized was very limited, there was nothing to indicate that safety challenges were going to be created when loons and their usage by large trucks are provided at median openings.

According to Reid et al. (2014), potential conflicts may arise at locations where directional crossovers are aligned with driveways or accesses to businesses. This conflict can also occur between vehicles that complete the U-turn crossovers and vehicles making a right turn at locations where an intersection aligns with the U-turn crossover. To address this challenge, distinct signal phases for each movement can be utilized, as determined by an engineering study (Reid et al., 2014).

Liu et al. (2008) carried out studies on 140 road sections in Florida aimed at exploring how the distance between driveways and MUT locations affects safety. The separation distances at selected sites ranged from 32m (105 ft) to 380m (1,247 ft) with a mean of 142m (491 ft). The findings revealed that for every 10% increase in the distance between these locations, there was a corresponding 3.3% decrease in overall crashes. The reported percentages represent the expected change in crashes associated with a 10% increase in the separation distance between driveways and MUTs based on the coefficients from the negative binomial regression model developed in the study. The models are written below:

$Y_1 = 0.347 (X_1)^{(1.0883)} (X_2)^{(-0.4880)} \exp(0.54X_3)$

$Y_2 = 0.117 (X_1)^{(1.2669)} (X_2)^{(-0.3545)} \exp(0.4497X_3)$

Where:

- Y_1 = expected number of target crashes in a street segment per year
- Y_2 = expected number of total crashes in a street segment per year
- X_1 = ADT per year in thousands
- X_2 = separation distance (m)
- X_3 = 1 if U-turns are provided at a signalized intersection; 0 otherwise

For the total crash model, the coefficient for the logarithm separation of distance β = -0.3545. Using the standard interpretation for log-transformed variables:

$\%\Delta Y = ((1 + p)^{\beta} - 1) \times 100$

where p = 0.10 (10% increase). Substituting, we obtain:

$\%\Delta Y = (1.10^{(-0.3545)} - 1) \times 100 = -3.3\%$

This indicates that a 10% increase in separation distance is expected to reduce total crashes by 3.3%. For example, if a segment experiences 100 total crashes per year, increasing separation by 10% would reduce crashes to approximately 97 per year.

These numerical examples demonstrate how increases in separation distance between driveways and MUTs lead to measurable reductions in both total and target crashes, confirming the safety benefits of providing longer maneuvering distances for vehicles making U-turns.

2.2 Safety Performance of U-turn Crossovers

This section presents literature related to the safety performance of U-turn crossover designs. Specific intersection designs that utilize U-turn crossovers discussed in this section include the following: reduced conflict intersections (RCI), median U-turn (MUT), thru-cut, reverse RCI, and redirect L&T. The following paragraphs summarize past studies on the safety performance of these alternative intersections.

It should be noted that there are other U-turn-based alternative intersections, such as the seven-phase intersection (Hummer et al. 2019) or combination designs like the displaced left-turn and median U-turn (DLT/MUT) intersection (Osafo-Gyamfi et al. 2025). While these alternatives were excluded from the current literature review, a recent NCDOT project (2023-20) has provided information on those designs. Readers are encouraged to read that report (Rasdorf et al. 2024) for more details on other alternative designs with U-turn crossovers.

2.2.1 Reduced Conflict Intersections (RCI)

The RCI, also known as the superstreet, J-turn, synchronized, or restricted crossing U-turn (RCUT) intersection, is a type of alternative intersection treatment where both through and left-turning traffic from the minor road make a right turn into the major road and negotiate a U-turn downstream. However, left turn movements from the major road are allowed at the main intersection, similar to the conventional intersection (Hughes et al., 2010). **Error! Reference source not found.** shows the typical layout of an RCI, with redirected movements highlighted in blue and red, respectively (Rasdorf et al. 2024).

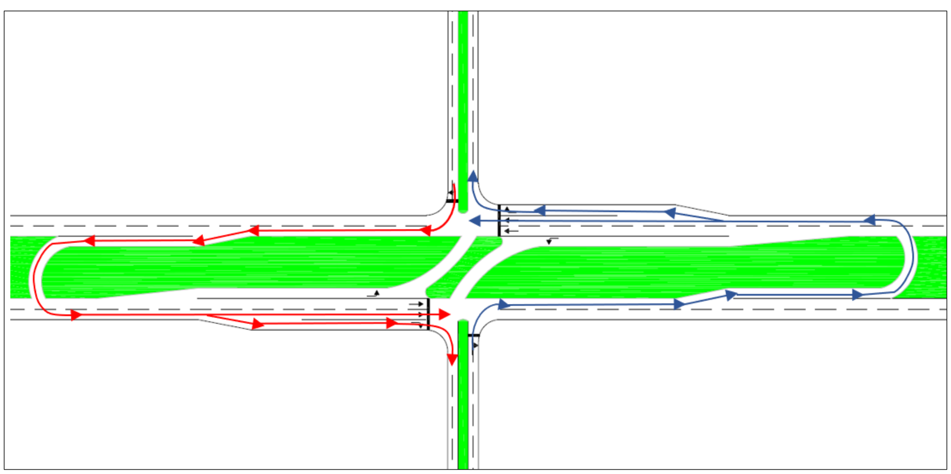

Figure 2.1 Geometry of RCI Intersection with Redirected Movements (Rasdorf et al. 2024)

RCI is an example that has proven to have several safety benefits, including reduced conflict points, increased distance between conflict points (more reaction time for drivers), and perfect signal progression (with almost perfect bandwidths) on the major street in both directions (Sun et al., 2019). A signalized RCI could also manage speed and decrease stops, which leads to safety improvements.

In 2010, Hummer et al. (2010) used an EB before-after study to evaluate the safety of signalized and unsignalized RCI intersections. A crash reduction of 46.2% was estimated for the conversion of typical unsignalized intersection with unsignalized RCI. Also, a reduction of 63% (CMF= 0.37) of FI crashes was estimated for replacing unsignalized intersections with unsignalized RCIs.

Edara et al. (2013) assessed the efficacy of the RCI designs in Missouri that were replaced with two-way-stop controlled intersections (TWSC). An EB (empirical bayes) before-after safety analysis was used to evaluate the crash data of five RCI sites in Missouri by the researchers. A traffic conflict analysis and a public survey were also utilized in the evaluation process. Their evaluation indicated that the implementation of the RCI design led to a notable 34.8% decrease in overall crash frequency and a significant 53.7% drop in fatal and injury (FI) crashes, all at a 95% confidence level. Disabling injury crashes per year were reduced by 86%, while minor injury crashes decreased by 50%. It is important to highlight that none of the five sites experienced fatal crashes post-RCI implementation. Right-angle crashes also dropped by 80%. The analysis also indicated that the average time to collision (TTC) for minor road turning vehicles was four times higher at the RCI sites compared to the control sites, highlighting improved safety. Some of the concerns raised through a public survey centered on merging difficulty after the U-turn, improper use of acceleration and deceleration lanes, limited U-turn radius for larger vehicles, and driver confusion.

More recently, Mishra & Pulugurtha (2022), assessed the safety performance of RCIs in rural and suburban areas by utilizing the EB before-after method. They evaluated 42 RCIs' safety effectiveness from a TWSC intersection or signalized intersection in rural and suburban areas. The results indicated a significant reduction in crash rates: a 70.63% decrease in total crashes and a 76.10% drop in FI crashes at unsignalized stop-controlled RCI. In suburban areas, there was a 64.86% decrease in total crashes and a 73.39% drop in FI crashes at unsignalized stop-controlled RCIs. Additionally, a 10.15% and 31.08% reduction in total crashes, and an 84.26% and 41.31% decrease in FI crashes were noted at a signalized RCI in rural and suburban areas, respectively.

In a recent study conducted on nine unsignalized RCIs located on high-speed rural highways in Mississippi (Molan et al. 2025a), CMFs estimated showed reductions from 40% to 56% for total crashes and from 57% to 75% for fatal and injury (FI) crashes. Estimating an average construction cost of about $3.8 million for the implementation of RCIs in Mississippi, a benefit-cost ratio equal to 19.4 was estimated.

Sun et al. (2019), in their study on the safety analysis of RCIs, evaluated the safety benefits of six RCIs in Louisiana by focusing on the entire RCI system, which consists of the intersection and its U-turns and the segments separating them. The evaluation of the safety performance of the RCIs was achieved by conducting a before-after crash analysis at the RCI only and the RCI system for a period of three years. The analysis revealed a total decrease in fatalities, a 41.15%

decrease in injury crashes, and a 22.3% reduction in property damage-only (PDO) crashes, specifically at the RCUT intersection.

The safety effectiveness of the RCI was determined in terms of the CMFs by utilizing the Improved Prediction Method (IPM) and the Empirical Bayes (EB) method. Utilizing the IPM method, which is essentially a before-after evaluation technique that improves crash predictions by accounting for regression-to-the-mean and traffic growth, the CMFs obtained for both the RCI-only and the RCI system were 0.69 and 0.86, respectively. A CMF value of 0.80 was obtained using the EB method focused on the RCI only because segments and intersections were treated separately, and the U-turn had no SPF.

2.2.2 Median U-turn (MUT)

Also referred to as the Michigan left, median U-turn (MUT) is a design where direct left turns are replaced by indirect left turns made through a downstream U-turn. **Error! Reference source not found.** illustrates the geometry of a typical MUT (Rasdorf et al. 2024). It should be mentioned that **Error! Reference source not found.** shows a typical MUT design with two critical signal phases at the middle intersection (due to redirecting left turns from all four approaches); however, there are also other variations of MUTs with a three-critical-phase traffic signal at the middle intersection due to redirecting left turns only on one direction (either only from major road, or only from minor road).

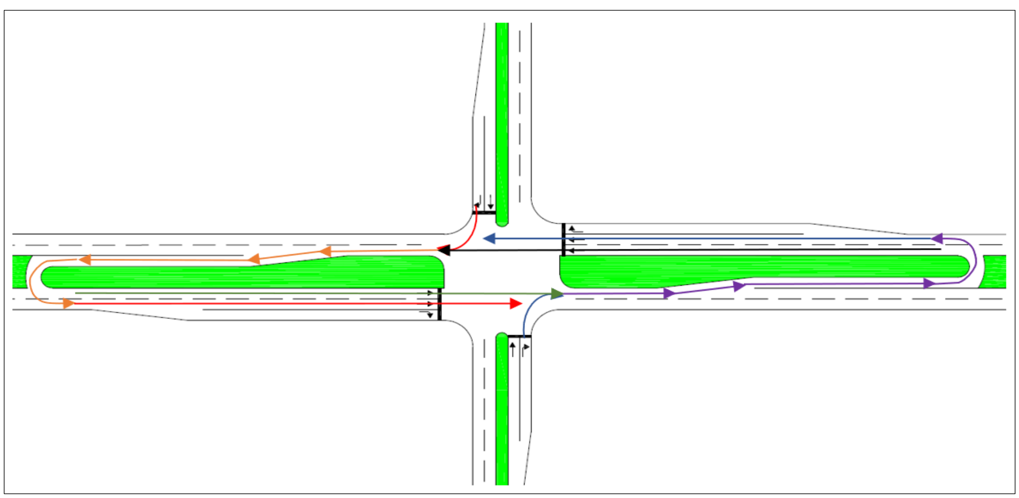

Figure 2.2 Geometry of MUT Intersection with Redirected Movements (Rasdorf et al., 2024)

To evaluate the safety performance of MUTs, Al-Omari et al. (2020) considered a large sample of case studies, including over 70 MUTs in Michigan, North Carolina, and Ohio, to evaluate the safety performance of MUTs. MUT intersections performed well in reducing total, PDO, rear-end, and opposite-direction sideswipe crashes. The CMF value for overall crashes in four-leg signalized intersections replaced by MUT intersections is estimated at 0.63. The CMF value for the fatal and injury crashes obtained is estimated at 0.77.

Jagannathan (2007) produced a synthesis of 25 studies conducted by various researchers. The report summarizes the benefits and drawbacks of the MUT in comparison to the signal-controlled conventional intersection, where permitted left turns are allowed on all approaches. It reported a reduction rate of 17%, 96%, and 61% for rear-end, angle, and sideswipe crashes on a similar conversion with conventional designs. Sourced primarily from the Michigan Department of Transportation (MDOT), he presents the design guidelines for the positioning and design of median crossovers, loons, directional, and bidirectional crossovers. The document covers the standards for applying MUTs, details about capacity and crashes at these intersections compared to conventional intersections, and considerations regarding signal phasing at median openings and traditional intersections.

Kay et al. (2022) conducted a study to quantify safety performance and develop analytical tools related to MUT intersections. Traffic crash data from signalized and unsignalized MUT intersections in Michigan was collected. To enable comparison with conventional designs, data from reference conventional intersections was also collected. The data analysis involved comparing conventional and MUTs with a focus on safety variations among different MUT design features. The analysis covered crash rates, types, severity distributions, patterns of severe injury collisions, and the development of safety performance functions and CMFs. The CMFs of 0.438 and 0.686 for fatal and injury crashes were estimated when implementing an unsignalized undivided two-lane two-way and an unsignalized divided four-lane into an MUT, respectively. In replacing the signalized intersection with undivided approaches to signalized MUTs, a CMF value of 0.656 was suggested for FI crashes and a CMF of 0.684 for PDO crashes.

Dixon et al. (2020) evaluated the safety analysis of unsignalized full median openings in close proximity to signalized intersections by conducting both quantitative and qualitative crash analyses based on data collected on some selected sites in five states: Arizona, Kansas, Missouri, Pennsylvania, and Texas. The quantitative analysis focused on crashes that occurred within the vicinity of unsignalized full median openings with at least one turn bay situated close to a signalized intersection. The main aim was to assess the quantity and severity of crashes that take place at these median openings with the objective of determining whether safety performance factors or crash modification factors (CMFs) could be developed. This was achieved by performing a corridor approach crash analysis based on data from the Arizona and Texas study sites, as well as other comparison sites with similar approaches in the same geographical location with similar average daily traffic (ADTs). In the analysis of the approach corridor safety, a correlation test that resulted in prospective variables was performed prior to conducting a statistical regression analysis. An unexpected revelation in all the safety analysis indicated that for any of the crash prediction models, the length of road from the median openings to the signalized intersections was insignificant.

The crash analysis for the Texas and Arizona intersection approaches led Dixon et al. (2020) to make several observations. The median opening type, the number of adjacent through lanes, the ADT, and the location of bus stops were all major variables in the Arizona-only total crash model. The facility speed limit and the bus stop variable also appeared to have a very strong correlation. The median opening type, the number of adjacent through lanes, and the ADT were significant variables in the Texas-only total crash model. The median opening type, the number of adjacent through lanes, and the ADT were included in the combined Arizona and Texas crash model. A positive coefficient was obtained for the median opening type and the ADT variable for the combined model, whereas the number of through lanes was found to be negative. Due to the limited sample size, there were relatively few injury crashes at the study sites, resulting in equations that produced a very low number of estimated crashes.

2.2.3 Redirect Left and Through (L&T)

Error! Reference source not found. shows the geometry of a redirect left and through (L&T) intersection (Rasdorf et al. 2024). This design redirects both the through and left turn movements of one of the approaches on the minor road to a downstream U-turn crossover on the major road of the intersection.

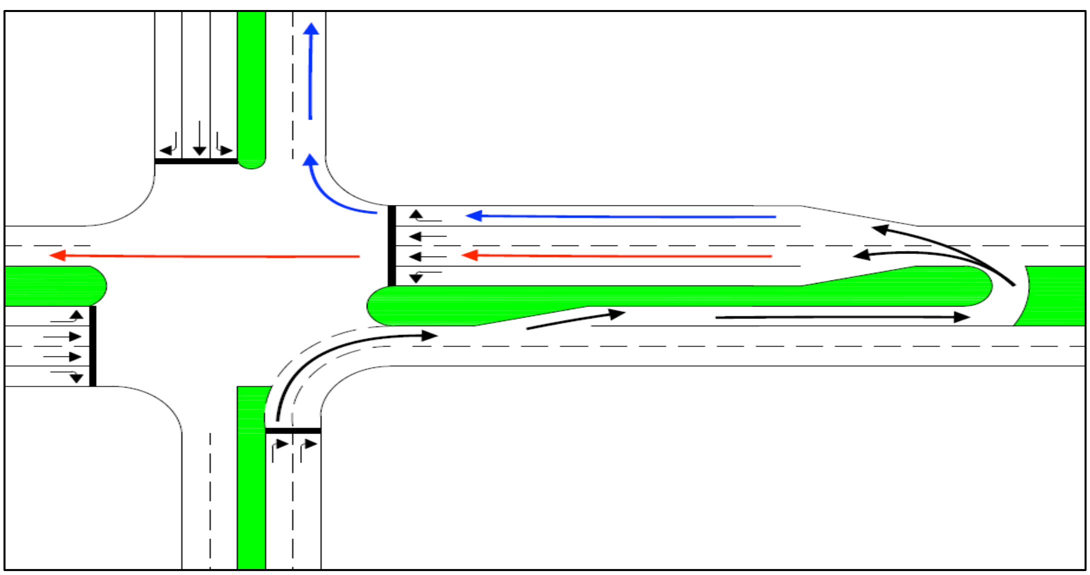

Figure 2.3 Geometry of a Redirect L&T Intersection (Rasdorf et al., 2024)

A recent publication (Molan et al. 2025b) showed high potential for improving traffic operations for the redirect L&T intersection compared to the conventional intersections. Also, the design has been included in another project (NCDOT Project 2023-20) by NCDOT (Rasdorf et al. 2024). It is important to highlight that the redirect L&T reduces the number of conflict points to 22 (ten conflicts fewer than the conventional design). Based on the literature review conducted in the

NCDOT Project 2023-20, there are at least three redirect L&T intersections in Lafayette, Louisiana: University Ave/Surrey St & US 90, E Verot School Rd & US 90, and Southpark Rd & US 90. The research team contacted the Louisiana DOT (LaDOTD) and learned that there are no CMFs developed yet for this type of alternative intersection in Louisiana; however, the safety analysis conducted on the same corridor with seven signalized intersections (including the three Redirect L&T intersections) showed significant crash reduction rates after implementing the new intersections on the corridor.

2.2.4 Thru-Cut

The thru-cut design (shown in Figure 2.4) redirects only minor street through movements (to the possible U-turn crossovers, or adjacent streets), retaining the left turn lanes for major street approaches. Based on the authors' knowledge, there are at least seven existing thru-cut intersections in North Carolina, Virginia, and Maryland. Also, in US-220 south of Roanoke in Virginia, six existing intersections will be replaced with thru-cuts. However, it should be mentioned that none of the thru-cut intersections in NC have U-turn crossovers. Some expected benefits of these conversions are higher capacity and fewer conflict points. Unfortunately, there is no CMF for thru-cut intersections currently; however, an initial crash analysis conducted by the NCDOT Safety Unit showed significant safety benefits for the thru-cut located in Holly Spring, NC.

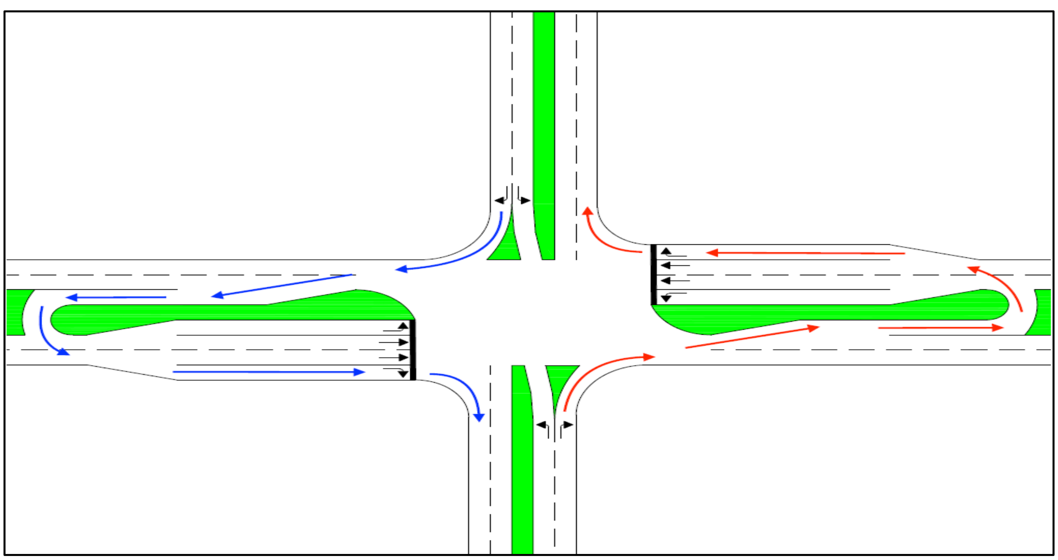

Figure 2.4 Geometry of Thru-Cut Intersection with Redirected Movements (Rasdorf et al., 2024)

2.2.5 Reverse RCI

The reverse RCI (shown in **Error! Reference source not found.**) redirects four traffic movements: through movements from each intersecting minor street and the left turn traffic from the major street. The reverse RCI design has only 14 conflict points, which is one of the lowest numbers among all the intersections, and good service for pedestrians could also be expected in a reverse RCI. Similar to thru-cut intersections, there are only a few real-life reverse RCIs, and there are no CMFs yet. Based on the study done by Luo et al. (2025), the reverse RCI could result in significantly lower travel times than the conventional intersection design; however, the overall travel time performance was not found to be as good as RCI and MUT designs in high-demand scenarios.

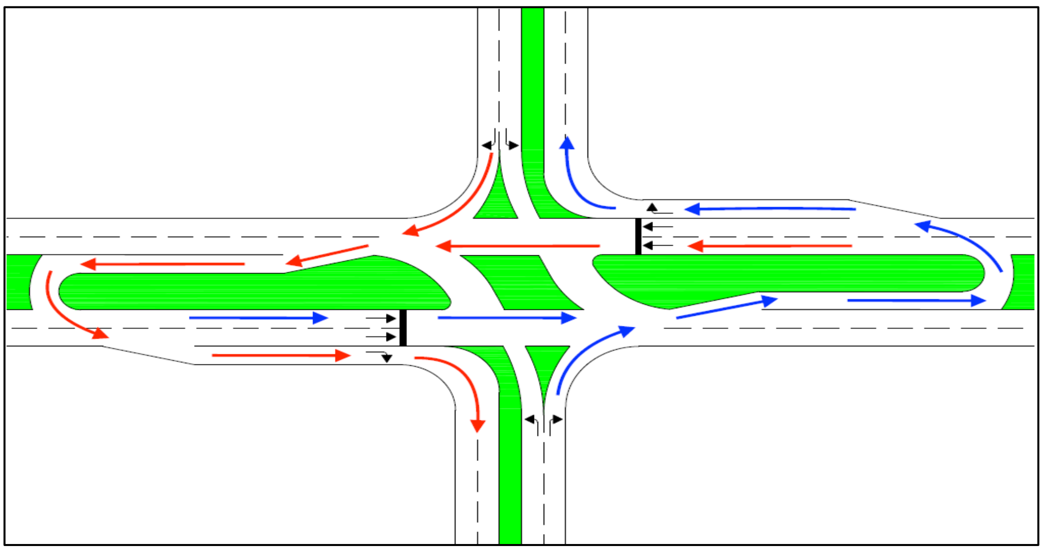

Figure 2.5 Geometry of Reverse RCI with Redirected Movements (Rasdorf et al., 2024)

2.3 CMF Dataset

As outlined in the proposal submitted to NCDOT in September 2022, the research team aimed to create a CMF dataset using information from previous studies related to CMFs developed in various intersections with U-turns. The primary objective was to categorize CMFs developed at U-turn crossovers with and without access points. However, upon reviewing past studies, only one of them provided a specific CMF for each of the included locations. **Error! Reference source not found.** presents a summary of CMF data obtained for six signalized RCIs from the review of the paper by Hummer et al. (2017).

Table 2.2. CMF Dataset for RCIs with/without Access Points Based on Hummer et al. (2017).

Location		Type of Intersection	U-turn 1			U-turn 2			CMF		AADT	
Site# / State	Name of Intersection		AP Count	Type of AP	U-turn spacing	AP Count	Type of AP	U-turn spacing	Overall	Injury	Before	After
1. North Carolina	US-421 south of Piner Rd., Wilmington	Signalized RCUT	9	Residential/ Business	1300	2	Residential/ Business	900	0.64-0.76	0.34-0.41	36,000	38,000
2. Alabama	US-231 NW of Dothan at Retail Dr	Signalized RCUT	3	Business	600	6	Business	900	0.15 – 0.17	0.23-0.26	36,000	38,000
3. Ohio	OH-4 in Hamilton at Hamilton-Mason Rd.	Signalized RCUT	0	N/A	1000	0	N/A	1050	0.15 - 0.47	0.17 – 0.22	12,000	17,000
4. Ohio	OH-4 in Hamilton at Tylersville Rd.	Signalized RCUT	0	N/A	1000	0	N/A	1000	0.57 – 0.64	0.62 – 0.69	20,000	17,000
5. Ohio	OH-4 in Hamilton at Symmes Rd	Signalized RCUT	0	N/A	850	0	N/A	850	1.2 – 1.49	1.24-1.9	20,000	25,000
6. Alabama	US-231 NW of Dothan at Plum Rd	Signalized RCUT	4	Business	850	0	N/A	750	0.51 – 0.56	0.45 – 0.55	26,000	27,000

AP=Access point

Overall, based on the study by Hummer et al. (2017), a CMF of 0.85 was estimated for total crashes and 0.78 for injury crashes. However, these CMFs did not exhibit statistical significance at the 95% or 90% confidence levels. The methodology utilized in the study was the before–after analysis with comparison sites. Data was collected from eleven (11) treatment sites in Alabama (AL), North Carolina (NC), Ohio (OH), and Texas (TX), which were characterized by suburban conditions with either high-speed six-lane or four-lane divided arterials with very little pedestrian crossings. However, it is important to highlight that during the review, the authors realized that out of the eleven RCIs proposed for the study, five RCIs no longer exist. They all had been replaced with Texas U-turn interchanges, possibly due to the high traffic demands at those sites. Therefore, **Error! Reference source not found.** only included the RCIs that still exist, while

Error! Reference source not found. shows the location of the five replaced RCIs identified, the number of access points, and the type of access for each U-turn crossover (before converting the RCIs to the Texas U-turn interchange design), the corresponding CMF for each of those RCIs, and the AADT for the before and after traffic condition resulting from the implementation of the RCI when the before/after study was conducted in 2017 (Hummer et al., 2017).

Reviewing **Error! Reference source not found.** and **Error! Reference source not found.**, the authors did not observe a specific trend or relationship concerning the impact of access points at U-turn crossovers on safety. For instance, based on **Error! Reference source not found.**, site #1 (in NC) has 12 access points at the U-turn crossovers, while the CMFs ranged between 0.64-0.76 for all crashes and 0.34-0.41 for injury crashes, respectively. Conversely, at site #5 (in **Error! Reference source not found.**), where there are no access points at the U-turn crossovers and the AADT is lower than at site #1, a CMF of 1.24-1.9 was identified. However, it is essential to note that these observations and findings might differ with a larger sample size, and **Error! Reference source not found.** and **Error! Reference source not found.** only includes 11 intersection sites.

Table 2.3. Replaced RCIs Identified in Hummer et al. (2017)

Location		Intersection	U-turn 1			U-turn 2			CMF		AADT	
Site# / State	**Name of Intersection**	**Existing Design**	**AP Count**	**Type of AP**	**U-turn spacing**	**AP Count**	**Type of AP**	**U-turn spacing**	**Overall**	**Injury**	**Before**	**After**
1. Texas	US-281 North of San Antonio at Stone Oak Pkwy./TPC	Texas U-turn Interchange	2	Business	1100	3	Business	1300	1.16 – 1.2	1-1.13	80,000	89,000
2. Texas	US-281 North of San Antonio at Evans Rd	Texas U-turn Interchange	5	Business	1050	2	Business	1050	0.97– 1.2	1.2 - 1.27	104,000	110,000
3. Texas	Loop-1604 West of San Antonio at Shaenfield Rd	Texas U-turn Interchange	1	Business	1300	1	Business	1300	0.72	0.5 – 0.7	58,000	79,000
4. Texas	TX-71 in Del Valle East of Austin at FM-973/Fallwell Ln	Texas U-turn Interchange	0	Business	1150	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5. Texas	Loop-1604 West of San Antonio at New Guibeau	Texas U-turn Interchange	2	Business	1500	N/A	N/A	N/A	0.48– 0.5	0.33 – 0.38	68,000	83,000

AP=Access point

2.4 Conclusions from the Literature Review

The underlisted summary highlights the key findings of the literature review:

- Driveways offering full access should preferably be situated outside the operational zones of nearby signal-controlled intersections.
- When assessing driveway placement, the volume and nature of traffic utilizing the access or driveway, possible conflicts with adjacent driveways, existing crash types and severity in the vicinity, and traffic volume on the main road must be taken into consideration.
- Rear-end and angle crashes are among the most common crash types in the vicinity of driveways and median openings.
- The number of driveways and side streets, U-turn type, and the number of arterial traffic lanes could impact the minimum required spacing between a median opening and the intersection.
- For every 10% increase in the distance between driveways and MUTs, there was a corresponding 3.3% decrease in overall crashes according to one study.
- Upon reviewing CMFs and SPFs developed for RCIs and MUTs across various states—each with its distinct policies regarding access points at U-turn crossovers—it appears that a CMF lower than one should be expected even for the RCIs and MUTs with access points at the U-turn crossovers. Nevertheless, since a definitive CMF is unavailable (for U-turns with access points), a comprehensive study is necessary to draw a conclusive statement (which is the primary objective of the current project).

2.4.1 Gaps in Literature

While valuable work has been done on the safety performance of signalized and unsignalized intersections with U-turn crossovers, specifically RCIs and MUTs and some studies done on access management, coursing through the literature revealed the following gaps:

- Limited literature on the impact of access points at a U-turn crossover of both signalized and unsignalized intersections.
- Limited literature on the development of CMFs for the newer alternative intersections with U-turn crossovers, such as thru-cut and reverse RCI.
- Limited literature on the impacts of bulb-outs on the safety of U-turn crossover locations.

Chapter 3. Overview of Methodology

With the overall goal of determining the safety effect of access control at the U-turn locations, there were at least two ways of conducting the research. One is a before-after analysis; in this approach, the intent is to find locations where the access control has changed over time. The project team explored this approach, but it was not feasible because it was very difficult to find a sufficient number of locations where such a change occurred. Additionally, most U-turn segments in Michigan were constructed decades ago (some more than 50 years ago), making a before–after study even more challenging.

The alternative approach is to conduct a cross-sectional analysis; in this approach, data are compiled for intersections with U-turns where some of the U-turns have access while other U-turns are access-controlled. Typically, with this approach, crash prediction models are estimated where the independent variables include AADT, relevant site characteristics, and information on access control, including the number and type of driveways if access is provided. Negative binomial regression is the usual model form that is used in these types of crash prediction models. Further details about the model structure are provided below.

Since North Carolina has primarily controlled access in the U-turns, it was not possible to find many U-turns with access. Hence, data from North Carolina could not be used. Fortunately, the project team was able to find intersections in Michigan where some U-turns had access while some U-turns had controlled access.

3.1 Development of Crash Prediction Models and Crash Modification Factors

Traditional linear regression techniques are generally inappropriate as crash data are comprised of non-negative integers. As an alternative, the Poisson distribution provides a starting point for the analyses. In the Poisson model, the probability of segment i experiencing y_i crashes in one year can be expressed as

$$P(y_i) = \frac{exp(-\lambda_i)\lambda_i^{y_i}}{y_i!} \qquad \text{(Equation 1)}$$

where P(y_i) is the probability of segment i experiencing y_i crashes, and λ_i is the Poisson parameter or the expected number of annual crashes for segment i, E[y_i]. The Poisson regression model relates the expected number of crashes on a segment, λ_i , to a function of explanatory variables, expressed as

$$\lambda_i = exp(\beta X_i) \qquad \text{(Equation 2)}$$

where X_i is a vector of explanatory variables and β is a vector of estimable parameters. A limitation of the Poisson distribution is the assumption that the mean and variance are equal, which often is not the case with crash data. Commonly with crashes, variance exceeds mean, leading to "overdispersion". The negative binomial model addresses this overdispersion by adding an unobserved heterogeneity term as,

$$\lambda_i = exp(\beta X_i + \varepsilon_i) \quad \text{(Equation 3)}$$

where $exp(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The inclusion of this term essentially allows the variance to differ from the mean as

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

This α is termed the overdispersion parameter. In the safety analysis, negative binomial regression models have been widely used (Hauer et al. 1988, Persaud and Dzbik, 1993; Oh et al., 2003) and accepted as the current practice for modeling crashes, as such models account for overdispersion. The negative binomial models in this analysis are used to develop crash modification factors (CMFs). CMFs represent the change in crashes associated with a unit change in a predictor variable. These factors are typically the ratio of the expected values of crashes with and without the change. The CMFs can be expressed as

$$CMF = \exp(\beta_j) \quad \text{(Equation 5)}$$

where β_j is the regression coefficient associated with the variable j. In this study, the CMFs were developed directly from the coefficients of the negative binomial models. CMF values less than 1.0 indicate that alternative treatment reduces the estimated average crash frequency compared to the base condition and vice versa.

Recently, mixed-effects negative binomial models have gained popularity due to the capability of accounting for spatial effects and heterogeneity across observations (Shankar et al., 1998). Unobserved heterogeneity can be defined as unknown variability in the effect of variables across the sample population (Stapleton et al., 2018, Chakraborty and Gates, 2020, 2023). It is imperative to address this issue of unobserved heterogeneity to avoid erroneous predictions resulting from the biased estimated parameters (Mannering et al., 2016). The issue with non-random sampling and unobserved heterogeneity in the data is addressed by including a combination of intersection ID- and year-specific random effects (intercepts) in the negative binomial models, effectively developing mixed-effects models. In a mixed-effects model, each intercept is drawn at random from the intercept distribution and is independent of the error term for any particular observation and uncorrelated with the independent variables.

Chapter 4. Data Collection

This chapter presents the procedures used for data collection and the methodology adopted to assess the impact of access points near the U-turn crossovers from existing Median U-turn (MUT) intersections in Michigan. It outlines the criteria for site selection, the process of collecting geometric and traffic data, and the identification and processing of the most recent years of readily available crash data over a five-year period (2019–2023). In addition, detailed information on access point characteristics was compiled to support access-related safety analysis.

4.1 Data Collection

The following sections elaborate on the site selection process and the data collected from MUTs in Michigan, including traffic and geometric features, historical crash data, and access point information.

4.1.1 Site Selection

The selection of study sites was a critical first step to ensure the analysis was conducted on locations representative of real-world U-turn configurations with varying access conditions. Sites were identified based on the presence of median U-turn (MUT) crossovers designed to accommodate redirected left-turn movements. The focus was to select MUT locations representing a range of conditions based on variables such as control type, number and location of access points, traffic demand, and area type (urban, suburban, or rural). Sites were chosen where detailed data (crash, traffic, and geometric data) could also be collected reliably. Additional consideration was given to the availability of access point data, roadway characteristics, and satellite imagery to support remote data collection.

It is important to note that the site selection was based on the presence of only one U-turn crossover on the same approach on the major roads across the state of Michigan. Therefore, U-turn segments with two U-turn openings on the same side of the intersection were excluded based on the scope of this study. **Error! Reference source not found.** illustrates an intersection with a U-turn segment with two U-turn openings on the left side of the network, compared to a segment with a single U-turn opening on the right side of the same intersection. It is important to note that there are also two U-turn openings on the northbound and southbound approaches of the same intersection shown in **Error! Reference source not found.**, although the full extent of those U-turn segments is not visible in the figure.

Figure 4.1 The Intersection of Warren Ave and 3rd Ave with Two U-turn Openings (on the Left Side) and One U-turn Opening (on the Right Side) in Detroit, Michigan

The map in **Error! Reference source not found.** shows the locations in Michigan where the study sites were identified. An inventory identified 370 U-turn segments. These sites had different control types (signal, stop sign, and yield sign) at the U-turn crossovers. These U-turn crossovers are a part of alternative designs, including median U-turn (MUT) intersections, reduced conflict intersections (RCIs), indirect left and cross (ILAC) intersections, and other configurations, as summarized in **Error! Reference source not found.**.

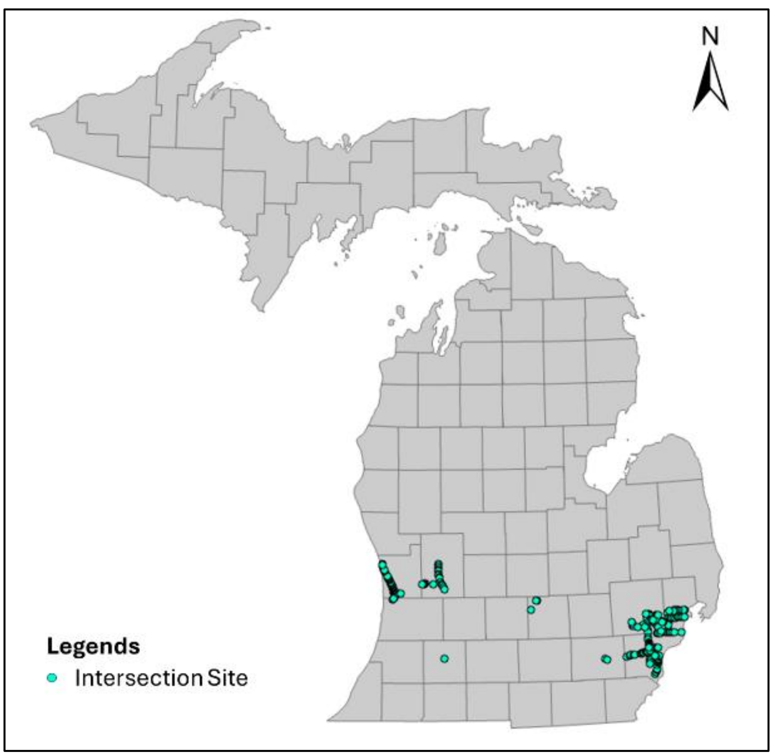

Figure 4.2 Location of U-turn Sites Selected in Michigan

Given that the primary objective of this study was to evaluate the safety impact of access points near U-turn segments rather than the functional differences between MUTs and other intersection types (e.g., RCI that redirect both through and left-turn movements), the analysis was limited to MUT sites to ensure consistency and comparability among sites included.

Table 4.1 Types of Sites Selected

Site Type	Sites Count
MUT	152
RCI and ILAC	24
Other Types	9
Total	**185**

4.1.2 Geometric and Traffic Data

Information was collected for each site to support a comprehensive safety analysis. Geometric characteristics of the intersections and U-turn segments were extracted using satellite imagery and Google Street View, allowing the research team to document features such as median width, U-turn radius, lane configuration, and traffic control type. Although field visits were not conducted, virtual inspection techniques provided sufficient detail to capture necessary design elements, including pavement markings and signage. Likewise, traffic data (AADT) were obtained from the GIS-based shapefiles maintained by the Michigan Department of Transportation (MDOT), which provides AADT estimates for state roadways. The AADT data used in this study was obtained from the year 2023.

Out of the identified 152 MUT sites, 20 sites were excluded due to missing traffic volume data on either the major or minor roads, an essential input for assessing safety performance. Further, turning movement count data at the main intersection or the U-turn crossovers was not included; the demands in the crossovers would be highly correlated to the through demands. The final dataset included 132 MUT sites (equivalent to 264 U-turns) with complete geometric and traffic data for further analysis. A description of the collected geometric and traffic characteristics for each site is provided in **Error! Reference source not found.**.

Descriptive statistics on the collected site information are provided in **Error! Reference source not found.**. It is important to note that these descriptive statistics are based on individual U-turn segments rather than entire intersections. As each MUT site was divided into two directional segments for analysis, the dataset includes a total of 264 U-turn segments representing 132 MUT sites.

It is to note that the U-turn radius was measured from the edge of the curb at the top of the inner U-turn to the center of the turn lane at intersections with one turn lane and from the center of the outer turn lane for intersections with two lanes. An example image was provided in Figure 4.3.

Figure 4.3 Example U-turn radius measurement from Google Earth aerial image

Also, the median width was measured at the widest point for side of the intersection and includes the median itself and the median shoulders. For the below example (Figure 4.4 Example median width measurement from Google Earth aerial image), the median width for the north side is 84 feet.

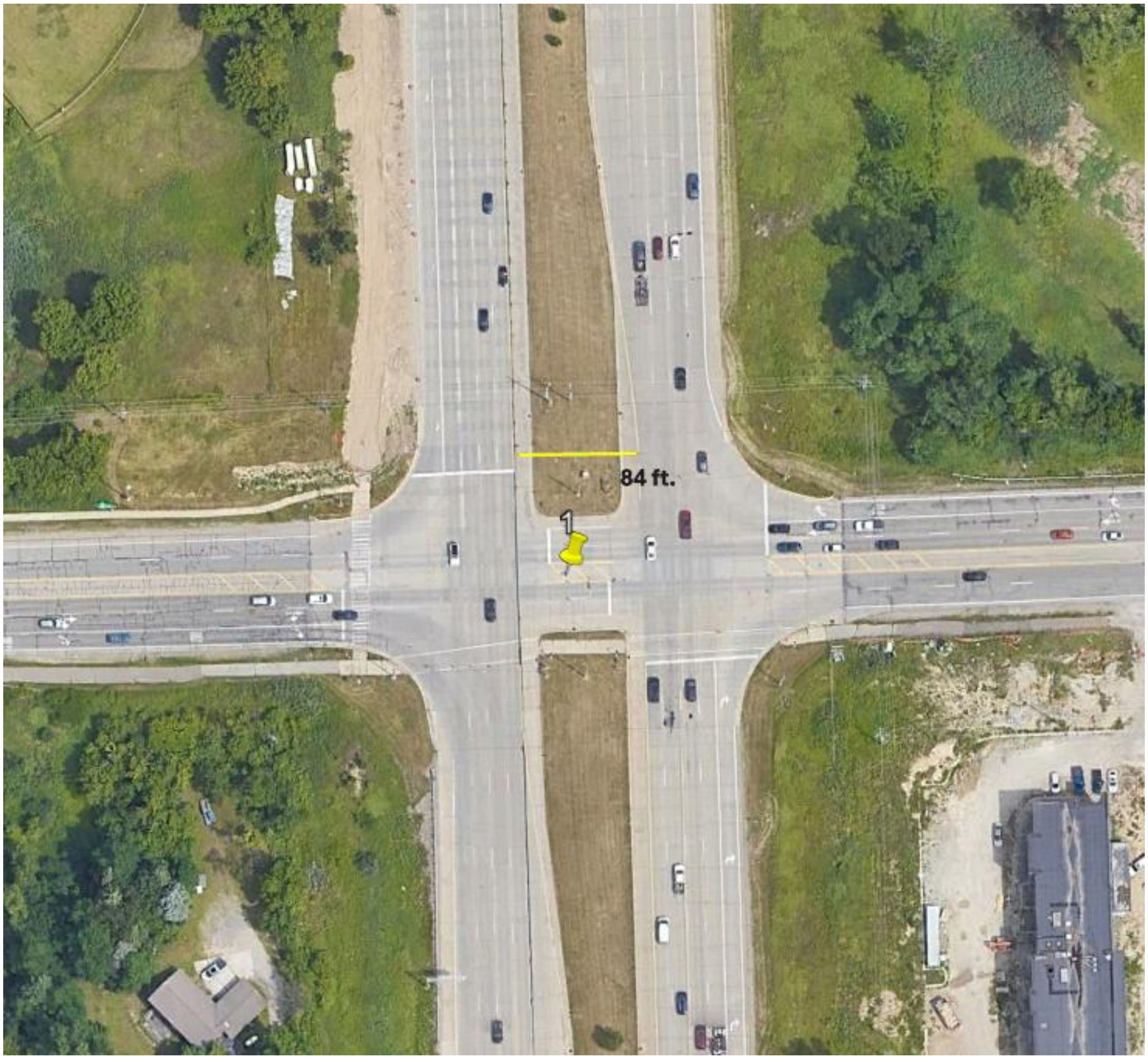

Figure 4.4 Example median width measurement from Google Earth aerial image

Table 4.2 Description of Geometric and Traffic Data Collected at Each Site

Data element	**Description**
Number of Approach Lanes	The number of lanes for right turn, through, and left turn for all major and minor road approaches was collected using satellite imagery.
Lane Width	The lane width for both major and minor roads was collected using satellite imagery.
Posted Speed Limit	The posted speed limit was collected using satellite imagery and street view for both major and minor roads.
Major and Minor AADT	The annual average daily traffic (AADT) was collected from Michigan Traffic Data for both major and minor roads.
Proportion of Trucks	The proportion of trucks on both major and minor roads was collected using Michigan Traffic Data.
Storage Lane Length for Right Turn	The storage length for right turn movement was measured using satellite imagery.
Taper Lane Length Right Turn	The taper length for right turn movement was measured using satellite imagery.
Left Turn Storage Lane Location U-turn	The presence of storage length for U-turn upstream of the main information was obtained using satellite imagery.
Longitudinal Grade at Intersection	Using AutoCAD, the longitudinal grade of the intersection was measured.
Number of Access Points	The total number of access points was collected within the influence area of each site in both merging and diverging directions.
Bulb-Out	The presence of bulb-out at the U-turn crossover was checked.
Skew Angle	The skew angle at both the middle intersection and the U-turn crossover was measured using the Heading tool in Google Earth software. It varies between 0 degrees to 90 degrees, with 0 being no skew.
U-turn Control Type	It represents the signal control type at the U-turn, such as stop control, yield control, or signal control.
Number of Lanes for U-turn	The number of lanes for U-turn movements was collected using satellite imagery.
Number of Lanes for U-turn Through	The number of lanes for through movement near the U-turn in both merging and diverging directions was collected.
U-turn Spacing	It represents the distance from the center of the middle intersection to the center of the U-turn, collected using satellite imagery.
U-turn Combination of Left & U-turns	It represents whether there is an access point (driveway) so close to the U-turn crossover that allows a vehicle to make a left directly from the U-turn lanes.
U-turn Storage Lane Length	The storage lane length for U-turn movement is the distance between the end of the taper to the midpoint of the U-turn, collected using satellite imagery.
U-turn Taper Lane Length	The taper lane length for U-turn movement was measured using satellite imagery.
U-turn Radius	The radius of the U-turn crossover was measured using satellite imagery.
U-turn Median Width	The width of the median near the U-turn crossover was measured using satellite imagery.
Traffic Signs/Pavement Markings Present at U-turn	Street views were checked to see if any traffic signs or pavement markings were present at the U-turn crossover.
Sight Distance Concerns U-turn	Satellite images and street view were checked to see if any sight visibility problems exist at the U-turn crossover such as trees, curves or hills.
Pedestrian Crosswalk at U-turn	A better phrase might be: Satellite images and street view were checked for the presence of a pedestrian crosswalk at the U-turn crossover.

Table 4.3 Descriptive Statistics of the Variables Used in Model Development

Variable	Unit/Description	Min.	Max.	Mean	S.D.
Total Crashes	count per year	0	46	5.7	5.97
Fatal-Injury Crashes	count per year	0	12	1.1	1.58
Property Damage Only Crashes	count per year	0	41	4.6	4.83
Distance from the middle intersection to the U-turn	feet	300	1,050	622.7	116.07
Binary variable representing presence of access point so close to the U-turn crossover allowing making a direct left from the U-turn lane	1=Yes, 0=No	0	1	0.33	0.47
Number of access points at U-turn segments in the merging direction	count	0	9	2.1	2.14
Number of access points at U-turn segments in the diverging direction	count	0	9	2.2	2.32
Number of side streets	count	0	6	0.85	1.22
Total number of access points including those for single homes, single stores, school or office, and factories	count	0	9	0.9	1.45
Total number of access points including those for shopping malls, banks, restaurants, supermarkets, and gas stations	count	0	8	1.5	1.86
Traffic control type at U-turn=Signal	1=Yes, 0=No	0	1	0.61	0.49
Traffic control type at U-turn=Stop sign	1=Yes, 0=No	0	1	0.29	0.45
Traffic control type at U-turn=Yield sign	1=Yes, 0=No	0	1	0.10	0.31
Number of lanes at U-turn	count	1	2	1.14	0.35
Number of through lanes in the merging direction	count	2	5	3.39	0.94
Number of through lanes in the diverging direction	count	2	5	3.39	0.94
Speed limit on major road	mph	35	55	48.07	5.73
Speed limit on minor road	mph	25	55	39.39	7.62
Lane width on major road	feet	10	11	10.93	0.25
Lane width on minor road	feet	10	11	10.41	0.49
AADT on major road	vehicles per day	9,767	84,843	43,482.1	14,490.15
AADT on minor road	vehicles per day	1806	57025	14351.2	10205.5
Truck percent on major road	percent	1.10	8.60	0.04	0.02
Truck percent on minor road	percent	1.25	6.50	0.03	0.007
Intersection angle at U-turn	degrees	57	122	98.6	9.7
U-turn radius	feet	15	152	40.8	19.6
Median width of U-turn segment	feet	17	187	69.3	35.0

Each U-turn crossover was classified based on the type of traffic control device present at the point where vehicles enter the U-turn. Three types of control were observed across the 264 U-turn segments: stop signs, yield signs, and signals. Stop signs typically require full vehicle stoppage before merging, yield signs permit merging with caution, and signalized U-turns are governed by dedicated traffic signal phases. The distribution of U-turn control types is summarized in **Error! Reference source not found.**. As shown, most of the U-turn crossovers were signal-controlled type.

Table 4.4 Distribution of U-turn Segments by Control Type

Control Type	**Counts**
Stop Sign	74
Yield Sign	28
Signal	162
Total	**264**

4.1.3 Crash Data

The primary source of crash data for this study was the Michigan Traffic Crash Facts (MTCF) Crash Query Website (Michigan Traffic Crash Facts, 2023). The research team collected crash data for five years (2019 through 2023) for the selected sites in Michigan. **Error! Reference source not found.** illustrates the steps followed to extract the crashes for the analysis, where points in red represent each crash. In total, there were 7,523 crashes over a period of five years (2019-2023) at these 264 U-turn segments. The crash reporting threshold in Michigan is death, personal injury, or property damage exceeding $1,000 or more.

Using AutoCAD Civil 3D, shapefiles were created for each of the 132 MUT sites, delineating their boundaries, to only include the crashes that fall within the influence area. The influence area was defined as extending 150 feet in each direction beyond the stop bar on minor roads and 150 feet in each direction beyond the U-turn on major roads, totaling 300 ft including both directions. However, if there was an adjacent intersection or U-turn within 150 ft beyond the U-turn, then the boundary was set up to the midpoint of two crossovers. Next, the shapefiles and crash points were projected using ArcGIS. Through the Spatial Join command, crashes located within each site's influence area were identified. Any crashes falling outside the designated site areas were removed, and after a thorough data-cleaning process, the final dataset was prepared. All the construction crashes and parking-related crashes were removed from the data set.

Based on the discussions with the experts from NCDOT, it was decided to exclude the crashes happening at the middle intersection, as there may be factors other than access points leading to these crashes. Therefore, crashes occurring within the intersection-only influence area, defined as the 150 ft zone beyond the stop bar on both major and minor approaches, were removed to isolate the safety effects of access points near U-turns.

Since MUT intersections include two U-turn crossovers (typically on opposite sides of the intersection), each site was divided into two separate U-turn segments — often referred to as western (left) and eastern (right) segments. Including pairs of similar sites in the database did not affect the outcome, and this segmentation was necessary because geometric characteristics such as offset distance, taper length, storage length, and lane count may vary between the two U-turns within the same site. As a result, the final dataset consisted of 264 U-turn segments, which formed the basis for subsequent segment-level analysis.

Figure 4.5 Steps for Selecting Crashes Under Considered Influence Area (in Site 34)

For each crash, variables that could impact the safety performance of the design were collected. Information such as crash severity, crash type, road surface condition during the crash, driver age group, and other variables were collected from the MTCF database. Similarly, GIS functions were applied to calculate the distance between the crash and the respective U-turn location.

Error! Reference source not found. provides a summary of related information on crashes considered for the analysis. It is important to note that all crash data included in this analysis pertains exclusively to the U-turn segments, with crashes occurring within the central intersection area explicitly excluded.

Table 4.5 Crash Information Collected for 132 MUT Sites

Category	Variable	Crash Count (of 7,523 total)	Percentage
Crash Severity	Fatal and Serious Injury (K+A)	88	1%
	Minor Injury (B+C)	1,422	19%
	Property Damage Only (O)	6,013	80%
Crash Type	Angle	986	13%
	Backing	44	1%
	Head-On	29	0%
	Rear-End	3,778	50%
	Sideswipe	1,746	23%
	Other	249	3%
Relation to Access Point*	Related to Access Point	2,126	28%
	Not Related to Access Point	5,397	72%
Road Surface Condition	Dry	5,823	77%
	Ice	123	2%
	Snow	243	3%
	Wet	1,194	16%
	Other	140	2%
Driver Age Group	Adult 25-59 years	3,140	42%
	Older 60+ years	1,838	24%
	Young 15-24 years	2,545	34%
Distance between Crash and U-turn Location	0-150 ft	3,840	51%
	150-300 ft	2,009	27%
	Greater than 300 ft	1,674	22%

Section* ***Error! Reference source not found.* *describes selecting access point-related crashes.*

4.1.4 Access Point Data

Information was collected for each access point located within the defined influence area of the study sites, as an example has been illustrated in **Error! Reference source not found.**. Satellite imagery and street view maps were used to identify and characterize each access point. A total of 1,139 access points were present in 132 MUT sites.

One of the primary characterizations was based on the directional orientation of the access point relative to the U-turn movement. Access points were classified as either diverging, where vehicles diverge from the mainline traffic to enter the U-turn; or merging, where vehicles re-enter the mainline after completing a U-turn maneuver (see **Error! Reference source not found.** for illustration).

Another characterizations was based on the spatial location of the access point: whether it was located near the U-turn, beyond the U-turn, in the middle section of the U-turn segment, or near the main intersection. Access points were also classified by access type, including one-way, two-way, right-in-right-out (RIRO) and left-in/right-in/right-out (LIRIRO) configurations. It should be mentioned that there are 20 sites with the LIRIRO configuration out of the 110 sites with the RIRO configuration. Finally, each access point was categorized by its driveway type, reflecting the adjacent land use. Eleven (11) types were identified, with side streets being the most common, followed by restaurants/fast food outlets, gas stations, and single-store retail.

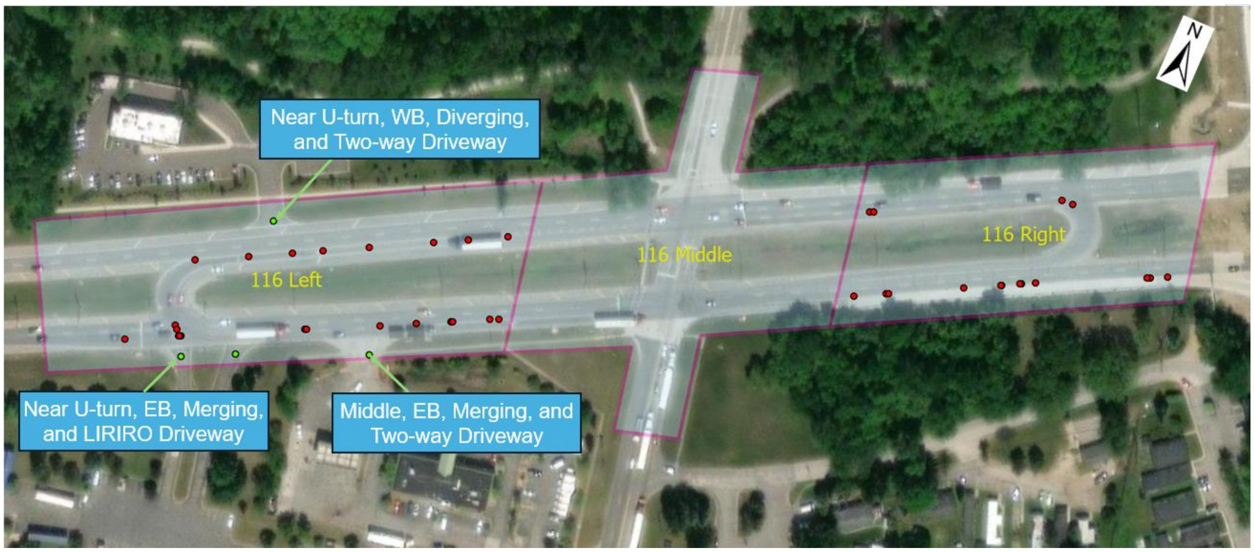

Figure 4.6 Access Point Information Collection at Site 116 (shown in green)

With crashes happening all across the U-turn segments, determining whether a crash was related to a specific access point posed a significant challenge. Due to the large number of crashes and time constraints, reviewing individual crash reports was not feasible. Instead, the research team adopted a spatial proximity approach, using distance from the access point as the primary criterion.

The research team manually reviewed and assigned crashes to respective access points as shown in **Error! Reference source not found.**. Through this manual process, 2,126 of the 7,523 total crashes were determined to be access point–related crashes. As this process was completed manually, engineering judgement of the research team was undeniably necessary to identify access-point-related crashes based on the location of crashes and the distance to the nearest driveway.

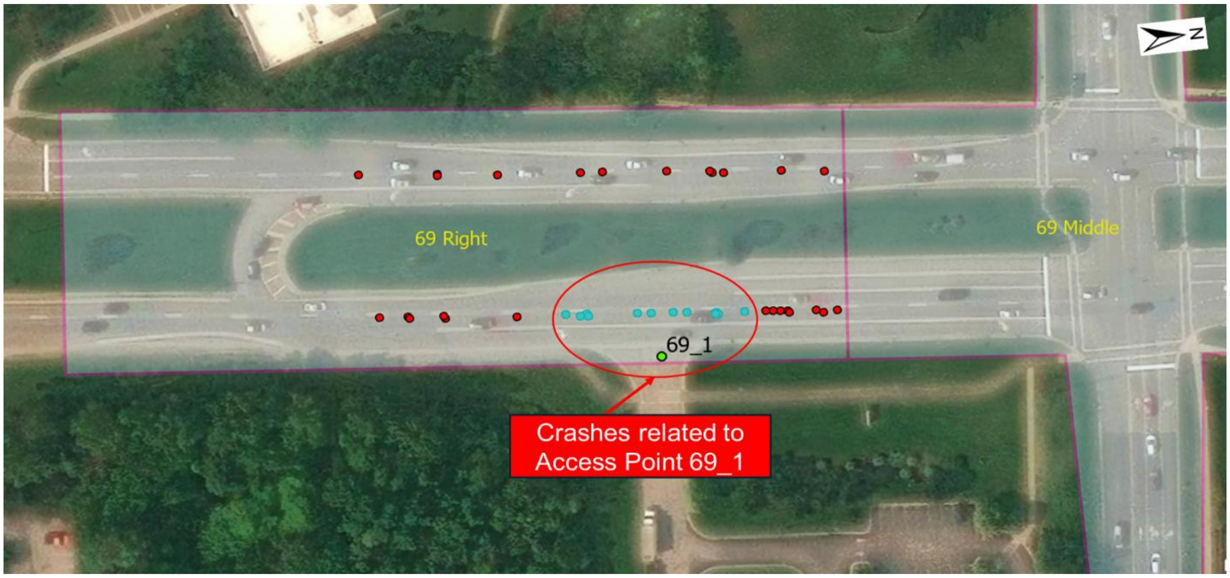

Figure 4.7 Manually Attributing Each Crash to Related Access Point in Site 69

A summary of access point counts and associated crash frequencies under each classification is presented in **Error! Reference source not found.**. In total, 23 variables related to the access point characteristics were collected, which are provided in the Appendix C.

Table 4.6 Access Point Categorization and Associated Crash Counts

Category	Variable	Access Point Count (1,139)	Percentage (Access Point)	Crash Count (2,126)	Percentage (Crash)
Direction	1. Merging	556	49%	1,345	63%
	2. Diverging	583	51%	781	37%
Location	1. Beyond U-turn	167	15%	295	14%
	2. Near the U-turn	287	25%	894	42%
	3. Middle	425	37%	836	39%
	4. Near the Intersection	260	23%	101	5%
Access Type	1. One-way (Only an Exit or an Entrance)	54	5%	90	4%
	2. Two-way (Exit and Entrance)	975	86%	1,837	86%
	3. RIRO (Right In/Right Out including Left-Right-In-Right-Out)	110	10%	199	9%
Driveway Type	1 Side Street	224	20%	956	45%
	2 Shopping Mall	24	2%	49	2%
	3 Bank	36	3%	56	3%
	4 Restaurant/Fast Food/Coffee Shop	177	16%	274	13%
	5 Supermarket	22	2%	88	4%
	6 Gas Station	131	12%	74	3%
	7 Single Home	30	3%	29	1%
	8 Single Store (with low turnover rate)	153	13%	197	9%
	9 School and Office Buildings	46	4%	89	4%
	10 Manufacturing and Plants	12	1%	18	1%
	11 Other	284	25%	296	14%
Number of Crashes	1. Zero	611	54%	0	0%
	2. Between 1 to 5	419	37%	930	44%
	3. Between 6 to10	63	6%	465	22%
	4. Between 11 to 20	31	3%	400	19%
	5. Greater than 20	15	1%	331	16%

Due to limited sample sizes in individual driveway categories, the research team grouped driveways based on estimated turnover rates, a concept in transportation engineering (mostly in parking studies) that reflects the number of vehicles utilizing a driveway (an access points) within a given time period, typically measured in vehicles per driveway per day (Thanh, 2017). This grouping approach also reflects the potential for conflict points due to vehicle movement intensity.

Driveways were classified into four categories:

1. Side Street: This category had the highest number of access points and was treated as a standalone group due to its distinct characteristics and sufficient sample size.
2. High Turnover Rate (HTR): This group includes driveways with relatively high vehicular activity (and shorter parking durations), potentially increasing exposure to conflict. It includes shopping malls, banks, restaurants/fast food establishments, supermarkets, and gas stations.

3. Low Turnover Rate (LTR): This group includes driveways with relatively lower vehicular turnover and typically longer parking durations. It includes single homes, single retail stores, school and office buildings, and manufacturing facilities.
4. Other: This group includes access points labeled as “Other” that did not fit into the categories above.

A summary of the access point and crash distribution across these categories of driveways is presented in **Error! Reference source not found.**.

Table 4.7 Driveway Categories by Turnover Rate and Associated Crashes

Type	**Access Point Count (1,139)**	**Proportion (Access Point)**	**Crash Count (2,126)**	**Proportion (Crash)**
Side Street	224	20%	956	45%
HTM	390	34%	541	25%
LTM	241	21%	333	16%
Other	284	25%	296	14%

To support statistical analysis, all relevant geometric, traffic, crash, and access point characteristics were compiled and merged at three levels: U-turn segment, access point, and individual crash.

Chapter 5. Analysis and Results

5.1 Preliminary Analysis: Crash Rates on U-turn Segments

In the preliminary analysis, crash rates were calculated to account for differences in traffic volumes across U-turn segments. This metric reflects the number of crashes per million entering vehicles (MEV) and is more appropriate for comparing sites with varying traffic demands. The equation used for calculating the crash rate is as follows (Golembiewski and Chandler, 2011):

$$Rspot = \frac{C \times 10^6}{365 \times T \times V} \quad \text{(Equation 6)}$$

Where,

R_{spot} = number of crashes per million entering vehicles (crashes/MEV)
C = total number of observed crashes
T = time period of analysis (years)
V = total traffic volume entering (Major Road AADT+ Minor Road AADT)

Regarding the number of entering vehicles used in Eq. 6, the research team did not have access to specific traffic volumes at access points (driveways) or U-turn movement counts. Instead, AADT data was substituted in this equation as the total entering volume for the preliminary analysis. For the final analysis (Section 5.2: Cross-sectional Model Development), land use and driveway types of access points were collected to help minimize the limitation caused by the lack of traffic data at access points (driveways). The initial findings from the crash rate analysis are provided below.

5.1.1 Comparison of Sites with U-turn Crossovers Allowing Left Turn vs. U-turn Only

Out of 264 U-turn segments analyzed, 86 were found to allow both U-turns and direct left turns into nearby access points, typically aligned across from the crossover, as illustrated in **Error! Reference source not found.**.

Figure 5.1 U-turn Crossovers with Adjacent Driveways Aligned for Left turn

Error! Reference source not found. presents a comparison of crash rates between U-turn segments that allow direct left-turn access and those that accommodate U-turn movements only.

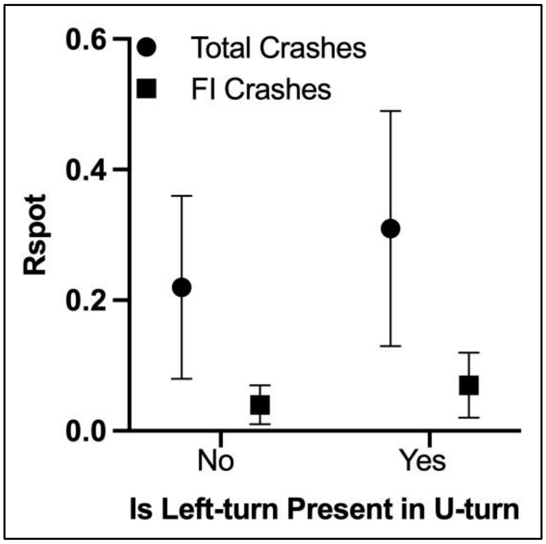

Figure 5.2 Crash Rates (crash/MEV) (Rspot) for U-turn Segments with and without Left-turn Access

The results indicate that U-turn segments permitting direct left turns exhibited higher average crash rates for both total crashes and fatal/injury (FI) crashes compared to those that did not allow left turns. For total crashes, the difference (0.22 vs 0.31 per million entering vehicles or MEV) is more pronounced, suggesting that the presence of dual-turn (U-turn and left turn) maneuvers at a single crossover may introduce greater conflict potential and operational complexity, thereby elevating crash risk. A similar trend (0.04 vs 0.07 per MEV) is observed for FI crashes. It indicates that the increase is also substantial for severe crashes. Statistical analysis confirmed that these differences were statistically significant ($p < 0.001$), with both the total crashes rates ($t=4.01$, degrees of freedom=134, $p<0.001$) and fatal/injury crash rates ($t=4.90$, degrees of freedom=124, $p<0.001$) at U-turn segments permitting left turns consistently higher than those with only U-turns. It must be noted that in the database, the average for total crashes is 0.25 crashes per MEV and that of the fatal and injury crashes is 0.05 crashes per MEV

These findings highlight the safety trade-offs involved in permitting left-turn access alongside U-turn functionality. Restricting direct left-turn movements at U-turn crossovers, particularly when closely aligned with adjacent driveways, may help reduce crash frequency and severity on these segments.

5.1.2 Comparison Between Segments with and without Access Points

At 25 selected MUT sites (comprising 50 U-turn segments), one segment had an access point while the other did not. **Error! Reference source not found.** illustrate two example sites (Site 5 and Site 71) where access points were present on only one of the two U-turn segments. Since all other geometric and traffic characteristics remained nearly identical between the two legs, these locations provided a valuable opportunity to compare crash rates under controlled conditions. Specifically, the crash rates of segments with access points were compared directly to their counterpart segments without access points to assess the safety impact.

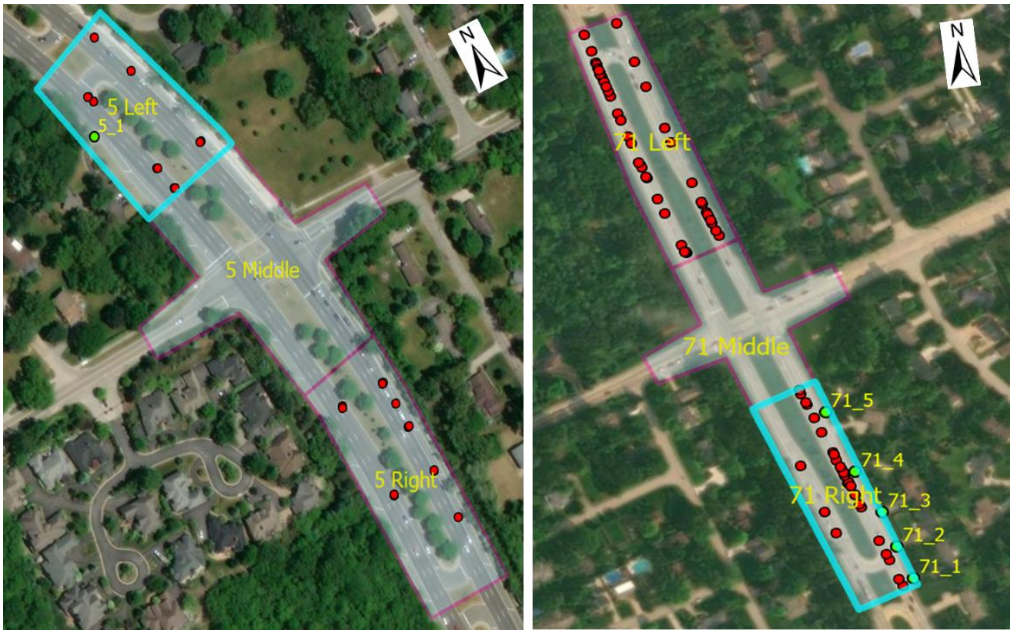

Figure 5.3 MUT Sites Having Access Points on Only One U-turn Segment, Highlighted in Blue (Site 5 and Site 71)

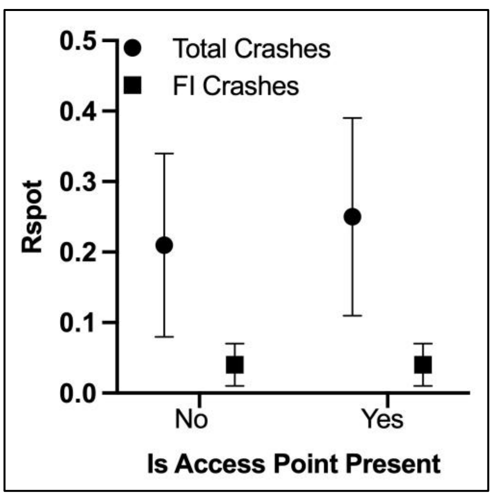

Figure 5.4 Crash rates (crash/MEV) (Rspot) for U-turn segments with vs. without Access Points

As shown in **Error! Reference source not found.**, U-turn segments with access points exhibited a higher average crash rate for total crashes (0.25 crashes/MEV) compared to their counterparts without access points (0.21 crashes/MEV). Although the difference in fatal and injury (FI) crash rates was less pronounced (0.042 per MEV for U-turns with access vs. 0.044 for U-turns without access), the trend remained consistent. Table 5.1 below provides more details on crash rates estimated for U-turn segments with and without access points. The table also presents the comprehensive crash cost per million entering vehicles for U-turn segments, estimated using National Safety Council (NSC, 2023) data.

Table 5.1 Crash Frequencies (Crashes/Year/U-turn Segment), Crash Rates (Crashes/MEV) and Comprehensive Crash Costs for U-turn Segments with and without Access Points

Crash Frequency (Crashes/Year/U-turn Segment)						
U-turn Segment [a]	**Fatal (K)**	**Injury Type A**	**Injury Type B**	**Injury Type C**	**PDO**	**Overall**
With Access	0.0000	0.0320	0.1920	0.8000	4.2960	5.3280
Without Access	0.0080	0.0560	0.2560	0.6640	3.5520	4.5280
Difference [b]	**-0.0080**	**-0.0240**	**-0.0640**	**0.1360**	**0.7440**	**0.8000**
Crash Rates (Crashes/MEV)						
U-turn Segment	**Fatal (K)**	**Injury Type A**	**Injury Type B**	**Injury Type C**	**PDO**	**Overall**
With Access	0.0000	0.0013	0.0095	0.0331	0.2008	0.2453
Without Access	0.0004	0.0024	0.0124	0.0277	0.1675	0.2099
Difference *	-0.0004	-0.0011	-0.0029	0.0054	0.0333	0.0353
Comprehensive Crash Cost ($/Year/U-turn Segment)						
U-turn Segment	**Fatal (K)**	**Injury Type A**	**Injury Type B**	**Injury Type C**	**PDO**	**Overall**
With Access	0	35,584	46,464	105,600	77,328	264,976
Without Access	109,640	62,272	61,952	87,648	63,936	385,448
Difference *	**-109,640**	**-26,688**	**-15,488**	**17,952**	**13,392**	**-120,472**

a In total, only 50 segments (25 U-turn segments with access, and 25 U-turn segments without access)
b Difference = (U-turns with Access) – (U-turns without Access)

These findings suggest that access points may increase crash potential, likely due to added turning maneuvers and increased vehicle conflict near the U-turn; however, the impact on fatal and injury (FI) crashes could be minimal. In fact, based on Table 5.1, slightly lower crash rates were even observed at U-turns with access for severities K, A, and B. By controlling site-level characteristics, this within-site comparison strengthens the evidence that limiting access near U-turn crossovers may improve overall safety performance. At an average site, the comprehensive crash cost associated with each U-turn segment with access points is estimated at approximately $120,000 per year lower than U-turn segments without access points based on National Safety Council (NSC, 2023).

It should be mentioned that one reason for the relatively large difference in crash costs ($120,000 per year) is the small sample size (only 50 U-turn segments) included in Table 5.1. Specifically, only one fatal crash was reported at these 50 U-turns, and that fatal crash occurred on a U-turn segment without access points.

On the other hand, it is expected that drivers travel faster in segments without access points compared to those with access points, and they may also be more cautious when driving on segments with access points. Moreover, at U-turns with access points, traffic entering or exiting access points typically create angles with the mainline flow that result in rear-end and sideswipe crashes due to merging and diverging conflicts, rather than crossing conflicts. Therefore, the presence of access points primarily led to more PDO crashes rather than more severe crashes in this part of the preliminary analysis (with only 50 U-turn segments).

5.2 Cross-sectional Model Development

Cross-sectional models were developed separately for total, fatal-injury (FI), and property damage only (PDO) crashes. As discussed in the previous chapter, this analysis evaluated the safety performance of only MUT sites. Several different models were developed initially with varying combinations of predictor variables. Ultimately, based on the p-values of the parameter estimates, AIC, and log-likelihood information, the best fit models were finalized as shown below (Table 5.2 through Table 5.4), considering the correlations between independent variables, and excluding the strongly correlated variables in the models simultaneously. A significance level of 0.1 (α = 0.1) was used in this analysis.

The models included several site characteristics data in the form of continuous variables, including U-turn spacing, counts of access points, lane numbers, and lane widths. Some other site-related factors, including traffic control type and direct left turn at U-turn lanes due to the presence of an access point closest to the U-turn, are included as categorical variables. Traffic volumes were included in natural log forms for both AADTs on major and minor roads, and, as such, its parameter estimate reflects an elasticity. The final models were developed excluding the statistically insignificant and highly correlated variables through a backward elimination process by the descending order of p-values. It is worth noting that, with the backward elimination process, the combinations of indicator variables in the final models developed slightly varied across these three models. For example, while the count of one-way access points was statistically significant for only FI crashes and it was retained in the final FI crash frequency model, it was not significant for PDO crashes and eventually removed from the final model for PDO crash frequency. Similarly, while the count of two-way access points was statistically significant for only PDO crashes and it was retained in the final PDO crash frequency model, it was not significant for FI crashes and eventually removed from the final model for FI crash frequency.

Additionally, it is important to mention that only the CMFs of interest in the form of the exponential of parameter coefficients (i.e., Exp(β)) are provided in the results. The regression analyses in this study were conducted using R statistical software version 4.3.1.

The crash prediction model (CPM) form for total crashes per year, as shown in $+ \beta_{UT\_Rad} * UT\_Rad + \beta_{UT\_MdW} * UT\_MdW) * AF_{UT\_LT} * AF_{TC\_Stp} * AF_{TC\_Yld})$ (Equation 7 through $AFTC\_Yld = Exp^{(\beta_{TC\_Yld} * I_{TC\_Yld})}$ (Equation 10, provides all the adjustment factors (AFs) in the model. Predictor variables determine which AFs are applicable to each observation in the dataset.

$$N_{Total} = Exp^{((\beta_0 + \beta_{Ln\_Maj\_AADT} * Ln\_Maj\_AADT + \beta_{UTurn\_Spac} * UTurn\_Spac + \beta_{Num\_AP\_Mrg} * Num_{AP\_Mrg} + \beta_{Num\_Sd\_Str} * Num_{Sd\_Str} + + \beta_{Num\_AP\_LTM} * Num_{AP\_LTM} + \beta_{Num\_AP\_RIRO} * Num_{AP\_RIRO} + \beta_{SL\_Min} * SL\_Min + \beta_{LW\_Maj} * LW\_Maj + \beta_{UT\_Rad} * UT\_Rad + \beta_{UT\_MdW} * UT\_MdW) * AF_{UT\_LT} * AF_{TC\_Stp} * AF_{TC\_Yld})} \quad \text{(Equation 7)}$$

with

$$AF_{UT\_LT} = Exp^{(\beta_{UT\_LT} * I_{UT\_LT})} \quad \text{(Equation 8)}$$
$$AF_{TC\_Stp} = Exp^{(\beta_{TC\_Stp} * I_{TC\_Stp})} \quad \text{(Equation 9)}$$
$$AF_{TC\_Yld} = Exp^{(\beta_{TC\_Yld} * I_{TC\_Yld})} \quad \text{(Equation 10)}$$

Similarly, for fatal-injury (FI) crashes,

$$N_{FI} = Exp^{((\beta_0 + \beta_{Ln\_Maj\_AADT} * Ln\_Maj\_AADT + \beta_{Ln\_Min\_AADT} * Ln\_Min\_AADT + \beta_{UTurn\_Spac} * UTurn\_Spac + \beta_{Num\_AP\_Mrg} * Num_{AP\_Mrg} + \beta_{Num\_Sd\_Str} * Num_{Sd\_Str} + \beta_{Num\_AP\_LTM} * Num_{AP\_LTM} + \beta_{Num\_AP\_OW} * Num_{AP\_OW} + \beta_{Num\_ThruLn\_Div} * Num\_ThruLn\_Div + \beta_{LW\_Maj} * LW\_Maj + \beta_{LW\_Min} * LW\_Min) * AF_{UT\_LT} * AF_{TC\_Stp} * AF_{TC\_Yld})} \quad \text{(Equation 11)}$$

And, for property damage only (PDO) crashes,

$$N_{PDO} = Exp^{((\beta_0 + \beta_{Ln\_Maj\_AADT} * Ln\_Maj\_AADT + \beta_{UTurn\_Spac} * UTurn\_Spac + \beta_{Num\_AP\_Mrg} * Num_{AP\_Mrg} + \beta_{Num\_AP\_Div} * Num_{AP\_Div} + \beta_{Num\_Sd\_Str} * Num_{Sd\_Str} + \beta_{Num\_AP\_LTM} * Num_{AP\_LTM} + \beta_{Num\_AP\_TW} * Num_{AP\_TW} + \beta_{Num\_Ln} * Num\_Ln + \beta_{SL\_Min} * SL\_Min + \beta_{LW\_Min} * LW\_Min) * AF_{TC\_Stp} * AF_{TC\_Yld})} \quad \text{(Equation 12)}$$

where N_{Total} = Predicted average total crash frequency per year

N_{FI} = Predicted average fatal-injury crash frequency per year

N_{PDO} = Predicted average property damage only crash frequency per year

β_0 = Regression coefficient for intercepts

$\beta_{Ln\_Maj\_AADT}$ = Regression coefficient for natural log of major AADT

$\beta_{Ln\_Min\_AADT}$ = Regression coefficient for natural log of minor AADT

β_{UTurn_Spac} = Regression coefficient for U-turn spacing in the total crash frequency model

$\beta_{Num\_AP\_Mrg}$ = Regression coefficient for the number of access points in merging direction

$\beta_{Num\_AP\_Div}$ = Regression coefficient for the number of access points in diverging direction

$\beta_{Num\_Sd\_Str}$ = Regression coefficient for the number of side streets

$\beta_{Num\_AP\_LTM}$ = Regression coefficient for the number of access points with low turnover rate (sum of access point counts for single homes, single retail stores, school and office buildings, and manufacturing facilities)

$\beta_{Num\_AP\_OW}$ = Regression coefficient for the number of one-way access points

$\beta_{Num\_AP\_TW}$ = Regression coefficient for the number of two-way access points

$\beta_{Num\_AP\_RIRO}$ = Regression coefficient for the number of right-in-right-out (including left-right-in-right-out) access points

$\beta_{Num\_ThruLn\_Div}$ = Regression coefficient for the number of through lanes in diverging direction

β_{Num_Ln} = Regression coefficient for the total number of lanes at U-turn crossover

β_{SL_Min} = Regression coefficient for the speed limit on minor approach

β_{LW_Maj} = Regression coefficient for the lane width on major approach

β_{LW_Min} = Regression coefficient for the lane width on minor approach

β_{UT_Rad} = Regression coefficient for U-turn radius

β_{UT_MdW} = Regression coefficient for U-turn median width

β_{UT_LT} = Regression coefficient for the indicator variable depicting cases whether U-turn is combined with left turn

β_{TC_Stp} = Regression coefficient for the indicator variable depicting cases whether U-turn is stop-controlled

β_{TC_Yld} = Regression coefficient for the indicator variable depicting cases whether U-turn is yield-controlled

Ln_Maj_AADT = Regression coefficient for natural log of major AADT (vehicles per day)

Ln_Min_AADT = Regression coefficient for natural log of minor AADT (vehicles per day)

$UTurn\_Spac$ = Regression coefficient for U-turn spacing (ft)

Num_AP_Mrg = Regression coefficient for the number of access points in merging direction

Num_AP_Div = Regression coefficient for the number of access points in diverging direction

Num_Sd_Str = Regression coefficient for the number of side streets

Num_AP_LTM = Regression coefficient for the number of aces points with low turnover rate (sum of access point counts for single homes, single retail stores, school and office buildings, and manufacturing facilities)

Num_AP_OW = Regression coefficient for the number of one-way access points

Num_AP_TW = Regression coefficient for the number of two-way access points

Num_AP_RIRO = Regression coefficient for the number of left-right-in-right-out (including left-right-in-right-out) access points

Num_ThruLn_Div = Regression coefficient for the number of through lanes in diverging direction

Num_Ln = Regression coefficient for the total number of lanes at U-turn crossover

SL_Min = Regression coefficient for speed limit on minor approach (mph)

LW_Maj = Regression coefficient for the lane width on major approach (ft)

LW_Min = Regression coefficient for the lane width on minor approach (ft)

UT_Rad = Regression coefficient for U-turn radius (ft)

UT_{MdW} = Regression coefficient for U-turn median width (ft)

I_{UT_LT} = Indicator variable depicting cases whether U-turn is combined with left turn

I_{TC_Stp} = Indicator variable depicting cases whether U-turn is stop-controlled

I_{TC_Yld} = Indicator variable depicting cases whether U-turn is yield-controlled

Based on these equations from Equation 13 through$AFTC_Yld$= $Exp(\beta TC\_Yld * I_{TC\_Yld})$ (Equation 10, let us consider 3 different scenarios as below:

1. <u>Scenario 1:</u> AADT = 10,000 vpd, U-turn spacing = 500 ft, U-turn combined with left turn = No, number of access points in merging direction = 0, number of side streets = 0, number of access points with low turnover rate = 0, number of RIRO access points = 0, traffic control = signalized, speed limit on minor approach = 40 mph, lane width on major approach = 11 ft, lane width on minor approach = 10 ft, U-turn radius = 40 ft, U-turn median width = 60 ft.

So, the predicted number of crashes per year for this scenario is

$Exp\Big(-14.500 + \big(0.9523 * Ln(10{,}000)\big) + (0.0006 * 500) + (0.0435 * 0) + (0.1023 * 0) + (-0.0549 * 0) + (0.0586 * 0) + (0.0234 * 40) + (0.2780 * 11) + (0.1393 * 10) + (-0.0053 * 40) + (0.0031 * 60)\Big)$ = 0.93 crashes per year

2. Scenario 2: AADT = 10,000 vpd, U-turn spacing = 600 ft, U-turn combined with left turn = Yes, number of access points in merging direction = 1, number of side streets = 1, number of access points with low turnover rate = 1, number of RIRO access points = 1, traffic control = signalized, speed limit on minor approach = 40 mph, lane width on major approach = 11 ft, lane width on minor approach = 10 ft, U-turn radius = 50 ft, U-turn median width = 70 ft.

$$Exp\Big(-14.500 + \big(0.9523 * Ln(10{,}000)\big) + (0.0006 * 600) + (0.0435 * 1) + (0.1023 * 1) + (-0.0549 * 1) + (0.0586 * 1) + (0.0234 * 40) + (0.2780 * 11) + (0.1393 * 10) + (-0.0053 * 50) + (0.0031 * 70)\Big) * (0.1221 * 1)$$ = 1.27 crashes per year

3. Scenario 4: AADT = 10,000 vpd, U-turn spacing = 500 ft, U-turn combined with left turn = Yes, number of access points in merging direction = 0, number of side streets = 0, number of access points with low turnover rate = 0, number of RIRO access points = 0, traffic control = signalized, speed limit on minor approach = 40 mph, lane width on major approach = 11 ft, lane width on minor approach = 10 ft, U-turn radius = 70 ft, U-turn median width = 60 ft.

$$Exp\Big(-14.500 + \big(0.9523 * Ln(10{,}000)\big) + (0.0006 * 500) + (0.0435 * 0) + (0.1023 * 0) + (-0.0549 * 0) + (0.0586 * 0) + (0.0234 * 40) + (0.2780 * 11) + (0.1393 * 10) + (-0.0053 * 70) + (0.0031 * 60)\Big) * (0.1221 * 1)$$ = 0.90 crashes per year

As we can see from these example, the models developed include both side streets and other access points together in the models. This suggests that these models provide CMFs of both side streets and other access points in their multiplicative form. However, separately, side streets are resulting in more crashes compared to other access points in merging or diverging (PDO crashes only) directions. This implies that reducing number of side streets close to U-turn crossover will lower the crash occurrences to a greater extent, compared to other access points. But for practical planning or designing purposes, reducing the number of side streets might be less likely to be feasible relative to the number of access points.

Table 5.2 Negative Binomial Model Results for Total Crash Frequency (per year)

Fixed Effects					
Parameter	**Estimate**	**SE**	**z-value**	**p-value**	**Exp(β)**
Intercept	-14.5000	1.9160	-7.5660	<0.001	
Natural log of major road AADT	0.9523	0.1090	8.7400	<0.001	
U-turn spacing	0.0006	0.0003	2.5420	0.0110	1.0006
U-turn combined w/ left turn = No	Baseline				
U-turn combined w/ left turn = Yes	0.1221	0.0608	2.0090	0.0446	1.1299
Count of access points in merging direction	0.0435	0.0141	3.0900	0.0020	1.0445
Count of side street access points	0.1023	0.0212	4.8310	<0.001	1.1077
Count of access points with low turnover rate	-0.0549	0.0172	-3.1900	0.0014	0.9465
Count of access points with right-in-right-out (RIRO)	0.0586	0.0307	1.9100	0.0561	
U-turn traffic control type = Signal	Baseline				
U-turn traffic control type = Stop sign	-0.4036	0.0762	-5.2940	<0.001	0.6679
U-turn traffic control type = Yield sign	-0.4713	0.1269	-3.7140	<0.001	0.6242
Speed limit on minor road	0.0234	0.0057	4.1050	<0.001	
Lane width on major road	0.2780	0.1523	1.8250	0.0679	
Lane width on minor road	0.1393	0.0750	1.8570	0.0633	
U-turn radius	-0.0053	0.0023	-2.2820	0.0225	0.9948
Median width of U-turn segment	0.0031	0.0014	2.1930	0.0283	1.0031
Random Effects					
Variance of random effect (intercept): Intersection ID	0.1098				
Std. dev. of random effect (intercept): Intersection ID	0.3313				
Variance of random effect (intercept): Year	0.0079				
Std. dev. of random effect (intercept): Year	0.0888				
Dispersion parameter (theta)	8.5302				
Akaike Information Criterion (AIC)	6348.0				
log-likelihood	-3156.0				

Table 5.3 Negative Binomial Model for Fatal and Injury (FI) Crash Frequency (per year)

Fixed Effects					
Parameter	**Estimate**	**SE**	**z-value**	**p-value**	**Exp(β)**
Intercept	-25.1900	3.2330	-7.7920	<0.001	
Natural log of major road AADT	1.3620	0.1558	8.7440	<0.001	
Natural log of minor road AADT	0.2204	0.0821	2.6860	0.0072	
U-turn spacing	0.0010	0.0003	2.8750	0.0040	1.0010
U-turn combined w/ left turn = No	Baseline				
U-turn combined w/ left turn = Yes	0.2290	0.0937	2.4440	0.0145	1.2573
Count of access points in merging direction	0.0671	0.0227	2.9510	0.0032	1.0694
Count of side street access points	0.0587	0.0340	1.7270	0.0843	1.0605
Count of access points with low turnover rate	-0.0546	0.0282	-1.9400	0.0524	0.9469
Count of one-way access points	0.0787	0.0440	1.7870	0.0740	
U-turn traffic control type = Signal	Baseline				
U-turn traffic control type = Stop sign	-0.5227	0.1194	-4.3770	<0.001	0.5929
U-turn traffic control type = Yield sign	-0.5132	0.1930	-2.6590	0.0078	0.5986
Number of through lanes in diverging direction	-0.1283	0.0615	-2.0870	0.0369	0.8796
Lane width on major road	0.4953	0.2599	1.9050	0.0567	
Lane width on minor road	0.2685	0.0962	2.7920	0.0052	
Random Effects					
Variance of random effect (intercept): Intersection ID	0.1124				
Std. dev. of random effect (intercept): Intersection ID	0.3353				
Variance of random effect (intercept): Year	0.0070				
Std. dev. of random effect (intercept): Year	0.0839				
Dispersion parameter (theta)	8.0138				
Akaike Information Criterion (AIC)	3406.2				
log-likelihood	-1686.1				

Table 5.4 Negative Binomial Model Results for Property Damage Only (PDO) Crash Frequency (per year)

Fixed Effects					
Parameter	**Estimate**	**SE**	**z-value**	**p-value**	**Exp(β)**
Intercept	-12.4000	1.2730	-9.7420	<0.001	
Natural log of major road AADT	1.0090	0.1047	9.6380	<0.001	
U-turn spacing	0.0006	0.0003	2.2390	0.0251	1.0006
Count of access points in merging direction	0.0832	0.0251	3.3120	<0.001	1.0867
Count of access points in diverging direction	0.0520	0.0271	1.9200	0.0548	1.0533
Count of side street access points	0.0950	0.0248	3.8260	<0.001	1.0996
Count of access points with low turnover rate	-0.0628	0.0195	-3.2200	0.0013	0.9392
Count of two-way access points	-0.0428	0.0235	-1.8240	0.0682	
U-turn traffic control type = Signal	Baseline				
U-turn traffic control type = Stop sign	-0.3615	0.0789	-4.5790	<0.001	0.6966
U-turn traffic control type = Yield sign	-0.3993	0.1285	-3.1080	0.0019	0.6708
Number of lanes at U-turn	0.2068	0.1004	2.0600	0.0394	1.2297
Speed limit on minor road	0.0236	0.0056	4.1860	<0.001	
Lane width on minor road	0.1344	0.0747	1.8000	0.0719	
Random Effects					
Variance of random effect (intercept): Intersection ID	0.1039				
Std. dev. of random effect (intercept): Intersection ID	0.3223				
Variance of random effect (intercept): Year	0.0074				
Std. dev. of random effect (intercept): Year	0.0861				
Dispersion parameter (theta)	8.634				
Akaike Information Criterion (AIC)	5943.9				
log-likelihood	-2955.9				

5.2.1 Summary of Findings

The model results revealed several interesting findings. The details of the model results are outlined below:

1. The counts of access points with different definitions, including access point types, and merge/diverge direction, were shown to have statistically significant impacts on crash likelihood for all crash severities to varying extents. Particularly, the count of access points in the merging directions (where the U-turning vehicles merge with the oncoming through traffic) was associated with higher crash likelihoods for total, FI and PDO crashes, compared to no access points in the merging direction.
2. Counts of access points in diverging direction (where U-turning vehicles leave the mainline to enter the U-turn segment) were associated with a higher likelihood for only PDO crashes, compared to no access points in diverging direction. Since U-turning traffic most likely uses the leftmost lanes to access the U-turn crossover, while vehicles entering or exiting access points typically use the rightmost lanes, increasing the number of access points may not lead to a higher number of fatal and injury crashes. It should be mentioned that drivers are prohibited from making a direct maneuver from a driveway (on the diverging direction) into the U-turn crossover based on existing pavement markings at the storage lanes of the U-turn crossovers. However, it is expected that drivers may not follow this, especially at sites where the next U-turn crossover is located much farther away.
3. Among the different access point types, while side streets were associated with higher crash likelihoods, that for access points with low turnover rates (LTR) were associated with lower likelihoods, consistently for all severities, compared to no access points of these types. In other words, while crash frequency is likely to increase if side streets are located within the influence areas of U-turns, it is likely to decrease if we allow driveways with low turnover rates. Although the lower crash likelihoods for access points with low turnover rates (LTR) may seem counterintuitive, this might be attributed to the typically negligible daily traffic entering or exiting such locations (single homes, school and office buildings, and manufacturing facilities). These access points do not pose significant safety concerns and may even cause drivers to be more cautious and reduce speed, due to the perceived potential for conflict. However, this finding warrants further investigation in future studies.
4. In terms of traffic control types, both stop control and yield control at the U-turn were shown to have lower crash likelihoods compared to signal control at the U-turn for all crash severities. The effect of traffic control type at the U-turn was most pronounced for FI crashes. This is counterintuitive and probably due to locations with signal control at the U-turn having higher average traffic volumes. Table 5.5 is provided below to show the traffic volume range and average for the three traffic control types including signalized, stop-controlled, and yield-controlled U-turns.

5. The variable representing whether there was an access point close to the U-turn crossover that allowed vehicles to make a left directly from the U-turn lane was found to be associated with greater likelihoods compared to no such access points for total and FI crashes, but no such effect was observed for PDO crashes. Also, this effect is much stronger for FI crashes compared to total crashes.
6. Increasing U-turn spacing was associated with slightly higher crashes for all crash severities, with the strongest effect for FI crashes. This is consistent with past studies in MN and MS (Moreland et al. 2024; Molan et al. 2025a). As a possible reason, the redirected traffic from minor streets may make lane changes more quickly at U-turns with shorter spacings in order to access the U-turn lanes. As a result, U-turning vehicles spend less time in the rightmost lane (the lane typically used by vehicles entering and exiting access points). From another perspective, these immediate lane changes (due to shorter U-turn spacing) are unlikely to pose a safety concern either, as all the MUTs included are signalized and there will be no weaving maneuvers. In other words, the redirected traffic (from minor streets) has reduced exposure to vehicles from adjacent access points at U-turns with shorter spacings. However, it should be noted that the lower number of crashes may also be attributed to the smaller influence area (or footprint) of U-turn segments located closer to the middle intersection. For example, a U-turn with spacing of 700 ft would have an influence area about 100 ft shorter than a U-turn with a spacing of 600 ft to the middle intersection.
7. Increasing the U-turn radius was associated with slightly lower likelihood for only total crashes. This is an expected finding as vehicles (especially trucks) would experience more gradual turnings.
8. A higher number of through lanes in the diverging direction was associated with a lower crash likelihood for only FI crashes. This should be a result of lower exposure between U-turning vehicles and traffic coming from access points, similar to the possible reason included for the U-turn spacings on the last page.
9. A higher number of lanes at U-turns was associated with a higher crash likelihood for only PDO crashes. This may be due to an increased number of lane change maneuvers, particularly when access points are located shortly after the U-turn and two vehicles make the turn simultaneously. In such cases, a vehicle in the left U-turn lane may attempt to move right to access a driveway right after merging to the major road. However, since most of these lane changes are likely to result in only sideswipe or rear-end collisions, they predominantly lead to PDO crashes rather than fatal or injury (FI) crashes.
10. A higher median width at U-turn segment was associated slightly greater crash likelihood for only total crashes. This could be due to factors similar to those discussed in the previous paragraph regarding the number of lanes at U-turns, as well as higher speeds and/or potential sight distance issues that can arise with wider medians.
11. It is important to note that, although access point type in terms of traffic direction (one-way, two-way, and RIRO) was included in the models, and some of them were

statistically significant, CMFs (i.e., Exp(β)) were not provided for them, as they were correlated with other access point count-related variables (particularly counts of access points in both merging and diverging directions, and counts of side streets).

12. The AADTs on the major roads were statistically significant with a positive association with crash frequency for all crash severities, with the greatest effect for FI crashes. However, minor road AADT had a significant positive association for only FI crashes.
13. Increasing the speed limit on the minor roads was associated with slightly greater crash occurrence for only total and PDO crashes. This might partly stem from the fact that the average crash counts were much higher for roads with >39 mph speed limit (the average value of this variable is approximately 39 mph), compared to those for ≤39 mph.
14. While increasing lane width on minor roads was associated with greater likelihoods for all crash severities, that on major roads was associated with higher crash occurrence for only total and FI crashes. Again, a further dive into the data showed both AADTs and crash frequencies were higher for wider lanes, compared to narrower lanes. Also, wider lanes could result in higher operational speeds (especially higher turning speeds for the redirected traffic from the minor streets).

Table 5.5 Traffic Control Types vs Traffic Volumes

Traffic Control Type	**AADT**	**Minimum**	**Maximum**	**Mean**
Signalized	Major road	15,657	84,843	48,625
	Minor road	3,216	52,809	19,758
Stop-controlled	Major road	36,312	61,601	45,630
	Minor road	1,806	26,414	8,953
Yield-controlled	Major road	40,267	40,267	40,267
	Minor road	9,410	9,410	9,410

Further, a summary of the results specific to U-turn related geometry and other characteristics, and their associated example interpretations are provided in Table 5.6. For each variable, quantification of these effects assumes that all other variables are held constant.

Table 5.6 Summary of effects of U-turn related variables on crash likelihoods

Parameter	**Total Crashes**	**FI Crashes**	**PDO Crashes**	**Example Interpretation**
U-turn spacing	+0.06%	+0.10%	+0.06%	An increase in U-turn spacing by 100 ft *increases* crashes by 0.06%, 0.10%, and 0.06% for total, FI, and PDO crashes, respectively.
U-turn combined w/ left turn = Yes	+12.99%	+25.73%	-	When U-turn have a left turn combined with it, it *increases* crashes by about 13% and 25.7% for total and FI crashes, respectively, compared to when the U-turn does not have a left-turn. No such effect (means no increase or decrease) of this variable is observed on PDO crashes.
Count of access points in merging direction	+4.45%	+6.94%	+8.67%	An increase in 1 (one) access point in merging direction results in *increase* in crashes by 4.45%, 6.94%, and 8.67% for total, FI, and PDO crashes, respectively.
Count of access points in diverging direction	-	-	+5.33%	An increase in 1 (one) access point in diverging direction results in *increase* in PDO crashes by 5.33%. No such effect (means no increase or decrease) of this variable is observed on total and FI crashes.
Count of side street access points	+10.77%	+6.05%	+9.96%	An increase in 1 (one) side street results in *increase* in crashes by about 10.8%, 6.1%, and 10% for total, FI, and PDO crashes, respectively.
Count of access points with low turnover rates	-5.35%	-5.31%	-6.08%	An increase in 1 (one) access point with low turnover rates results in *decrease* in crashes by about 5.4%, 5.3%, and 6.1% for total, FI, and PDO crashes, respectively.
Count of one-way access points	-	+8.19%	-	An increase in 1 (one) one-way access point results in *increase* in FI crashes by about 8.2%. No such effect (means no increase or decrease) of this variable is observed on total and PDO crashes.
Count of two-way access points	-	-	-4.19%	An increase in 1 (one) two-way access point results in *decrease* in PDO crashes by about 4.2%. No such effect (means no increase or decrease) of this variable is observed on total and PDO crashes.
Count of access points with right-in-right-out (RIRO including LRIRO)	+6.03%	-	-	An increase in 1 (one) RIRO access point results in *increase* in total crashes by about 6%. No such effect (means no increase or decrease) of this variable is observed on FI and PDO crashes.
U-turn traffic control type = Stop sign	-33.21%	-40.71%	-30.34%	Stop-controlled U-turns result in *decrease* in crashes by about 33.2%, 40.7%, and 30.3% for total, FI, and PDO crashes, respectively, compared to signalized U-turns.
U-turn traffic control type = Yield sign	-37.58%	-40.14%	-32.92%	Yield-controlled U-turns result in *decrease* in crashes by about 37.6%, 40.1%, and 32.9% for total, FI, and PDO crashes, respectively, compared to signalized U-turns.

The "-" denotes no statistically significant effect of the variable on crash frequency

Table 5.6 Summary of effects of U-turn related variables on crash likelihoods (continued)

Parameter	Total Crashes	FI Crashes	PDO Crashes	Example Interpretation
Number of lanes at U-turn	-	-	+22.97%	An increase in 1 (one) lane at U-turn results in *increase* in PDO crashes by about 23%. No such effect (means no increase or decrease) of this variable is observed on total and FI crashes.
Number of through lanes in diverging direction	-	-12.04%	-	An increase in 1 (one) through lane in diverging direction results in *decrease* in FI crashes by about 12%. No such effect (means no increase or decrease) of this variable is observed on total and FI crashes.
U-turn radius	-0.52%	-	-	An increase in U-turn radius by 25 ft *decreases* total crashes by 12.4%. No such effect (means no increase or decrease) of this variable is observed on FI and PDO crashes.
Median width of U-turn segment	+0.31%	-	-	An increase in U-turn median width by 5 ft *increases* total crashes by 1.55%. No such effect (means no increase or decrease) of this variable is observed on FI and PDO crashes.

The "-" denotes no statistically significant effect of the variable on crash frequency

Figure 5.5 through Figure 5.7 display comparative graphical representations of predicted total crash frequency comparing its base condition with respect to each specific U-turn related characteristics and average daily traffic volumes. In these plots, lane widths on major and minor approaches are fixed at 11 and 10 feet, and speed limit is fixed at 40 mph, which are the closest average values in the data analyzed. In total 9 different reference conditions (shown in dashed lines) are compared with the base condition. The details of considerations for generating these plots are given below:

- **SPF base condition:** No access point in merging direction, no side streets, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn. This is depicted as the black solid line.
- **SPF for U-turn combined with a left-turn:** This shows the predicted crash frequency for U-turns that are combined with a left-turn. All other attributes are same as the base condition, i.e., no access point in merging direction, no side streets, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), and no U-turn spacing.
- **SPF for access points in merging direction:** This shows the predicted crash frequency with 1 (one) access point in the merging direction. All other attributes are same as the base condition, i.e., no side streets, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for

this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn.

- **SPF for side streets:** This shows the predicted crash frequency with 1 (one) side street. All other attributes are same as the base condition, i.e., no access point in merging direction, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn.
- **SPF for U-turn spacing:** This shows the predicted crash frequency with a U-turn spacing of 100 feet. All other attributes are same as the base condition, i.e., no access point in merging direction, no side streets, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), and U-turn is not combined with a left-turn.
- **SPF for U-turn radius:** This shows the predicted crash frequency for U-turns with 45 feet radius, implying 5 feet increase in U-turn radius compared to the base condition. All other attributes are same as the base condition, i.e., no access point in merging direction, no side streets, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn median width of 60 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn.
- **SPF for U-turn median width:** This shows the predicted crash frequency for U-turns with 65 feet median width, implying 5 feet increase in U-turn median width compared to the base condition. All other attributes are same as the base condition, i.e., no access point in merging direction, no side streets, no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn.
- **SPF for access points with low turnover rates:** This shows the predicted crash frequency with 1 (one) access point with low turnover rates. All other attributes are same as the base condition, i.e., no access point in merging direction, no side streets, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn.
- **SPF with 1 (one) side street and 1 (one) access point in the merging direction:** This shows the predicted crash frequency with 1 (one) side street and 1 (one) access point in the merging direction. All other attributes are same as the base condition, i.e., no access points with low turnover rates, no access points of RIRO type, signalized traffic control, U-turn radius of 40 feet (average value for this variable in the data), U-turn median width of 60 feet (average value for this variable in the data), no U-turn spacing, and U-turn is not combined with a left-turn.

- **SPF with 1 (one) side street, 1 (one) access point in the merging direction, U-turn spacing of 100 feet, U-turns combined with a left-turn, U-turns radius of 45 feet, and U-turn median width of 65 feet:** This shows the predicted crash frequency with 1 (one) side street, 1 (one) access point in the merging direction, U-turn spacing of 100 feet, U-turns combined with a left-turn, U-turns radius of 45 feet, and U-turn median width of 65 feet. All other attributes are same as the base condition, i.e., no access points with low turnover rates, and signalized traffic control.

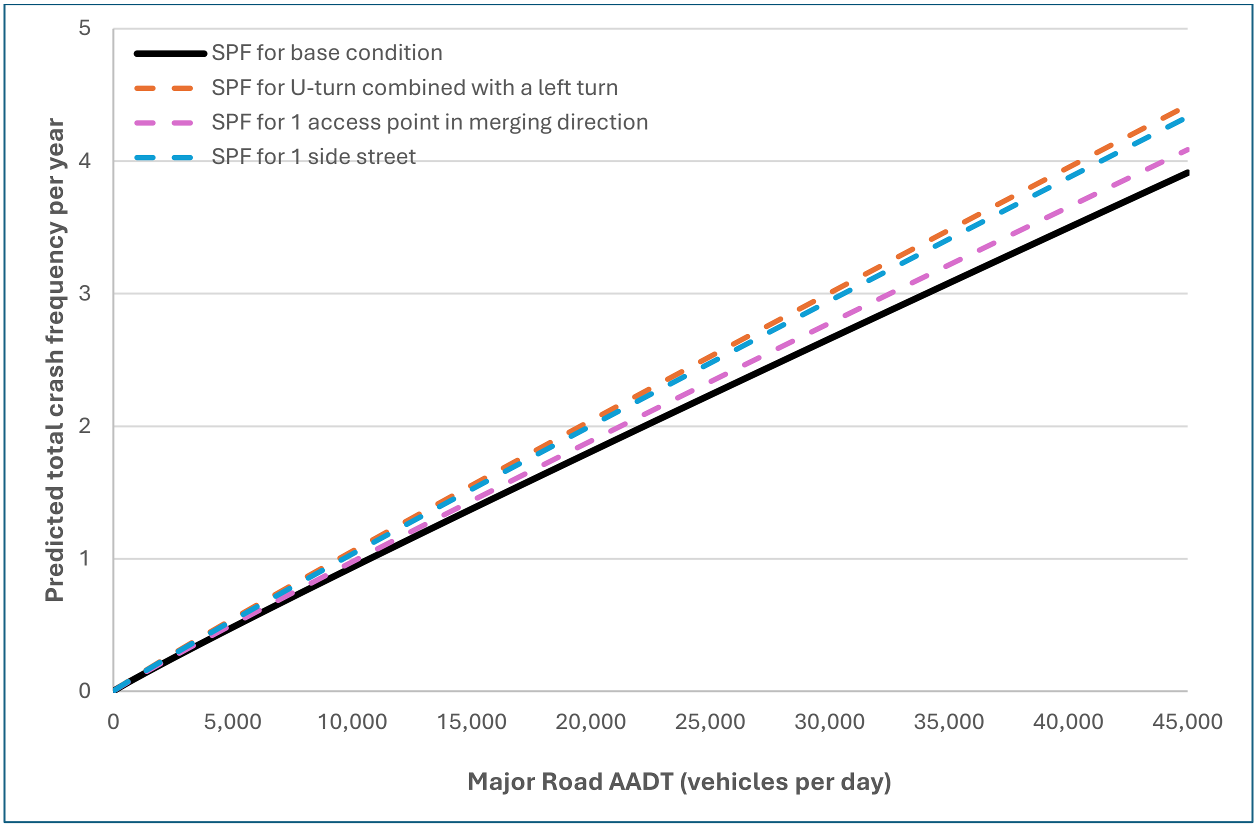

Figure 5.5 Model estimates for total crash frequency per year (plot 1)

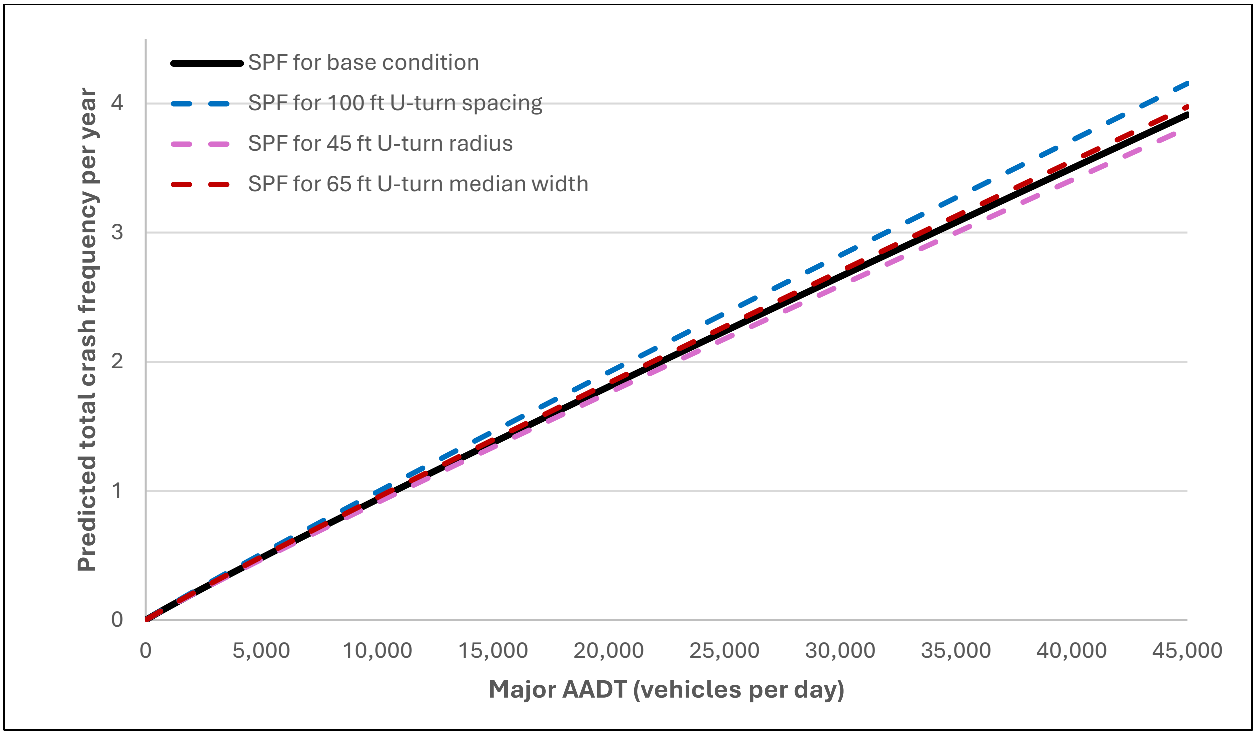

Figure 5.6 Model estimates for total crash frequency per year (plot 2)

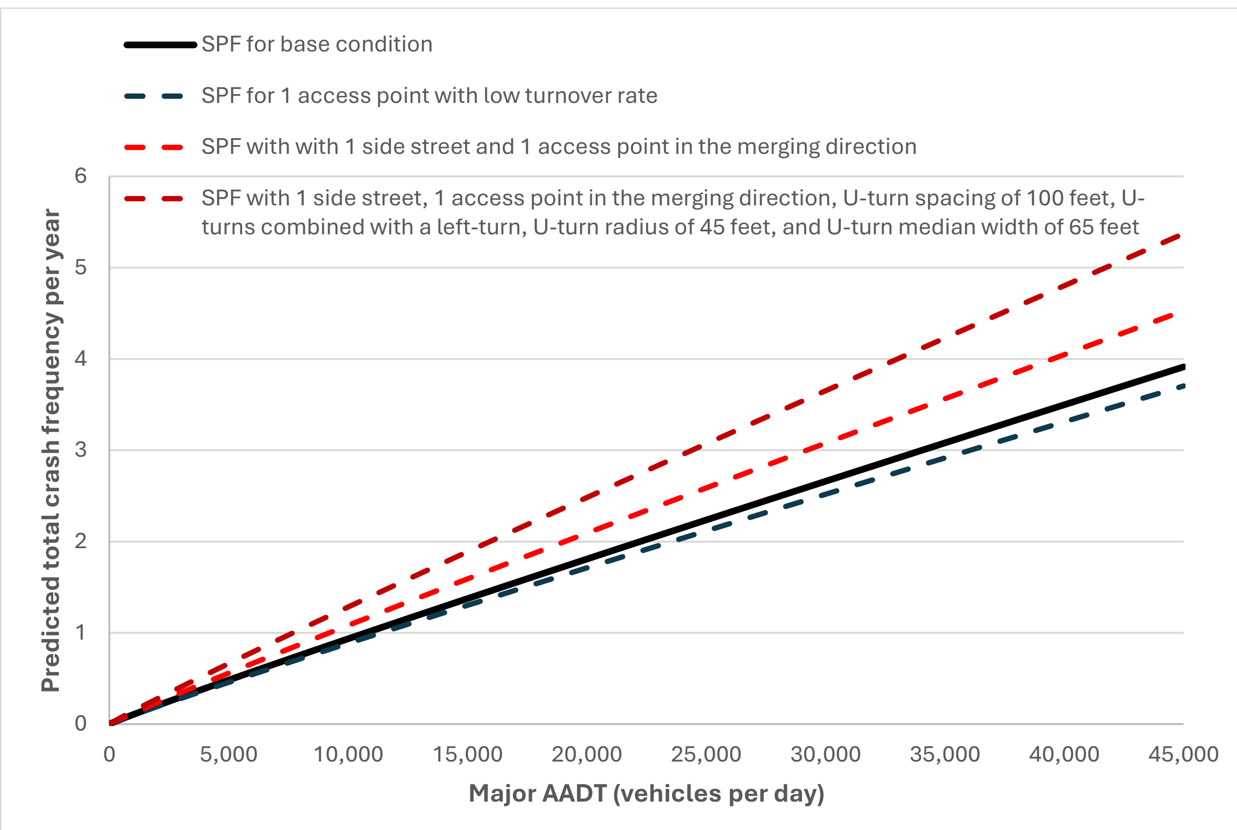

Figure 5.7 Model estimates for total crash frequency per year (plot 4)

5.2.2 Recommended CMFs

As noted before, a Crash Modification Factor (CMF) is a multiplicative factor that indicates the expected number of crashes that would be expected after implementing a countermeasure. CMFs with a value less than 1.0 indicate an expected decrease in crashes, while those greater than 1.0 indicate an expected increase in crashes.

To estimate the number of crashes after implementing a countermeasure, one should multiply the predicted number of crashes without the countermeasure by the CMF value. CMFs help identify the most cost-effective strategy when considering various countermeasures, prioritize safety investments by comparing the expected crash reduction for different countermeasures, and evaluate the effectiveness of the project. CMFs can also be used in benefit-cost analyses to determine if the safety benefits of a project outweigh the costs. Practitioners can use the CMF in quantifying safety in many ways, including as part of the roadway management process, roadway safety audits, alternatives development and analysis, and design decisions. As discussed earlier, some of the results are counterintuitive, and the project team made their best judgement in selecting features for the recommended CMFs.

5.2.2.1 CMFs for Number of Access Points in the Merging Direction

Based on the models estimated, here are the recommended crash modification functions for the number of access points (N_M) in the merging direction:

- Total Crashes: CMF = exp(0.0435*N_M)
- Fatal and Injury Crashes: CMF = exp(0.0671*N_M)
- Property Damage Only Crashes: CMF = exp(0.0832*N_M)

The N_M of 0 corresponds to the situation without any access points in the merging direction, and this is the base condition with a CMF of 1.0. Users can input the number of access points to get the corresponding CMF. For example, an increase of one (1) access point in the merging direction (i.e., N_M =1) is expected to increase crashes of 4.45 percent, 6.94 percent, and 8.67 percent for total, fatal and injury (FI), and property damage only (PDO) crashes, respectively. Note that the average crash frequency for access points in merging direction (i.e., counts of access points in merging direction > 0) is approximately 6.5 crashes per year, 1.3 crashes per year, and 5.2 crashes per year, for total, FI, and PDO crashes, respectively.

5.2.2.2 CMF for Number of Access Points in the Diverging Direction

For the number of access points in the diverging direction (N_D), crash modification functions are recommended only for PDO crashes, because this variable was not statistically significant in the other two models i.e., FI and total crashes:

- Property Damage Only Crashes: CMF = exp(0.0520*N_D)

Here again, N_D of 0 corresponds to the situation without any access points in the diverging direction, and this is the base condition with a CMF of 1.0. Users can input the number of access points to get the corresponding CMF. For example, an increase of (1) access point in the diverging direction (i.e., N_D =1) is expected to result in an increase of 5.53 percent for PDO crashes. Note that the average PDO crash frequency for access points in diverging direction (i.e., counts of access points in diverging direction > 0) is approximately 5.0 crashes per year.

5.2.2.3 CMFs for Number of Side Streets

Based on the models estimated, here are the recommended crash modification functions for the number of side streets (N_S):

- Total Crashes: CMF = exp(0.1023*N_S)
- Fatal and Injury Crashes: CMF = exp(0.0587*N_S)
- Property Damage Only Crashes: CMF = exp(0.0950*N_S)

N_S of 0 corresponds to the situation without any side streets, and this is the base condition with a CMF of 1.0. Users can input the number of side streets to get the corresponding CMF. For example, an increase of one (1) side street type access point resulted in higher crash occurrences by 10.77 percent, 6.05 percent, and 9.96 percent for total, FI, and PDO crashes, respectively. Note that the average crash frequency for side streets (i.e., counts of side streets > 0) is approximately 6.1 crashes per year, 1.3 crashes per year, and 4.8 crashes per year for total, FI, and PDO crashes, respectively.

5.2.2.4 CMFs for Allowing Left Turns from the U-Turn Lane

The base condition for this CMF is that left turns are not allowed directly from the U-turn lanes. If left turns are allowed, the CMFs associated with these are the following for total and FI crashes. However, no such effect is observed for PDO crashes:

- Total Crashes: CMF = exp(0.1221*LT_{UTurn})
- Fatal and Injury Crashes: CMF = exp(0.2290* LT_{UTurn})

LT_{UTurn} is a binary variable with a value of 0 and 1. LT_{UTurn} of 0 corresponds to the situation where left turns are not allowed directly from the U-turn lanes, and this is the base condition with a CMF of 1.0. Similarly, LT_{UTurn} of 1 corresponds to the situation where left turns are allowed directly from the U-turn lanes. The CMF results indicate that situations where left turns are allowed directly from the U-turn lanes resulted in higher crash occurrences by 12.99 percent, and 25.73 percent for total and FI, crashes, respectively, compared to situations where left turns are not allowed directly from the U-turn lanes. Note that the average crash frequency for U-turn allowing left-turns from the U-turn lanes is approximately 7.9 crashes per year and 1.7 crashes per year, for total and FI crashes, respectively.

5.2.2.5 CMF for Increase in Radius of U-turns

This CMF is expressed on the basis of the increase in the radius of the U-turn in feet (I_R). The base condition is that $I_R = 0$. The following crash modification function is only recommended for total crashes, as no such effect is observed for FI and PDO crashes:

- Total Crashes: $CMF = \exp(-0.0053*I_R)$

Users can input the increase in radius to determine the CMF. For example, an increase in the radius of 25 feet at the U-turn will lead to a CMF of 0.876, i.e., about a 12% reduction in total crashes. Note that the average total crash frequency for sites with U-turn radius greater than 40 ft, which is the average U-turn radius of all sites, is approximately 6.1 crashes per year.

5.2.2.6 CMF for Increase in the Number of Through Lanes in Diverging Direction

The increase in the number of through traffic lanes in the diverging direction is denoted by T_D. The base condition is $T_D = 0$. The following crash modification function is recommended for fatal and injury crashes. However, no such effect is observed for total and PDO crashes:

- Fatal and Injury Crashes: $CMF = \exp(-0.1283*T_D)$

Users can input the increase in the number of lanes in the diverging direction to determine the CMF. For example, an increase of 1 (one) lane in the diverging direction is expected to lead to a CMF of 0.88, i.e., a 12 percent reduction in FI crashes. Note that the average FI crash frequency for sites with number of lanes in diverging direction greater than 3, which is the average number of lanes in the diverging direction of all sites, is approximately 1.4 crashes per year.

Chapter 6. Conclusions and Future Research

This study used data from 132 MUTs (264 U-turns) from the State of Michigan to investigate the safety aspects of access control at the U-turns. Crash data from 2019 to 2023 were used to estimate crash prediction models relating counts of crashes (total, fatal-and-injury, and PDO) with the characteristics of the U-turns. Some of the U-turns were access-controlled, while others had access. Crash prediction models were estimated using negative binomial regression. The coefficients from these models could be used to derive crash modification factors and crash modification functions. The models produced useful results but also had some results with potential for further investigations in future studies. The project team used their best judgment to develop recommended CMFs for selected features of the U-turns which were summarized in Section 5.2.2.

The following are selected results from the evaluation:

1. Access points with different definitions, including access point types and merge/diverge direction, were shown to have statistically significant impacts on crash likelihood for all crash severities to varying extents. Particularly, access points in the merging directions were associated with higher crash likelihoods for total, FI and PDO crashes, compared to no access points in the merging direction. However, access points in diverging direction were associated with higher likelihood for only PDO crashes, compared to no access points in a diverging direction.
2. Among the different access point types, while side streets were associated with higher crash likelihoods, access points with low turnover rates were associated with lower likelihoods, consistently for all severities, compared to no access points of these types. The lower crash likelihoods for access points with low turnover rates (compared to no access points) may be counterintuitive, but the lower crash likelihood for low turnover rates compared to side streets is as expected.
3. The variable representing whether there was an access point close to the U-turn crossover that allowed a vehicle to make a left directly from the U-turn lanes was found to be associated with greater crash likelihoods compared to no left turns for total and FI crashes, but no such effect was observed for PDO crashes. Also, this effect is much stronger for FI crashes compared to total crashes.
4. Increasing the U-turn radius was associated with slightly lower likelihood for total crashes.
5. An increase in the number of through lanes at U-turns in the diverging direction was associated with a lower crash likelihood for FI crashes.

Crash modification factors and/or crash modification functions were recommended for the following parameters:

- Number of access points in the merging direction,
- Number of access points in the diverging direction,
- Number of side streets,
- Allowing left turns from the U-turn lanes,
- Increase in the radius of U-turns,
- Increase in the number of through lanes in the diverging direction.

The findings from this study help provide recommendations to transportation practitioners and researchers to improve the safety performance of MUTs with regard to the access points/driveways and side streets in the near proximity of the MUT crossovers. For example, while for both access points in the merging and diverging directions were found to increase crash likelihoods, design recommendations might include consolidating closely-spaced access points, essentially minimizing the access point density adjacent to MUTs, and therefore minimizing traffic conflicts. Also, U-turns without left turns and with higher number of through lanes in diverging directions could be suggested to improve the safety performance.

Based on the study findings, the research team was able to identify the following avenues for future research:

- This study identified that access points with lower turnover rates (LTR) resulted in lower crash occurrence compared to no access points with LTR. This finding warrants further investigation, including design considerations based on estimated turnover rates at access points in future research.
- The impact of access points on safety could be incorporated into existing tools and methods, such as the FHWA Safe System Intersection (SSI) framework (Porter et al., 2021). The SSI scores, as estimated following FHWA's methodology, do not currently consider the impact of access points near intersections, even though these access points introduce additional conflict points within the intersection network.
- Identifying crashes that occurred primarily due to access points requires reviewing each crash report individually. This was not feasible in the current study due to the high number of crashes involved (over 7,000). However, future studies employing video-analytic tools to identify near-miss events over a period of one week or more could be useful to further investigate the safety impact of access points.
- Recommendations for thresholds for traffic volumes (AADT or hourly volume) at U-turn crossovers and access points could be helpful to inform the design and selection of access point types (e.g., left-in, RIRO, two-way driveway, or one-way driveway). In the current study, the research team could not consider the traffic volume of access points as a factor

in the analysis, as volume data were not available from online resources. Obtaining such data would have required field data collection, which was not feasible within the scope of this project, as all locations were in another state (Michigan), and over 1,100 access points were collected through data collection efforts.

- Lastly, future research should attempt to account for differences in crash trends during COVID years.

6.1 Implementation and Technology Transfer

The CMFs developed in this research provide valuable information to NCDOT's state of knowledge and are expected to be used as part of the safety management process and for alternative analysis. These CMFs will be of interest to NCDOT's traffic safety and traffic management units and offer insights pertaining to the safety effects of MUTs and their nearby access points to transportation researchers, professionals, and industry experts. The research team held meetings with NCDOT Steering and Implementation Committee throughout this project to receive their feedback and ascertain that the study meets the expectations. To encourage and facilitate implementation, the research team will value the opportunity of presenting this research as part of a webinar and invite attendees from various groups within NCDOT including the Traffic Safety Unit, Traffic Management Unit, Roadway Design Unit, the 14 Divisions within NCDOT, and the Project Management Staff. The research team also aspires that the products from this project will follow up with research articles to conference proceedings and/or peer-reviewed journal articles.

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Appendix A: List of variables and their associated statistical significance

Table 7: The exhaustive list of variables considered in the model development and their associated statistical significance in the final model

Variable	Total Crashes	FI Crashes	PDO crashes
U-turn spacing (ft)	Significant	Significant	Significant
Left turn combined with U-turn crossover	Significant	Significant	Not significant
Number of access points in merging direction	Significant	Significant	Significant
Number of access points in diverging direction	Not significant	Not significant	Significant
Number of side streets	Significant	Significant	Significant
Number of access points with low turnover rates	Significant	Significant	Significant
Number of access points with high turnover rates	Not significant	Not significant	Not significant
Number of one-way access points	Not significant	Significant	Not significant
Number of two-way access points	Not significant	Not significant	Significant
Number of RIRO access points	Significant	Not significant	Not significant
Traffic control = Stop	Significant	Significant	Significant
Traffic control = Yield	Significant	Significant	Significant
Number of through lanes in the merging direction	Not significant	Not significant	Not significant
Number of through lanes in the diverging direction	Not significant	Significant	Not significant
Total number of lanes at U-turn	Not significant	Not significant	Significant
Intersection angle at U-turn (degrees)	Not significant	Not significant	Not significant
U-turn radius (ft)	Significant	Not significant	Not significant
Median width of U turn segment (ft)	Significant	Not significant	Not significant
AADT on major road (veh/day)	Significant	Significant	Significant
AADT on minor road (veh/day)	Not significant	Significant	Not significant
Truck percent on major road (%)	Not significant	Not significant	Not significant
Truck percent on minor road (%)	Not significant	Not significant	Not significant
Speed limit on major road (mph)	Not significant	Not significant	Not significant
Speed limit on minor road (mph)	Significant	Not significant	Significant
Lane width on major road (ft)	Significant	Significant	Not significant
Lane width on minor road (ft)	Significant	Significant	Significant

Appendix B: Data for all 132 sites

The analysis data comprising only MUT sites are added here as an attachment. In this data, each site is repeated twice (bringing the total number of observations to be 264 = 2x132 MUT sites) separately for left- and right-side characteristics.

Appendix B_Analysis Data.xlsx