2023

Report SPR-FY22(012)

Final Report
26-1121-4058-001

Inventory, Operations, and Safety at Free Right-Turn Ramps

Aemal Khattak, PhD
Director, Mid-America Transportation Center
Professor, Department of Civil & Environmental Engineering
University of Nebraska-Lincoln

Jonathon Camenzind, MS
Graduate Research Assistant
Department of Civil &
Environmental Engineering
University of Nebraska-Lincoln

MM Shakiul Haque, PhD
Postdoctoral Research Associate
Department of Civil &
Environmental Engineering
University of Nebraska-Lincoln

Mid-America Transportation Center
330E Prem S. Paul Research Center at
Whittier School 2200 Vine Street
Lincoln, NE 68583-0851

(402) 472-8126
http://matc.unl.edu

This report was funded through a grant from the U.S. Department of Transportation Federal Highway Administration. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. Department of Transportation.

INVENTORY, OPERATIONS, AND SAFETY AT FREE RIGHT-TURN RAMPS

Dr. Aemal J. Khattak, PhD
Director, Mid-America Transportation Center
Professor, Department of Civil & Environmental Engineering
University of Nebraska-Lincoln
Lincoln, NE 68583

Dr. MM Shakiul Haque, PhD
Postdoctoral Research Associate
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln
Lincoln, NE 68583-0851

Jonathon Camenzind, MS
Graduate Research Assistant
Department of Civil & Environmental Engineering
University of Nebraska-Lincoln
Lincoln, NE 68583-0851

Sponsored by
Nebraska Department of Transportation and U.S. Department of Transportation Federal Highway Administration

May 31, 2023

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SPR-FY22(012)		

4. Title and Subtitle
Inventory, Operations, and Safety at Free Right-Turn Ramps

5. Report Date
May 31, 2023

6. Performing Organization Code

7. Author(s)
Dr. Aemal J. Khattak, Jonathon Camenzind, Dr. MM Shakiul Haque

8. Performing Organization Report No.
26-1121-4058-001

9. Performing Organization Name and Address
University of Nebraska-Lincoln
2200 Vine Street, PO Box 830851
Lincoln, NE 68583-0851

10. Work Unit No.

11. Contract or Grant No.
SPR-FY22(012)

12. Sponsoring Agency Name and Address
Nebraska Department of Transportation
1500 Nebraska 2
Lincoln, NE 68502

13. Type of Report and Period Covered
NDOT Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This research focused on traffic safety and operational performance of rural, minor approach stop-controlled intersections with free right-turn (FRT) ramps. The objectives of the research were to:

- Create a statewide inventory of rural FRT ramp intersections and provide to the Nebraska Department of Transportation (NDOT),
- Using NDOT 10-year crash data, conduct statistical safety analysis of rural FRT intersections extending ¼-mile in each direction from the intersection,
- Study vehicular operations at rural intersections with and without FRT ramps including a comparison of vehicular conflicts, and
- Develop guidelines for operations and safety tradeoffs to assist with NDOT projects on maintaining similar locations, removing, or reconstructing ramps.

As of 2023, 79 FRT ramps exist at 68 rural highway intersections in Nebraska. FRT ramps may be located on three-legged or four-legged intersections and may be on the minor, the major, or both minor and major approaches of the same intersection. The research compared the 68 rural FRT ramp intersections to 24 similar non-FRT rural intersections to identify differences in crash frequencies, crash rates, and crash severity using 2010-2019 crash data from NDOT. The analysis did not show any statistically significant differences between the two intersection groups. This result is identical to a 1995 Nebraska-based study of rural FRT ramp intersection safety.

The research investigated vehicular conflicts between right-turning vehicles by pairing six non-FRT intersections with six FRT ramp intersections and collecting data using video recording equipment. The comparison was between vehicular conflicts experienced by right-turning traffic on the same approach of the FRT ramp and non-FRT intersections. Data analysis showed that non-FRT right-turns on the minor approach, major approach with no exclusive right-turn lane, and major approach with an exclusive right-turn lane experienced statistically significantly higher conflicts per 1,000 entering right-turning vehicles than FRT ramp intersections.

A VISSIM microsimulation model of traffic operations at FRT ramp intersections and non-FRT intersections enabled the creation of 324 scenarios, based on varying traffic and roadway geometry. Assuming a 20-year lifespan, benefit cost (B/C) analysis was conducted for combinations of discount rates (4%, 6%, and 8%), major road AADT (5,000; 10,000; 15,000), minor road AADT (2,500; 5,000; 7,500), percent right turning traffic (10%, 25%, 50%), FRT ramp radius in feet (650; 1,200; 1,800) and speed limit in mph (45, 55, 65). Traffic operational benefits are the basis for considering FRT ramp construction, reconstruction, or removal at rural, minor approach stop-controlled intersections in Nebraska. The reason is the absence of any discernable differences in safety at FRT ramp and comparable non-FRT intersections. NDOT can make more informed decisions on FRT ramp intersections based on guidance in this report.

17. Key Words	18. Distribution Statement
Safety, Intersection, Free Right Turn, Ramp, Traffic, Operations	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	157	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Transportations nor the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report.

The United States (U.S.) government and the State of Nebraska do not endorse products or manufacturers. This material is based upon work supported by the Federal Highway Administration under SPR-1(19) (M092). Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration."

This report has been reviewed by the Nebraska Transportation Center for grammar and context, formatting, and 508 compliance.

NOTE: This report uses the term 'crash' to refer to vehicular collisions on roadways resulting in property damage and/or injuries and fatalities. However, the term 'accident' is also used when referring to legacy items or when referencing or quoting published literature.

Acknowledgments

The authors thank the members of the Technical Advisory Committee (Alan Swanson, Scott Milliken, Kris Fornoff, Kyle Christensen, Abe Anshasi) for their guidance and input throughout this study. The authors are thankful for the help received from the NDOT Research Division (Mark Fischer, Lieska Halsey, Dina Harris) with all aspects of this research project. Abdul Farhan (UNL student) is acknowledged for his help with data collection and extraction from recorded video.

Table of Contents

TECHNICAL REPORT DOCUMENTATION PAGE i
Disclaimer ii
Acknowledgments iii
Abstract viii
Chapter 1 Introduction 2
1.1 Background 2
1.2 Research Objectives 4
1.3 Report Outline 5
Chapter 2 Literature Review 6
2.1 Free Right-Turn Ramps 6
2.2 Rural, Unsignalized Intersections 13
2.3 Sight Distance 15
2.4 Acceleration and Deceleration Lanes 16
Chapter 3 Inventory of FRT Ramp Intersections 17
3.1 Identifying FRT Ramps and their Intersections 17
3.2 FRT Ramp Intersection Characteristics 19
3.3 Traffic Volume 20
Chapter 4 Inventory of Comparison Intersections 22
Chapter 5 Safety Analysis 25
5.1 Methodology 25
5.1.1 Empirical Bayes Method 25
5.1.2 Crash Frequency and Crash Rate with Test of Significance 26
5.1.3 Modeling Crash Frequencies 28
5.1.4 Method Selection 30
5.2 Data Collection 30
5.3 Analysis and Results 33
5.4 Significance Testing 37
5.5 Modeling Results 37
Chapter 6 Traffic Conflict Analysis 40
6.1 Background 40
6.2 Methodology 40
6.2.1 Conflict Definitions 42
6.3 Conflicts Observed at Each Site 44
6.3.1 Category 1: Low AADT, 3-Leg 45
6.3.2 Category 2: Low AADT, 4-leg 45
6.3.3 Category 3: Medium AADT, 3-Leg 46
6.3.4 Category 4: Medium AADT, 4-Leg 47
6.3.5 Category 5: High AADT, 3-Leg 48
6.3.6 Category 6: High AADT, 4-Leg 49
6.4 Analysis and Results 50
Chapter 7 Traffic Operations Analysis 53
7.1 Background 53
7.2 Methodology 54
7.3 Data Preparation 55
7.3.1 Data Collection Site Characteristics 55

7.3.2 Data Collection and Processing 61
7.4 Microsimulation Modelling 63
7.4.1 Microsimulation Model Calibration Method 64
7.4.2 Calibration and Validation Results 68
7.4.3 Sensitivity Analysis 70
7.5 Feasibility Studies of FRT Ramp 71
7.5.1 Scenario Development 72
7.5.2 Operational and FRT Construction Costs 73
7.5.3 Benefit Cost Analysis 75
Chapter 8 Summary and Conclusions 78
8.1 Research Summary and Results 78
8.1.1 Inventory of FRT and non-FRT Intersections 78
8.1.2 Safety Analysis 79
8.1.3 Conflict Analysis 80
8.1.4 Operational Analysis 82
8.2 Conclusions 83
8.3 Limitations and Future Research 84
References 86
Appendix A 91
Appendix B 110
Appendix C 113
Appendix D 139
Appendix E 142

List of Figures

Figure 1.1 Typical FRT Ramp Sketch (McCoy et al., 1995).. 3

Figure 2.1 Dilemma Zone Faced by Drivers on the Minor Approach (Pawar & Patil, 2017)..... 14

Figure 3.1 Map of all FRT Ramp Intersections in Nebraska 18

Figure 4.1 Map of Non-FRT Intersections for Comparison 24

Figure 5.1 Crashes from 2010-2019 at N16/N35 FRT Intersection 31

Figure 5.2 Crash Severity Comparison 32

Figure 5.3 Crash Type Comparison 33

Figure 6.1 Miovision Scout Camera (https://miovision.com/scout/scout-hardware) 42

Figure 6.2 Low AADT, 3-Leg Intersections 45

Figure 6.3 Low AADT, 4-Leg Intersections 46

Figure 6.4 Medium AADT, 3-Leg Intersections.. 47

Figure 6.5 Medium AADT, 4-Leg Intersections.. 48

Figure 6.6 High AADT, 3-Leg Intersections 49

Figure 6.7 High AADT, 4-Leg Intersections 50

Figure 7.1 Three-Legged One-way Stop-Controlled Intersection with FRT Ramp at Bone Creek, Nebraska (Location coordinates: 41.333405, -97.129290)... 56

Figure 7.2 Four-legged Unsignalized Intersection with an FRT Ramp at Marietta, Nebraska (Location coordinates: 41.2341865, -96.502896)... 57

Figure 7.3 Three-legged Unsignalized Regular Intersection at David City, Nebraska (Location coordinates: 41.206305, -97.129958) 59

Figure 7.4 Four-legged Unsignalized Regular intersection at Avoca, Nebraska (Location coordinates: 40.813046, -96.178535) 60

Figure 7.5 Data Collection Devices 61

Figure 7.6 Miovision Device Locations at the Four Test Sites.. 62

Figure 7.7 Miovision Data Extraction using MAC Addresses 63

Figure 7.8 Vehicle Pattern Observed Using Unique Object from Miovision............................. 63

Figure 7.9 Microsimulation Model Calibration Algorithm (Haque et al., 2022)......................... 65

Figure 7.10 Critical Left-Turn Movement from Minor Road to Major Road............................. 68

List of Tables

Table 2.1 Comparison of Public's Concerns of FRT Removal and Findings of McCoy's Research 8
Table 2.2 Summary of FRT-Related Research 12
Table 3.1 Breakdown of the Intersections Containing FRT Ramps 18
Table 3.2 Breakdown of FRT Ramp Approaches 19
Table 3.3 2018 AADT by Intersection Type 20
Table 4.1 Non-FRT Ramp Intersection AADT Averages 23
Table 5.1 Crash Frequency Comparison 35
Table 5.2 Crash Rate Comparison 36
Table 5.3 Negative Binomial Model for 10-year Crash Frequency 39
Table 6.1 Intersections for Conflict Analysis 41
Table 6.2 Conflict Analysis Results 51
Table 6.3 Traffic Conflict Scenario Results 52
Table 7.1 Microsimulation Calibration Results for Intersections with and without FRT Ramp . 69
Table 7.2 Calibrated Microsimulation Parameter Values for Drive Behavior and Gap Acceptance Model 70
Table 7.3 Sensitivity Analysis Results of Three Scenarios 71
Table 7.4 Cost Components and Unit Values for Operation, Construction and Maintenance 74
Table 7.5 Benefit cost ratio (B/C) for FRT Ramp under Different Traffic and Geometric Conditions 76

Abstract

This research focused on traffic safety and operational performance of rural, minor approach stop-controlled intersections with free right-turn (FRT) ramps. The objectives of the research were to:

- Create a statewide inventory of rural FRT ramp intersections and provide to the Nebraska Department of Transportation (NDOT),
- Using NDOT 10-year crash data, conduct statistical safety analysis of rural FRT intersections extending ¼-mile in each direction from the intersection,
- Study vehicular operations at rural intersections with and without FRT ramps including a comparison of vehicular conflicts, and
- Develop guidelines for operations and safety tradeoffs to assist with NDOT projects on maintaining similar locations, removing, or reconstructing ramps.

As of 2023, 79 FRT ramps exist at 68 rural highway intersections in Nebraska. FRT ramps may be located on three-legged or four-legged intersections and may be on the minor, the major, or both minor and major approaches of the same intersection. The research statistically compared the 68 rural FRT ramp intersections to 24 similar non-FRT rural intersections to identify differences in crash frequencies and crash rates using 2010-2019 crash data from NDOT. The analysis did not show any statistically significant differences between the two intersection groups. This result is identical to a 1995 Nebraska-based study of rural FRT ramp intersection safety.

The research investigated vehicular conflicts between right-turning vehicles by pairing six non-FRT intersections with six FRT ramp intersections and collecting data using video recording equipment. The comparison was between vehicular conflicts experienced by right-

turning traffic on the same approach of the FRT ramp and non-FRT intersections. Data analysis showed that non-FRT right-turns on the minor approach, major approach with no exclusive right-turn lane, and major approach with an exclusive right-turn lane experienced statistically significantly higher conflicts per 1,000 entering right-turning vehicles than FRT ramp intersections.

A VISSIM microsimulation model of traffic operations at FRT ramp intersections and non-FRT intersections enabled the creation of 324 scenarios, based on varying traffic and roadway geometry. Assuming a 20-year lifespan, benefit cost (B/C) analysis was conducted for combinations of discount rates (4%, 6%, and 8%), major road Annual Average Daily Traffic (AADT) (5,000; 10,000; 15,000), minor road AADT (2,500; 5,000; 7,500), percent right turning traffic (10%, 25%, 50%), FRT ramp radius in feet (650; 1,200; 1,800) and speed limit in mph (45, 55, 65). Traffic operational benefits are the basis for considering FRT ramp construction, reconstruction, or removal at rural, minor approach stop-controlled intersections in Nebraska. The reason is the absence of any discernable differences in the crashes at FRT ramp and comparable non-FRT intersections. NDOT can make more informed decisions on FRT ramp intersections based on guidance in this report.

Chapter 1 Introduction

1.1 Background

Free right-turn (FRT) ramps are alternative right-turn lane designs for intersecting highways. In Nebraska, FRT ramps can be found in both rural and urban areas. In rural areas, they are typically located at two-way stop-controlled (TWSC) intersections, meaning traffic on the major road is free-flowing, while traffic on the minor road is controlled by a stop sign. Previous research, design standards, warrants, etc. are sparse, so there is no universal definition of an FRT ramp. For this research, a study conducted by McCoy et al. (1995) titled *Guidelines for Free Right-Turn Lanes at Unsignalized Intersections on Rural Two-Lane Highways*, was relied upon as a starting point when looking for definitions and common characteristics of FRT ramps. Therefore, an FRT ramp is being defined as it was in McCoy's research as "a turning roadway at an intersection to provide for free-flowing right-turn movements".

Figure 1.1 represents a typical FRT ramp in Nebraska, as depicted by McCoy. From the figure, the FRT ramp is located on the minor approach which is stop-controlled, with the major approach being uncontrolled. Leading to the ramp is a deceleration lane to separate the through traffic from the right-turning traffic. At the end of the ramp is an acceleration lane, which provides a safe merge with through traffic on the major approach. At the exit of the FRT ramp, before the acceleration lane, is a yield sign which indicates the right-turning vehicles must yield to the major through traffic, which has the right-of-way.

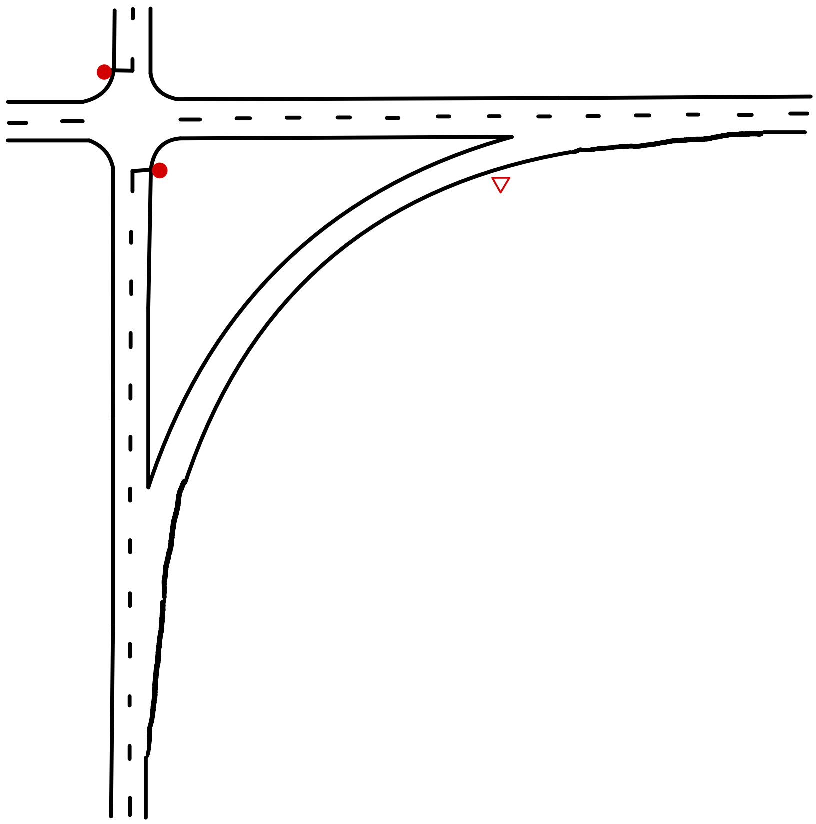


Figure 1.1 Typical FRT Ramp Sketch (McCoy et al., 1995)

The layout of an FRT ramp is not exclusive to the figure presented above. For example, FRT ramps may also be located on the major approach, or even on both a major and minor approach at the same intersection. Additionally, rather than having an acceleration lane to merge with the crossing-through traffic, a designated lane may exist, so that right-turning drivers do not have to merge at all. In this case, the yield sign would not be present. While there are no strict guidelines for what dictates a free right-turn ramp, the focal concept is that a free right-turn ramp is a right-turn lane design found at rural two-way stop-controlled highway intersections, in which right-turning vehicles can make unimpeded right turns separated from through traffic, at free-flow speeds.

The idea in constructing free right-turn ramps at intersections is to reduce delay for right-turning vehicles, as well as make the turning maneuver safer by separating the right-turning traffic from the through traffic. The specific benefits experienced from the use of an FRT ramp by right-turning drivers differ slightly from when it is located on the minor approach versus when it is located on the major approach. As in Figure 1.1, when an FRT ramp is located on the minor approach, delay is reduced because the driver does not have to slow to a stop, wait for an acceptable gap in traffic, then turn right. Instead, the driver can turn at a comfortable speed and merge with the crossing-through traffic. For the case of the ramp being located on the major approach, conflict is reduced in addition to delay reduction. Typically, rural highways are two lanes, therefore, through traffic and right-turning traffic have to share the same lane at intersections. If a vehicle on the major road slows to make a right turn and there is no right-turn lane of any kind, a following-through vehicle traveling at a high rate of speed will have to slow down to avoid a rear-end collision. The FRT ramp eliminates this problem by separating the traffic. These various scenarios will be explored in this research.

1.2 Research Objectives

The main objective of the research is to statistically assess the safety of rural FRT intersections using the crash frequencies and crash rates, along with a two-sample t-test. Other objectives include:

- Identification of rural FRT intersections including geographic locations in Nebraska for analysis,
- Identification of rural non-FRT intersections that are similar to the FRT intersections based on considerations of intersection geometry and traffic characteristics,

- Collection of police-reported crashes for rural FRT intersections as well as for the non-FRT intersections for the period 2010-2019,
- Safety analysis using the collected data,
- Operational analysis of right-turning traffic at FRT intersections (conflict comparison of right-turning traffic at FRT and non-FRT intersections), and
- Safety and operational tradeoff analysis to determine the feasibility of FRT ramps.

1.3 Report Outline

This research was conducted in six steps.

1. A detailed literature review of free right-turn ramps and topics associated with safety at rural, highway intersections.
2. Collection of Nebraska crash data from 2010 to 2019.
3. Collection of traffic conflicts using video recording equipment.
4. Statistical analyses of the traffic crash data.
5. Statistical analyses of the conflict data.
6. Examination of the safety and conflict results.
7. Feasibility studies of FRT ramps.

Chapter 2 Literature Review

Published literature on free right-turn ramps is somewhat scarce, as the concept is not widely utilized by many state transportation agencies. For those states that do use FRT ramps at rural intersections, guidelines, design standards, safety analyses, etc., are limited. This literature review first presents a discussion of the studies that are directly related to FRT ramps, followed by other topics that are related and relevant to traffic operations and safety of rural, unsignalized intersections containing an FRT ramp. These other topics include operations and safety at unsignalized, rural intersections, intersection sight distance, and acceleration and deceleration lanes.

2.1 Free Right-Turn Ramps

Free right-turn (FRT) ramps, also referred to as FRT lanes in prior research, are being defined in this study as "turning roadways for free-flowing right-turn movements at intersections, typically used to provide a high level of service at high-speed, high-volume intersections" (McCoy et al., 1995). The terms "FRT ramps" and "FRT lanes" will be used synonymously, as different reports use different verbiage, although they identify the same concept. A study conducted by McCoy et al. (1995) of the University of Nebraska-Lincoln, developed traffic volume warrants for when it was necessary to construct an FRT lane at two, two-lane rural, unsignalized intersections. Also included in the study was a discussion of the public's perspective regarding FRT lanes and a safety analysis comparing intersections with and without an FRT lane.

During the period in which McCoy's research was being conducted, an intersection in Genoa, Nebraska was going through the process of having an existing FRT lane removed. Citizens that frequented the intersection opposed this decision. From the perspective of the drivers, FRT lanes remedy concerns that non-FRT approaches present. Some of these concerns, stated by citizens via a survey, were the inconvenience of having to slow down and stop to make a right turn, needing to speed back up to merge with cross traffic, and difficulty in making right turns for large trucks, especially in icy conditions. Because of the speed changes and sudden stopping required to turn, citizens believed that the occurrence of rear-end crashes would be significantly lower with FRT lanes present at the intersection.

These concerns were tested through a safety analysis in which 32 approaches with an FRT lane on two, two-lane rural highways were selected. These approaches had stop-controlled or uncontrolled through traffic with yield-controlled or uncontrolled FRT lanes. Fifty-seven non-FRT approaches with similar traffic and geometric characteristics were chosen for comparison. The safety analysis concluded that the presence of an FRT lane did not affect the frequency, severity, or types of accidents that occurred on approaches to unsignalized intersections of rural two-lane highways. Rear-end accidents were shown to decrease with the presence of an FRT lane, but these results were not statistically significant.

During field tests of intersections with FRT and non-FRT lanes, McCoy et al. (1995) concluded that FRT lanes reduce travel distances, speed changes, and delays of right-turning vehicles. After conducting a benefit-cost analysis, traffic volume warrants were created in which an intersection's right-turning daily volume and percent trucks traffic determined whether an FRT lane was warranted or not. Percent trucks was included because FRT lanes were found to provide greater operational cost savings to trucks than to passenger cars. Because the crash analysis was not statistically significant, it was not included as a part of the FRT warrants. In the recommendations of this research, it was stated: "FRT lanes should not be promoted to enhance safety, but to improve operational efficiency of right-turn movements" (McCoy et al., 1995).

Table 2.1 provides a summary of McCoy's research in terms of the public's concerns regarding the removal of an FRT lane at an intersection in Genoa, Nebraska compared to the findings from the study.

Table 2.1 Comparison of Public's Concerns of FRT Removal and Findings of McCoy's Research

Public's Concerns of FRT Lane Removal	Research Findings	Public's Concerns Supported through Research?
An intersection with an FRT lane would be safer than an intersection without an FRT lane	A safety analysis concluded that the presence of an FRT lane does not affect the frequency, severity, or types of accidents that occur	No
FRT lanes remedy the inconvenience of having to slow down, stop, and speed back up when completing a right turn	Data from field tests revealed that FRT lanes reduce travel distances, speed changes, and delays of right-turning vehicles	Yes
FRT lanes make the right-turning process for trucks easier and safer, especially at night and during icy conditions	Data from field tests revealed that FRT lanes provide even greater operational cost savings to trucks than they do to passenger cars	Yes

A study by Yang (2008) established warrants for FRT lanes as well. In this research, a statistical model was developed based on the concept of two-lane roadways where a decelerating right-turning vehicle forces the following through vehicle to decelerate to avoid a possible rear-end collision (Yang, 2008). Warrants were subsequently created where the total through traffic volume of the approach and the percentage of right-turning traffic determined whether an FRT lane was necessary. It was noted that traffic volume should not be the only factor in the decision of whether or not to construct an FRT lane. According to Yang (2008), in cases where other operational or safety factors have a significant impact, engineering judgment should be used.

The National Cooperative Highway Research Program (NCHRP) Report 208 titled *Design Guidance for Channelized Right-Turn Lanes* (2014), provides a good understanding of FRT ramps, when they may be warranted, and their advantages and disadvantages. The primary reasons for adding an FRT ramp are to increase vehicular capacity at intersections, reduce delay to drivers by allowing them to turn at higher speeds, reduce unnecessary stops, clearly define the appropriate path for right-turn maneuvers at skewed intersections or at intersections with high right-turning traffic volumes, improve safety by separating the points at which crossing conflicts and right-turning traffic merge conflicts occur, and to permit the use of large curb radii to accommodate large turning vehicles (Potts et al., 2014). A significant advantage of FRT ramps is that delay to right-turning drivers is reduced. Yield-controlled FRT ramps can reduce right-turn delay by 25 to 75 percent compared to conventional right-turn lane designs (Potts et al., 2014). The use of acceleration and deceleration lanes can also reduce delay by allowing vehicles to separate from through traffic and have easier merge capabilities. An issue with FRT ramps is the conflict of turning vehicles with pedestrians. However, because the focus of this research is on rural intersections where there is little-to-no pedestrian traffic, that concern should not be of much influence, which was also stated in the NCHRP report.

The *NDOT Roadway Design Manual* (2012) does not contain much information on FRT ramps. They are identified in the text as “free-flow right-turn lanes.” These lanes are defined as channelized right-turn lanes at intersections, providing free-flow turn movements. The design of these turn lanes consists of "a deceleration lane leading to a horizontal curve, providing a gradual speed reduction with a more natural turning path for the driver" (Nebraska Department of Transportation, 2012). The document then references "Widths for Turning Roadways at Intersections" in *A Policy on Geometric Design of Highways and Streets (2011)* for further information.

Similar to the FRT ramp as defined in this research, a free right-turn channel is a free-flowing right-turn lane that is separated from through traffic, with a designated lane after the right-turn movement (Macfarlane et al., 2011). This design differs from an FRT ramp in that it requires no merging once the right-turn movement has been made. Free right-turn channels reduce delay, fuel emissions, and right-turn conflicts with crossing through traffic. A problem found with this design is that drivers tend to yield to cross traffic upon completing the turn even though it is not necessary, due to the added lane designated for right-turning traffic. This conflict thus increases delay at the intersection. A remedy suggested by the researchers was to add signage instructing drivers that they do not need to yield.

In another study regarding free right-turn channels, an email survey asked approximately 1,000 responding participants to indicate how they would behave at several right-turn lane designs at signalized intersections (i.e., STOP, YIELD, PROCEED, WAIT) (Macfarlane et al., 2011). These designs included free right-turn channels, yield right-turn channels, and standard right-turn lanes. The results showed that a statistically significant proportion of drivers behaved similarly at all intersection treatments, regardless of signage or channelization. This results in unnecessary added delay, as a free right-turn channel's purpose is to eliminate delay for right-turning vehicles.

Table 2.2 provides a summary of the related research on FRT ramps and the main findings and/or conclusions drawn from them.

Table 2.2 Summary of FRT-Related Research

Research Topic	Author(s)	Main Findings
Free Right-Turn Lanes	McCoy et al., 1995	The presence of an FRT lane does not affect the frequency, severity, or types of accidents that occur
		The public often prefers FRT lanes, compared to non-FRT lanes, noting perceived safety and operational benefits
Free Right-Turn Lanes	Yang, 2008	Warrants were created for free right-turn lanes, based on total through volume and percentage of right turns
		It is recommended that volume should not be the only consideration when deciding to construct a free right-turn lane or not
Channelized Right-Turn Lanes	Potts et al., 2014	Yield-controlled FRT ramps can reduce right-turn delay by 25 to 75 percent, compared to conventional right-turn lane designs
Free-Flow Right-Turn Lanes	Nebraska Department of Transportation, 2012	These lanes consist of a deceleration lane leading to a horizontal curve, providing a gradual speed reduction with a more natural turning path for the driver
Free Right-Turn Channels	Macfarlane et al., 2011	FRT channels reduce delay, fuel emissions, and right-turn conflicts with crossing through traffic
		FRT channels provide a designated lane after the right-turn maneuver, rather than just an acceleration lane
		Drivers tend to yield to cross traffic after completing the turn, creating unnecessary added delay
Free Right-Turn Channels	Macfarlane et al., 2011	It was found that a statistically significant portion of drivers behave similarly at all intersection treatments, regardless of signage or channelization

2.2 Rural, Unsignalized Intersections

Intersections, compared to roadway segments, have greater potential for traffic crashes due to the complexity of traffic movements and potential conflicts between vehicles on the major and minor approaches (Kim et al., 2006). A typical rural, unsignalized intersection is a two-way, stop-controlled (TWSC) intersection. At these intersections, the major roadway traffic is free-flowing (uncontrolled), while the minor roadway traffic is stop-controlled. Drivers on the minor approach must decide on an acceptable gap in traffic to proceed through the intersection or make a turn. These intersections typically experience a higher crash frequency and severity than other rural intersections because of the difficulty in selecting gaps and poor decision-making by drivers on the minor approach (Leckrone et al., 2011). Comparing unsignalized and signalized, rural intersections, it has been noted that 90 percent of fatalities occur at the former, while 10 percent of fatalities occur at the latter (Pawar & Patil, 2017). The area of the major roadway segment where minor approach drivers must analyze conflicts is often called the "dilemma zone." The dilemma zone is the zone of a major roadway segment over which, if a vehicle is present with a certain speed, a dilemma is created for minor road vehicles regarding maneuvering (Pawar & Patil, 2017). If drivers on the minor approach are aggressive or misjudge the vehicles in the dilemma zone, potential conflict arises. Table 2.2, taken from Pawar and Patil's (2017) research, illustrates situations in which a driver can easily reject a gap, easily accept a gap, and one in which a dilemma arises where the decision is not clear.

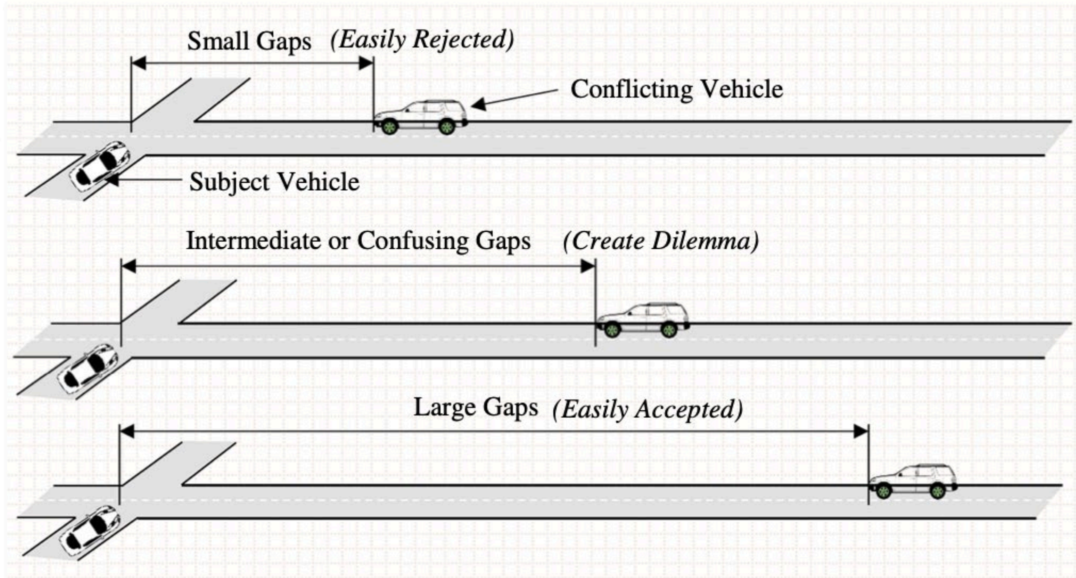


Figure 2.1 Dilemma Zone Faced by Drivers on the Minor Approach (Pawar & Patil, 2017)

An Indiana study analyzed 600 TWSC intersections and determined potential solutions to reducing the frequency and severity of crashes at these intersections. The authors recommended adding acceleration lanes, increasing the intersection angle, widening medians to more than 80 feet, and improving recognizability of intersections to improve safety (Leckrone et al., 2011). In an Iowa study, changes to signage on the minor roads and median were investigated by adding a double-yellow center line in the median and yield/stop bars, adding advance in-lane rumble strips for minor roadway traffic, and right- and left-turn lanes were recommended for safety improvement (Maze et al., 2004). There is no "fix-all" solution to solving the safety issues at rural, unsignalized intersections and many state agencies take measures that best suit their economic and operational needs.

On the topic of the minor approach of TWSC intersections, operations are also significantly influenced by the drivers' behavior. Drivers' decision on gap acceptance when judging vehicles in the “dilemma zone” affects delay at the intersection (Khattak & Jovanis, 1990). Some drivers are more conservative and experience anxiety in these situations, and they may not accept gaps that would be considered acceptable, thus increasing the delay experienced by the following vehicles. The type of signage present on the minor approach also has effects on traffic operations. Comparing stop control and yield control, yield control shows a decrease in travel time, gasoline consumption, and exhaust emissions (Hall et al., 1978).

2.3 Sight Distance

Sight distance at rural, unsignalized intersections can be a potential safety hazard for vehicles on the minor approach. If an exclusive right-turn lane is present on the major road, drivers on the minor road have restricted sight distance. This can be dangerous because vehicles traveling on the major roadway are traveling at high speeds, so if a minor approach driver’s view is obstructed by a right-turning vehicle, a potential conflict could arise if the driver on the minor approach enters the intersection and does not see a vehicle traveling through on the major road (Zeidan & McCoy, 2000). A study of right-turn-on-red situations at signalized intersections revealed that with the obstructed sight distance, right-turning vehicles on the minor approach often accepted smaller gaps, which could have increased conflicts as a result (Yan & Richards, 2009). A solution to the sight distance obstruction, presented by an Auburn University research team, is to offset the right-turn lane on the major approach, thus giving vehicles on the minor approach a clearer view of traffic on the main road (Zhou et al., 2017). This idea was studied at the University of Nebraska as well, in which design guidelines were provided on how to maximize the sight distance at TWSC intersections by using offset right-turn lanes (Schurr & Foss, 2010). Research on offset right-turn lanes in Nebraska was explored further in 2018, where economic and safety benefits were compared to intersections with non-offset right-turn lanes or no right-turn lanes at all (Khattak & Kang, 2018).

2.4 Acceleration and Deceleration Lanes

Acceleration and deceleration lanes provide both operational and safety benefits when accompanied by an FRT ramp. Deceleration lanes provide a means of safe deceleration outside the through-lane traffic and a means of separating right-turning vehicles from other traffic at stop-controlled intersection approaches (Potts et al., 2007). In low-traffic scenarios like FRT ramp locations, drivers can decelerate earlier and at higher speeds than in high-traffic scenarios, thus creating the expectation of a safe decelerating environment (Calvi et al., 2012). Potential conflicts increase as the deceleration lane length decreases; therefore, careful consideration should be taken when designing deceleration lanes (Bared et al., 1999).

Acceleration lanes provide an opportunity for vehicles to complete the right-turn maneuver unimpeded and then accelerate parallel to the cross-street traffic before merging. Depending on the type of traffic control, traffic volume, and other characteristics, acceleration lanes can reduce right-turn delay by 65 to 85 percent (Potts et al., 2014). Traffic volumes on the major roadway affect whether or not a driver accepts a gap when merging, and merging length increases as traffic volume increases. Unlike deceleration lanes, the length of the acceleration lane does not significantly influence drivers' speed, decision-making, or conflicts (Calvi & De Blasiis, 2011). From McCoy's research, a survey was sent out to which 37 states' transportation agencies responded, and the majority of the concerns regarding FRT ramps was safety while merging from the FRT lane to the through traffic, therefore, an acceleration lane was highly suggested when designing FRT ramps (McCoy et al., 1995).

Chapter 3 Inventory of FRT Ramp Intersections

At the beginning of this research, there was no complete inventory of the FRT ramps in Nebraska. The first objective of this research, therefore, was to develop one.

3.1 Identifying FRT Ramps and their Intersections

The process began using the latest edition of the *Nebraska Highway Reference Logbook*, which identifies structures, grade changes, and other important characteristics of the highways, spurs, and connecting links in Nebraska by their numbered highway markings. Using a simple keyword search of the pdf file of the logbook, "RAMP" was searched, in which interchanges, weigh station entrances and exits, and a multitude of right-turn lane designs, including free right-turn ramps, were selected. Of the approximately 1,200 results, the interchanges and weigh stations were eliminated through a simple search on Google Earth, using the highway markings provided in the logbook as reference. With roughly 200 "ramps" remaining, criteria were developed so that only suitable FRT ramps would be selected for this study. These criteria included: the ramps being located in rural areas, with uncontrolled or yield-controlled traffic operations at the merge point; the major road being free-flowing (uncontrolled); and the minor road through traffic being stop-controlled. In the end, 79 FRT ramps were identified at 68 intersections, with 11 intersections having 2 FRT ramps. Figure 3.1 presents all 68 rural FRT ramp intersections on the Nebraska highway system.

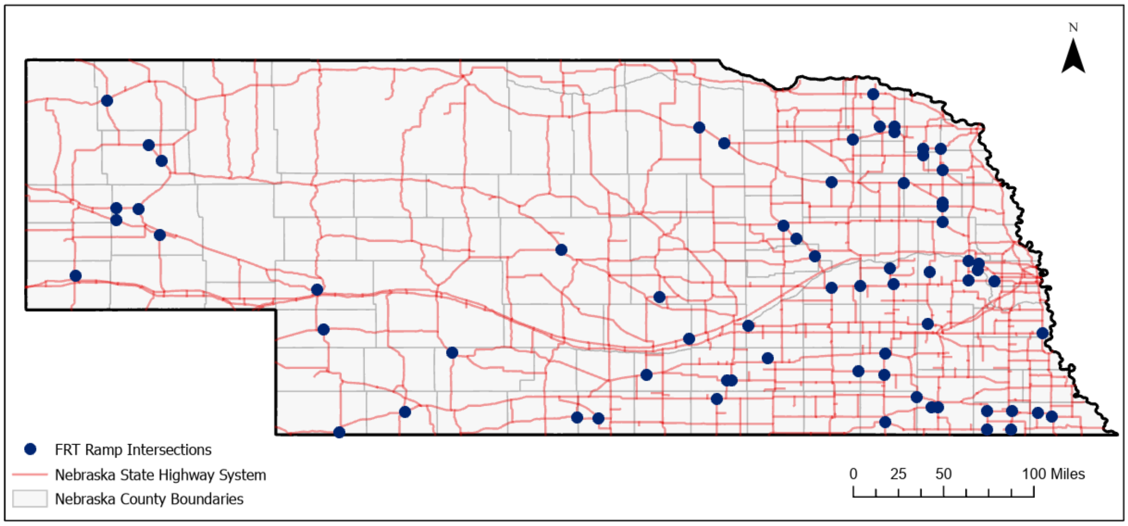


Figure 3.1 Map of all FRT Ramp Intersections in Nebraska

Table 3.1 shows the number of intersections containing an FRT ramp, categorized into three-legged and four-legged intersections, as well as showing whether these intersections contain one or two FRT ramps. It is clear from the table that four-legged intersections are home to the majority of the two-ramp fixtures, with only one three-legged intersection having two FRT ramps. Additionally, it is a fairly even split between three-legged and four-legged intersections in relation to the presence of at least one FRT ramp.

Table 3.1 Breakdown of the Intersections Containing FRT Ramps

	3-Leg Intersections	4-Leg Intersections	All Intersections
Intersections with:			
1 FRT Ramp	30	27	57
2 FRT Ramps	1	10	11
Total	**31**	**37**	**68**

Regarding the FRT ramps themselves, rather than their intersections, Table 3.2 shows the number of FRT ramps at each intersection configuration, and if their location is on the major (uncontrolled) or minor (stop-controlled) approach. Although the number of intersections containing an FRT ramp are fairly even between three-legged and four-legged, four-legged intersections have more FRT ramps in total due to the significant number of intersections containing two ramps. Also, from the table, the majority of the FRT ramps are located on the major approach rather than the minor approach, especially for three-legged intersections.

Table 3.2 Breakdown of FRT Ramp Approaches

	3-Leg Intersections	4-Leg Intersections	All Intersections
FRT Ramps	**32**	**47**	**79**
On Minor Approach	5	18	23
On Major Approach	27	29	56

3.2 FRT Ramp Intersection Characteristics

With the FRT ramps identified, their characteristics and the characteristics of their intersections were of interest. Using Google Earth and NDOT's Pathweb online database, information describing the intersection, such as the number of legs, presence of lighting, and county, were recorded. Regarding the major and minor roads of the intersections, information such as the number of lanes, presence of shoulders, surface material, etc., were recorded. Additionally, for the FRT ramp itself, signage present, type of channelizing island, FRT radius, FRT length, and presence of acceleration and deceleration lanes were recorded. These data were stored in an Excel spreadsheet for easy access. Appendix A provides a complete list of the variables that were logged as a part of the FRT ramp intersection inventory process, some basic

FRT intersection characteristics, and a breakdown of the FRT intersections and ramps by the county they are located in.

3.3 Traffic Volume

In addition to the characteristics in Appendix A, the traffic volume of the FRT ramp intersections from 2010 to 2019 was obtained to match the years of crash data used for this study. Because the intersections of interest are in rural areas, traffic volume was not always easily attainable. NDOT produced state highway Annual Average Daily Traffic (AADT) maps for 2010, 2012, 2014, 2016, and 2018, however, there were no reliable data found for the odd years. To substitute the missing data, this research used a simple average between the even years. For example, the 2011 AADT was taken as an average of the 2010 and 2012 values. To find the AADT of each intersection and give the total entering traffic volume, each highway leg's AADT was summed. In a few four-legged intersection cases, the fourth leg was unpaved or a non-highway local road. A value of 50 was used for the AADT of that leg, as NDOT stated that as typical practice. The traffic volume data for each FRT intersection, for each year from 2010 to 2019 is tabulated in Appendix A.

For identifying non-FRT comparison intersections, the year 2018 was chosen as the best option to represent the AADT of the intersections. This is because it is the most recent data available, while not being affected by potentially skewed values as a result of the COVID-19 pandemic. Table 3.3 shows the average 2018 AADT values of three-legged, four-legged, and all intersections with an FRT ramp.

Table 3.3 2018 AADT by Intersection Type

Intersection Type	3- Legged Intersections	4-Legged Intersections	All Intersections
Number of Intersections	31	37	68
Average 2018 AADT	8518	8478	8496

Chapter 4 Inventory of Comparison Intersections

Non-FRT ramp intersections were identified to serve as comparison locations to the FRT ramp intersections. Efforts were made to identify non-FRT ramp intersections that were similar to the FRT ramp intersections based on the number of legs, total through lanes of the major approach, and range of AADT. The first criterion was finding two-way stopped-controlled (TWSC) intersections located in rural areas. The majority of the FRT ramp intersections were two, two-lane highways, so that was the secondary deciding factor. Using the 2018 AADT of the FRT intersections, summary statistics were calculated, giving the average, range, and quartiles accounting for all FRT ramp intersections in Nebraska. The intersections were then divided into FRT ramps located at both three-legged and four-legged intersections. The year 2018 was selected for the AADT because the post 2018 years were potentially influenced by the COVID-19 pandemic and may not be representative of “normal” values. For three- and four-legged intersections, the quartile values were used as limits for three ranges of AADT—"Low," "Medium," and "High." Six categories exist with these AADT ranges: Low, Medium, and High AADT for three-legged intersections and Low, Medium, and High AADT for four-legged intersections. Four sites were identified for each of these categories to comply with the other criteria, totaling 24 non-FRT ramp comparison intersections. The AADT ranges, as well as the 2018 AADT averages for the selected comparison sites, are given in Table 4.1.

Table 4.1 Non-FRT Ramp Intersection AADT Averages

Three-Legged Intersections				
AADT Range	Lower Limit	Upper Limit	Number of Non-FRT Ramp Intersections	Average 2018 AADT
LOW	4,657	6,720	4	5,203
MEDIUM	6,721	10,098	4	7,808
HIGH	10,099	27,050	4	15,323
Four-Legged Intersections				
LOW	4,714	9,068	4	7,120
MEDIUM	9,069	13,888	4	11,349
HIGH	13,889	23,338	4	15,983

The locations of the non-FRT ramp comparison intersections are identified in Figure 4.1. The majority of the intersections selected for this study were in Eastern Nebraska for the needs of the conflict analysis, which will be presented later. Field visits had to be made to many of these sites, therefore they were chosen for shorter travel times.

Appendix B has basic non-FRT intersection characteristics, location by county, and the ten-year AADT values for each site.

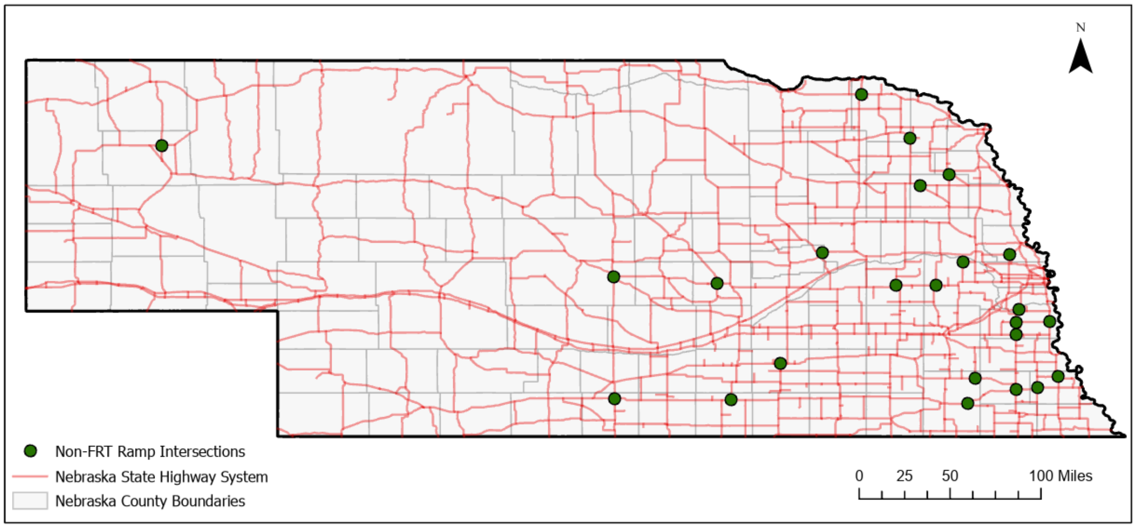


Figure 4.1 Map of Non-FRT Intersections for Comparison

Chapter 5 Safety Analysis

5.1 Methodology

The research team considered several methods for the safety analysis of the FRT ramp intersections. The first was the Empirical Bayes method, the second was a comparison of crash frequencies and crash rates with a t-test measuring significance, while the last method was the use of the Poisson family of models for modeling crash frequencies.

5.1.1 Empirical Bayes Method

Before-after studies are often used in transportation safety analyses. To determine the effect of some treatment, safety before and after the treatment can be measured, and if nothing else changes, any change in safety can be attributed to the treatment. This is referred to as a simple or naïve before-after study because the assumption that no other variables affect changes between the two periods is simplistic. A comparison group is often used to account for this shortcoming. The idea is that any other variables (i.e., weather, geometric characteristics, etc.) that may affect safety, will do so similarly to the sites with and without the treatment in the before and after periods, thus eliminating the flaw of the naïve before-after study, although issues may still arise with this procedure.

The Empirical Bayes method is thought to be the best version of the before-after study using a comparison group, as it accounts for the regression-to-mean problem and offers more precise estimations (Hauer, 1997). The Empirical Bayes method requires information about the safety of other similar entities, referred to as the reference population, and the crash history of the entity.

5.1.2 Crash Frequency and Crash Rate with Test of Significance

Crash frequency and crash rate are two representations of safety for roadway segments and intersections. Crash frequency (F) is a straightforward crash count during a specified time period (usually 12 months) or the total number of crashes (C) divided by the number of years (N), as shown by Equation 5.1, giving crashes per year as an output.

$$F = \frac{C}{N} \tag{5.1}$$

A limitation of relying on simple crash frequency for safety assessment is that it does not account for traffic volume, which is known to substantially impact crash frequency. Therefore, when comparing a low-AADT intersection to a high-AADT intersection, the latter will inherently have a higher crash frequency due to the greater possibility of crash occurrence (i.e., greater crash exposure). Crash rate, on the other hand, accounts for exposure, setting all locations, from those with low AADT to high AADT on an even playing field. Crash rate (R) was calculated by using Equation 5.2,

$$R = \frac{C * 1{,}000{,}000}{N * V * 365} \tag{5.2}$$

where C is the total number of crashes in the study period, N is the number of years of data, and V is the daily entering traffic volume. Crash rate is given as crashes per million entering vehicles.

When comparing the crash frequency or crash rate of a group of intersections, it is good practice to use a test of significance to identify whether any changes in safety are statistically significant or not. Because the crash rates of FRT ramp intersections and non-FRT ramp intersections were compared in this case , a two-sample t-test was used to measure the significance of the two means. The null hypothesis of the two-sample t-test is $H_0\colon \mu_1 = \mu_2$, or $H_0\colon \mu_1 - \mu_2 = 0$, meaning that there is no observed difference between the two tested means. The alternative hypothesis is $H_A\colon \mu_1 \neq \mu_2$, or $H_A\colon \mu_1 - \mu_2 \neq 0$, meaning there is an observed difference between the two tested means. A two-sample t-statistic is calculated from the data in question and compared to a critical t-value that is determined from the Student's t-table, given the degrees of freedom and a chosen alpha value (probability of making a Type 1 error: rejecting the null hypothesis when it is true). If the two-sample t-statistic is greater than the critical t-value, it can be said that sufficient evidence is available to reject the null hypothesis and conclude that the two means are different. If the two-sample t-statistic is less than the critical t-value, it would be concluded that there is not sufficient evidence to reject the null hypothesis.

The two-sample t-statistic was calculated using Equation 5.3, with $\bar{x}_1 - \bar{x}_2$ being the difference in means, $(\mu_1 - \mu_2)_0 = 0$, n_1 and n_2 being the sample sizes of the two populations, and s_p^2 being the pooled sample variance. The pooled sample variance is calculated using Equation 5.4, with s_1^2 and s_2^2 being the sample variances of the two respective populations.

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)_0}{\sqrt{\frac{s_p^2}{n_1} + \frac{s_p^2}{n_2}}} \tag{5.3}$$

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{5.4}$$

5.1.3 Modeling Crash Frequencies

Crash frequencies comprise of count data that are appropriately modeled with the Poisson family of models. The basic Poisson model is a statistical model used for analyzing count data, in which the model assumes that the count data follow a Poisson distribution, which describes the probability of observing a certain number of events in an interval or area. The Poisson distribution is a probability distribution that is characterized by a single parameter, λ, which represents the mean or expected value of the count data. The distribution assumes that the events occur independently and at a constant rate over time or area. The count data are modeled as a function of one or more explanatory variables, which can be categorical or continuous. The model assumes that the logarithm of the expected count, denoted by log(λ), is a linear function of the explanatory variables. Equation 5.5 represents the model.

$$\log(\lambda) = \alpha + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_p x_p \tag{5.5}$$

where λ is the mean or expected value of the count data, x is the explanatory variable, and α and β are the intercept and coefficients of the explanatory variables, respectively. An advantage of the Poisson model is its simplicity and ease of interpretation. It assumes that the events occur independently and at a constant rate, which makes it suitable for analyzing count data that satisfies these assumptions. The model assumes that the variance of the count data is equal to its mean, which may not always be the case in practice. In cases where the variance of the count data is larger than the mean, indicating overdispersion, the negative binomial model may be more appropriate.

The negative binomial model is a statistical model for count data when the data exhibit overdispersion, which occurs when the variance of the data is larger than the mean. The negative binomial distribution is a probability distribution that describes the probability of observing a certain number of events in a given interval or area. The distribution is characterized by two parameters: the mean or expected value, denoted by μ, and the dispersion parameter, denoted by α. The mean represents the average number of events that are expected to occur, while the dispersion parameter measures the degree of variation in the data. The count data are modeled as a function of one or more explanatory variables, which can be categorical or continuous. The model assumes that the count data follows a negative binomial distribution and estimates the parameters of the distribution using maximum likelihood estimation. Equation 5.6 presents the model equation.

$$\log(E(Y|x)) = \beta_o + \beta_1 x1 + \beta_2 x_2 + ... + \beta_p x_p \tag{5.6}$$

where Y is the count data, x is the explanatory variable, β_o is the intercept, and β_1, $\beta_{2, \ldots,}$ β_p are the estimated coefficients of the explanatory variables. The log link function is used to ensure that the predicted values are non-negative.

One of the main advantages of the negative binomial model is its flexibility in handling overdispersed count data. The model can also handle data with excess zeros, which occur when a large proportion of the data points have a count of zero. This is achieved by adding an extra parameter to the model, known as the zero-inflation parameter, which measures the proportion of excess zeros in the data.

5.1.4 Method Selection

While the Empirical Bayes method is a good option for measuring changes in safety due to a safety treatment (in this case the FRT ramp), this research lacked clear "before" and "after" periods. The before period for each site would be the duration before the FRT ramp was constructed, and the after period would be the duration from when it was constructed up until the present day. Because this information was not available, it was impossible to conduct a before-after analysis using the Empirical Bayes method. Therefore, this research relied on comparisons of crash frequencies and crash rates of FRT-ramp and non-FRT-ramp intersections and tests for significance thereafter, as well as modeling crash frequencies using the negative binomial model (overdispersion in crash data, i.e., mean < variance).

5.2 Data Collection

The NDOT provided police-reported crashes in Nebraska from 2010 to 2019, along with the crash location geographic coordinates (latitude and longitude). These crashes were uploaded to ArcGIS and plotted using their geographic coordinates. Also using ArcGIS, shapefiles for the FRT ramp and non-FRT ramp intersections were created and plotted along with the crashes. The research took into consideration crashes reported within a quarter-mile of the center point of the intersection for each intersection leg and for each site. For each FRT-ramp and non-FRT-ramp intersection, polygon buffers were created in ArcGIS with a radius of 0.25 miles. Crashes occurring in these created buffers were then exported into separate shapefiles corresponding to each intersection. Figure 5.1 illustrates this process for the four-legged State Highway 16/State Highway 35 FRT intersection located in Wayne County.

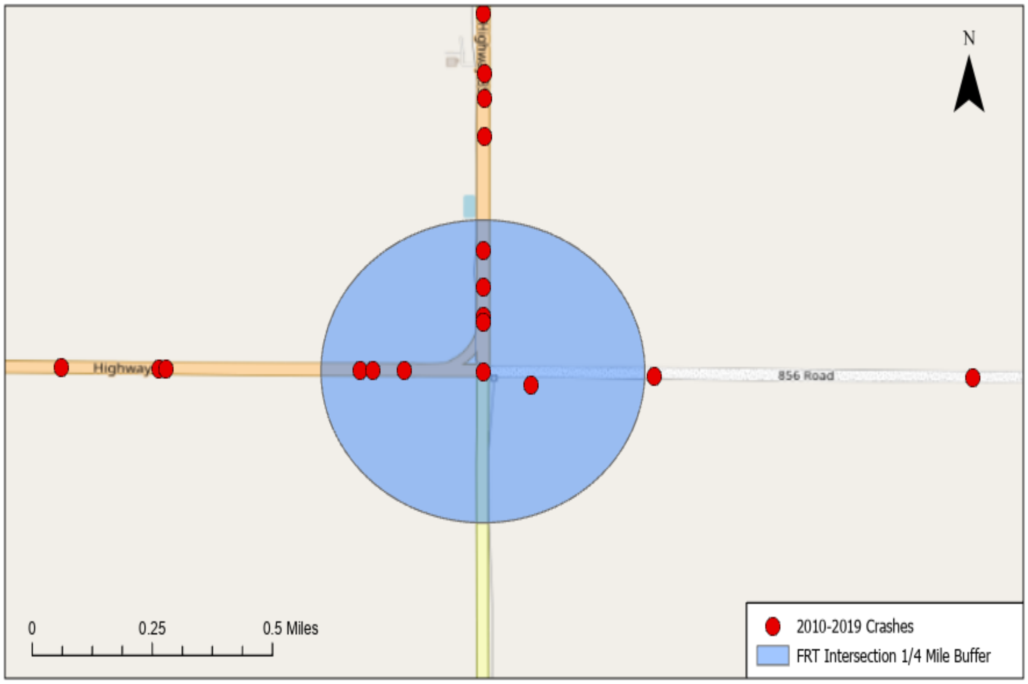


Figure 5.1 Crashes from 2010-2019 at N16/N35 FRT Intersection

With shapefiles created for each FRT and non-FRT intersection containing the crashes occurring a quarter-mile from the center point of the intersection, the attribute tables were exported as an Excel file for data analysis. Examples of data found in these attribute tables include crash severity, crash type, number of involved vehicles, road conditions, weather conditions, and presence of alcohol impairment, to name a few. Appendix C details the crashes reported at each intersection, for each year, for both FRT and non-FRT intersections.

Figure 5.2 compares the crash severity experienced at all FRT-ramp and non-FRT-ramp intersections. These categories are presented on the x-axis in order of increasing severity. The categories correspond to the usual KABCO severity scale as: K = fatal injury, A = suspected serious injury,/disabling injury, B = visible injury, C = possible injury, and O = property damage only, while the non-reportable crash category is not included in the KABCO scale. Overall, the comparison reveals little differences in crash severity between the FRT-ramp and non-FRT-ramp intersections. The most notable finding is that the FRT intersections (1.41%) experienced 0.40% more fatal crashes from 2010 to 2019 than the non-FRT intersections (1.01%).

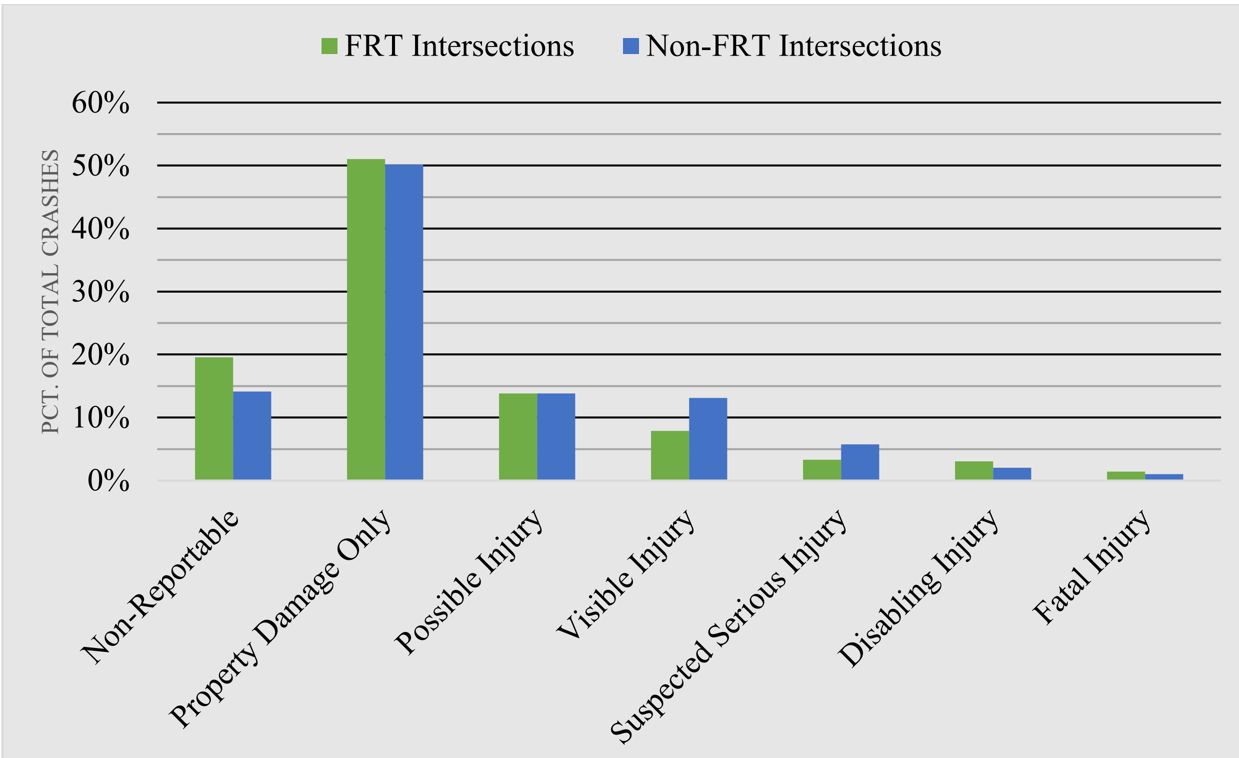


Figure 5.2 Crash Severity Comparison

Figure 5.3 presents a crash type comparison of FRT-ramp intersections and non-FRT-ramp intersections. Two findings are notable; the first is the FRT-ramp intersections had 7.53% fewer rear-end crashes than the non-FRT-ramp intersections. This supports the theory discussed in the Literature Review that by separating through and right-turning traffic, rear-end crashes would be less prevalent. The second finding is that FRT intersections had 9.35% more sideswipe crashes than non-FRT intersections. This intuitively makes sense because the FRT ramp forces a merging maneuver where sideswipe crashes would likely result with turning and crossing traffic conflicting more frequently than in cases where FRT ramps were not present.

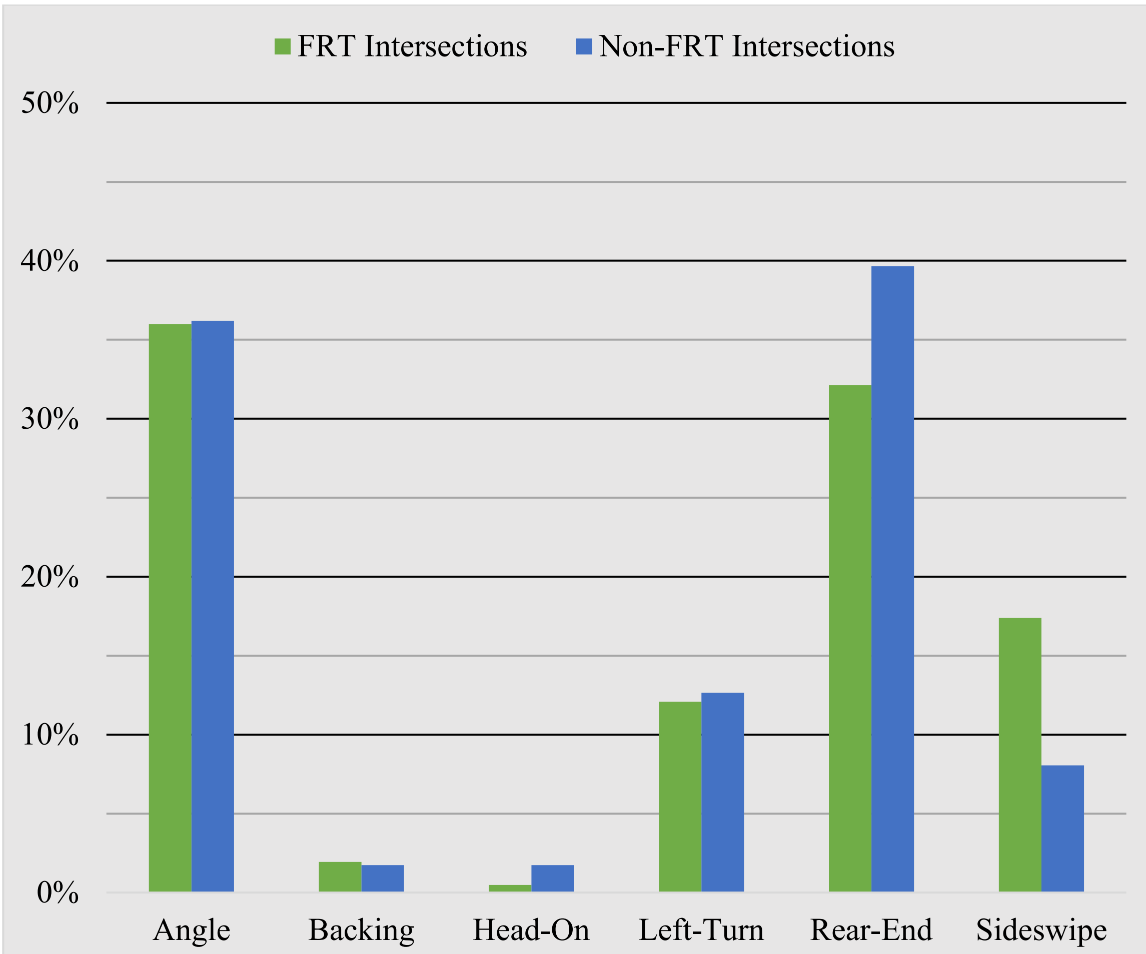


Figure 5.3 Crash Type Comparison

5.3 Analysis and Results

Calculations of crash frequencies and crash rates for each intersection were based on Equation 5.1 and Equation 5.2, respectively. For crash rate, calculations were made for each year from 2010 to 2019, as well as collectively over the ten years, which is tabulated in Appendix C. With these values, many comparisons were made to search for any trends or significant differences. These comparisons included FRT vs non-FRT intersections with varying AADT and intersection legs, using the AADT ranges of low, medium, and high that were developed in Table 4.1. Additionally, comparisons of FRT intersections by the approach on which the FRT ramp is located were made to the non-FRT intersections. Table 5.1 presents the 20 scenarios where different comparisons were made. For viewing ease, the bolded items in the crash frequency columns indicate that they were higher than their counterpart. Of the 20 scenarios, the FRT intersections had a higher crash frequency in 14 scenarios.

Table 5.2 presents the same comparisons, but crash rate was analyzed instead of crash frequency. From comparing the 20 scenarios, the FRT intersections had higher crash rates in all but one scenario.

Table 5.1 Crash Frequency Comparison

Scenario	Comparison1		Comparison2	
	Sample Intersections	Crash Frequency (crashes/year)	Sample Intersections	Crash Frequency (crashes/year)
1	Low AADT, 3-Leg FRT	**0.856**	Low AADT, 3-Leg Non-FRT	0.525
2	Low AADT, 4-Leg FRT	0.664	Low AADT, 4-Leg Non-FRT	**0.925**
3	Low AADT, All Legs FRT	**0.760**	Low AADT, All Legs Non-FRT	0.725
4	Medium AADT, 3-Leg FRT	0.763	Medium AADT, 3-Leg Non-FRT	**1.025**
5	Medium AADT, 4-Leg FRT	**1.413**	Medium AADT, 4-Leg Non-FRT	0.975
6	Medium AADT, All Legs FRT	**1.088**	Medium AADT, All Legs Non-FRT	1.000
7	High AADT, 3-Leg FRT	**3.014**	High AADT, 3-Leg Non-FRT	1.925
8	High AADT, 4-Leg FRT	**2.486**	High AADT, 4-Leg Non-FRT	2.050
9	High AADT, All Legs FRT	**2.750**	High AADT, All Legs Non-FRT	1.988
10	All 3-Leg FRT	**1.319**	All 3-Leg Non-FRT	1.158
11	All 4-Leg FRT	1.170	All 4-Leg Non-FRT	**1.317**
12	All FRT	**1.245**	All Non-FRT	1.238
13	FRT on Major Road, 3-Leg	1.112	All 3-Leg Non-FRT	**1.158**
14	FRT on Minor Road, 3-Leg	**2.625**	All 3-Leg Non-FRT	1.158
15	FRT on Major Road, 4-Leg	1.095	All 4-Leg Non-FRT	**1.317**
16	FRT on Minor Road, 4-Leg	0.738	All 4-Leg Non-FRT	**1.317**
17	FRT on Both Major and Minor Road , 4-Leg	**1.660**	All 4-Leg Non-FRT	1.317
18	FRT on Major Road, All Legs	**1.104**	All Non-FRT	1.238
19	FRT on Minor Road, All Legs	**1.367**	All Non-FRT	1.238
20	FRT on Both Major and Minor Road, All Legs	**1.755**	All Non-FRT	1.238

Table 5.2 Crash Rate Comparison

Scenario	Comparison1		Comparison2	
	Sample Intersections	Crash Rate (crashes/million vehicles)	Sample Intersections	Crash Rate (crashes/million vehicles)
1	Low AADT, 3-Leg FRT	**0.546**	Low AADT, 3-Leg Non-FRT	0.294
2	Low AADT, 4-Leg FRT	**0.428**	Low AADT, 4-Leg Non-FRT	0.389
3	Low AADT, All Legs FRT	**0.478**	Low AADT, All Legs Non-FRT	0.349
4	Medium AADT, 3-Leg FRT	0.263	Medium AADT, 3-Leg Non-FRT	**0.382**
5	Medium AADT, 4-Leg FRT	**0.352**	Medium AADT, 4-Leg Non-FRT	0.253
6	Medium AADT, All Legs FRT	**0.315**	Medium AADT, All Legs Non-FRT	0.306
7	High AADT, 3-Leg FRT	**0.517**	High AADT, 3-Leg Non-FRT	0.353
8	High AADT, 4-Leg FRT	**0.441**	High AADT, 4-Leg Non-FRT	0.408
9	High AADT, All Legs FRT	**0.480**	High AADT, All Legs Non-FRT	0.379
10	All 3-Leg FRT	**0.459**	All 3-Leg Non-FRT	0.350
11	All 4-Leg FRT	**0.410**	All 4-Leg Non-FRT	0.351
12	All FRT	**0.432**	All Non-FRT	0.351
13	FRT on Major Road, 3-Leg	**0.417**	All 3-Leg Non-FRT	0.350
14	FRT on Minor Road, 3-Leg	**0.547**	All 3-Leg Non-FRT	0.350
15	FRT on Major Road, 4-Leg	**0.448**	All 4-Leg Non-FRT	0.351
16	FRT on Minor Road, 4-Leg	**0.360**	All 4-Leg Non-FRT	0.351
17	FRT on Both Major and Minor Road , 4-Leg	**0.388**	All 4-Leg Non-FRT	0.351
18	FRT on Major Road, All Legs	**0.429**	All Non-FRT	0.351
19	FRT on Minor Road, All Legs	**0.448**	All Non-FRT	0.351
20	FRT on Both Major and Minor Road, All Legs	**0.395**	All Non-FRT	0.351

5.4 Significance Testing

To further investigate these findings, a two-sample t-test was performed to identify the statistical significance of the differences in the crash frequencies and crash rates between FRT and non-FRT intersections. Using the collected data, a t-statistic was calculated for each comparison in Table 5.1 and Table 5.2 and was compared to a critical t-value found using the t-table in Appendix D. Due to the large data set and multiple comparisons, the SAS programming language was used to calculate the t-statistics. Appendix D contains detailed results of the t-tests for crash frequency and the crash rate at alpha levels of both 0.05 and 0.10 (probability of making a type 1 error, which rejects the null hypothesis when it is true). For the results discussed here are based on an alpha value of 0.05, giving a 95% confidence level.

For the comparisons of crash frequency between FRT and non-FRT intersections, there were no statistically significant findings.

For the comparisons of crash rates between FRT and non-FRT intersections, there was one statistically significant finding: For FRT intersections that have an FRT ramp on the major approach, either at three-leg or four-leg intersections, a statistically significant higher crash rate was observed when compared to non-FRT intersections of all-leg types.

5.5 Modeling Results

The 10-year crash frequency data for 68 FRT ramps and 24 comparison sites were analyzed using a Negative binomial regression model. Different independent variables such as 10-year total AADT (in thousands), number of intersection legs (3 or 4), intersection skew, presence of lighting, presence of nearby buildings, and presence of nearby rail tracks were explored for their effects on the 10-year crash frequency. Table 5.2 presents the estimated model results. The model consists of a constant, the 10-year total AADT (in thousands), along with an

FRT ramp indicator variable that distinguishes between the FRT ramp and the comparison site observations. It also includes the dispersion parameter alpha (different than the alpha value used in hypothesis testing). The statistical significance of this parameter indicates appropriateness of the Negative binomial model. Also, greater values of 10-year total AADT were statistically significantly associated with greater 10-year crash frequencies (i.e., crashes increase with increasing AADT). The FRT indicator was statistically not significant showing that there was no difference in 10-year crash frequencies at FRT-ramp intersections and comparable non-FRT-ramp intersections after accounting for the AADT effect. Various other variables were tested in the model specification, but none showed statistical significance. The main findings were that the total 10-year AADT was associated with the 10-year crash frequencies, but the modeling effort did not uncover evidence of differences in the 10-year crash frequencies across FRT-ramp intersections and comparable non-FRT intersections.

Table 5.3 Negative Binomial Model for 10-year Crash Frequency

Parameter	Description	Estimated Coefficient	Standard Error	t-Statistic	P-Value
Constant	Model constant	1.408	0.174	8.06	0.000
Total AADT	Total 10-year AADT in thousands	0.010	0.001	8.67	0.000
FRT Indicator	1 if FRT, 0 for comparison site	0.121	0.148	0.82	0.413
Alpha	Dispersion parameter	0.199	0.046	4.34	0.000
Model Summary Statistics					
Number of observations	92				
Log likelihood (LL) function	-287.464				
Restricted LL function	-333.269				
Chi-squared (P-value)	91.61025 (0.000)				
Pseudo R-squared	0.137				

Chapter 6 Traffic Conflict Analysis

6.1 Background

Crash data, in the form of crash rate or crash frequency, is a typical metric used to measure safety at intersections. Although a common practice, it has its flaws. For example, crash data one sees in research is *reported* crashes, meaning there is no way to know how many crashes actually occurred. Each state has its own reporting criteria in the form of a dollar amount; so if a crash occurs, but there is minimal-to-no repair cost, it potentially will not be reported. Additionally, in single-vehicle crashes, crashes occurring at night, or situations where one or more drivers are under the influence of alcohol or drugs, drivers may opt not to report the crash, even if it is considered reportable. In lower traffic and rural areas, such as where this research was conducted, it would be safe to assume that not all of the actual crashes are reported because of the above factors and lack of witnesses or recording equipment in these types of areas.

Safety analyses using traffic conflicts are a widely used and standardized method. A traffic conflict is defined as a traffic event involving two or more vehicles, where one or both drivers take evasive action such as braking or swerving to avoid a collision (Parker Jr & Zegeer, 1989). To have a reliable set of conflict data, adequate time for observation and a good understanding of what type of conflict is of interest.

6.2 Methodology

For this research, 12 sites were selected for the conflict analysis using the AADT ranges of three-legged and four-legged intersections, identified in Table 6.1.

Table 6.1 Intersections for Conflict Analysis

	AADT Range	FRT Intersection [2018 AADT]		Non-FRT Intersection [2018 AADT]	
3-Legged Intersections	Low	N-4/N-103	[5,460]	N-31/N-50	[5,349]
	Medium	N-15/N-65	[9,975]	N-22/L-63A	[8,510]
	High	US-77/N-109	[20,390]	N-15/N-92	[13,891]
4-Legged Intersections	Low	N-74/US-281	[6,815]	N-9/N-16	[6,994]
	Medium	N-15/N-92	[12,366]	N-1/N-50	[13,595]
	High	US-77/N-92	[21,614]	N-1/US-34	[14,570]

During field visits to these locations, Miovision Scout cameras (Figure 6.1) were affixed to utility poles or sturdy signage posts at the intersections where a good view of the right-turning vehicles could be observed. The cameras were then left for a minimum of 72 hours to ensure adequate data to perform an analysis. There were a few instances where the 72-hour mark was not reached due to the camera's battery dying or the memory card becoming full, but in the end, it was determined sufficient data were obtained to run the analysis confidently.

At the FRT intersections, the camera was positioned to view the right-turning vehicle's interaction with the crossing-through traffic. At the non-FRT intersections, the camera was positioned at the right turn on the same approach as its FRT counterpart. For example, if an FRT ramp was located on the major approach of an intersection, the right-turn movement observed at the non-FRT intersection of similar AADT was also on the major approach. These scenarios will be discussed in detail in a later section.

Figure 6.1 Miovision Scout Camera (https://miovision.com/scout/scout-hardware)

6.2.1 Conflict Definitions

To get accurate data, sound definitions needed to be created to ensure uniformity across all sites when reviewing the videos. In general, a traffic conflict was defined as a traffic event involving two or more vehicles, where one or both drivers take evasive action such as braking or swerving to avoid a collision. When reviewing videos for FRT intersections and non-FRT intersections, different traffic conflicts were observed, depending on the presence of an FRT and other movements at the intersection.

For FRT intersections, there was one conflict that was of interest. This was defined as a merging conflict.

1. **A Merging conflict** – present when a vehicle with yield control impedes a right-of-way vehicle's path, causing the right-of-way vehicle to slow, swerve or brake to avoid a collision (Fazio et al., 1993).

For non-FRT intersections, there were several conflict types, depending on the number of intersection legs, turning movements, and the presence of exclusive right-turn lanes on the major approach. These conflicts are:

2. **Right-turn, same-direction conflict** – also referred to as a rear-end conflict. This is present when a vehicle on the major approach slows to make a right turn, where no exclusive right-turn lane is present, causing a follow-through vehicle to brake or cross the painted centerline to avoid a rear-end collision (Parker Jr & Zegeer, 1989).
3. **Opposing left-turn conflict** – occurs when a vehicle turning right with the right-of-way, must brake to avoid an opposing left-turn vehicle that makes its turn in front of the right-turning vehicle's path (Parker Jr & Zegeer, 1989).
4. **Through, cross traffic from left conflict –** occurs when a right-turning vehicle on the major approach slows to make a right turn and a vehicle from the minor approach on the left enters the intersection and impedes the right-of-way of the right-turning vehicle (Parker Jr & Zegeer, 1989).
5. **Right-turn-on-red (RTOR) conflict** – a conflict observed at signalized intersections but is also useful for identifying conflict for right-turning vehicles on the minor approach of a two-way stop-controlled intersection. This conflict is present when a right-turning vehicle stopped on the minor approach misjudges the gap in the crossing-through traffic and proceeds to make its right turn, causing the crossing vehicle to slow or stop to avoid a collision (Parker Jr & Zegeer, 1989).

These conflicts will be illustrated in the following section, to show which conflicts were experienced at each intersection and where.

It should be noted that although traffic conflicts are believed to be a sound method of evaluating safety at intersections, there are both liberal and more strict definitions, depending on the research study conducted. For example, in some studies, conflict is only recorded if near-miss crashes occur, being the most extreme scenario. In other studies, conflict may be recorded if vehicles slow down or brake, with the assumption that a crash would occur if they did not. Additionally, some studies record conflict as single-vehicle traffic violations, such as a vehicle not stopping at a stop sign, making a wide turn, or turning on the shoulder (Parker Jr & Zegeer, 1989). Because this research was conducted at rural intersections where traffic volume is lower and fewer conflicts may inherently result, a more liberal approach was taken in identifying conflicts. However, because this research was focused on conflicts with right-turning vehicles and other vehicles at the intersection, traffic violations and other single-vehicle conflicts were not included.

6.3 Conflicts Observed at Each Site

In this section, sketches of the FRT and non-FRT intersections are presented, with the types of conflicts observed for the right-turning vehicles. The conflicts defined above are indicated by the number corresponding to the conflict. To restate those conflicts, they are identified as follows:

1. Merging Conflict
2. Right-Turn, Same Direction Conflict
3. Opposing Left-Turn Conflict
4. Through, Cross Traffic from Left Conflict

5. RTOR Conflict

6.3.1 Category 1: Low AADT, 3-Leg

The intersection to the left of Figure 6.2 is the FRT ramp located at N-4/N-103 in Gage County. For this case, the only conflict observed was the merging conflict of the right-turning vehicles using the FRT ramp and the crossing-through traffic. The intersection to the right of Figure 6.2 is a non-FRT intersection located at N-31/N-50 in Sarpy County. Because the FRT ramp is located on the major approach of the intersection, the right turn located on the non-FRT intersection that was observed is also on the major approach. The right-turning vehicles share a lane with the through traffic, therefore, the conflicts present at this intersection are the right-turn, same-direction conflict, as well as opposing left-turn conflict.

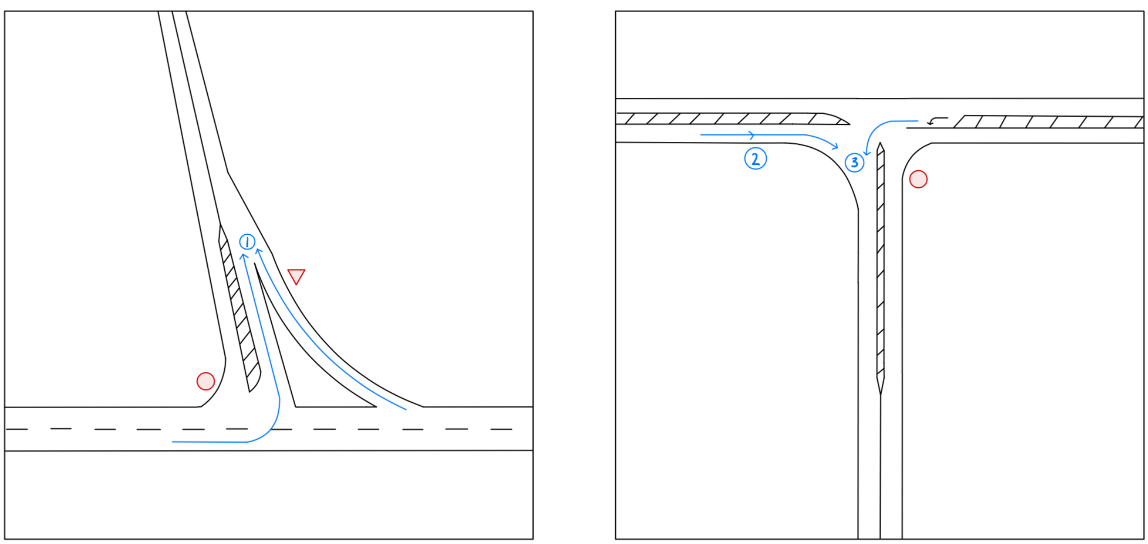


Figure 6.2 Low AADT, 3-Leg Intersections

6.3.2 Category 2: Low AADT, 4-leg

The intersection to the left of Figure 6.3 is the FRT ramp located at N-74/US-281 in Adams County. For this case, the only conflict observed was the merging conflict of the right-turning vehicles using the FRT ramp and the crossing-through traffic. The intersection to the right of Figure 6.3 is a non-FRT intersection located at N-9/N-16 in Thurston County. Because the FRT ramp is located on the major approach of the intersection, the right turn located on the non-FRT intersection that was observed is also on the major approach. The right-turning vehicles share a lane with the through traffic, therefore, the conflicts present at this intersection are the right-turn, same direction conflict, opposing left-turn conflict, and through, cross traffic from left conflict.

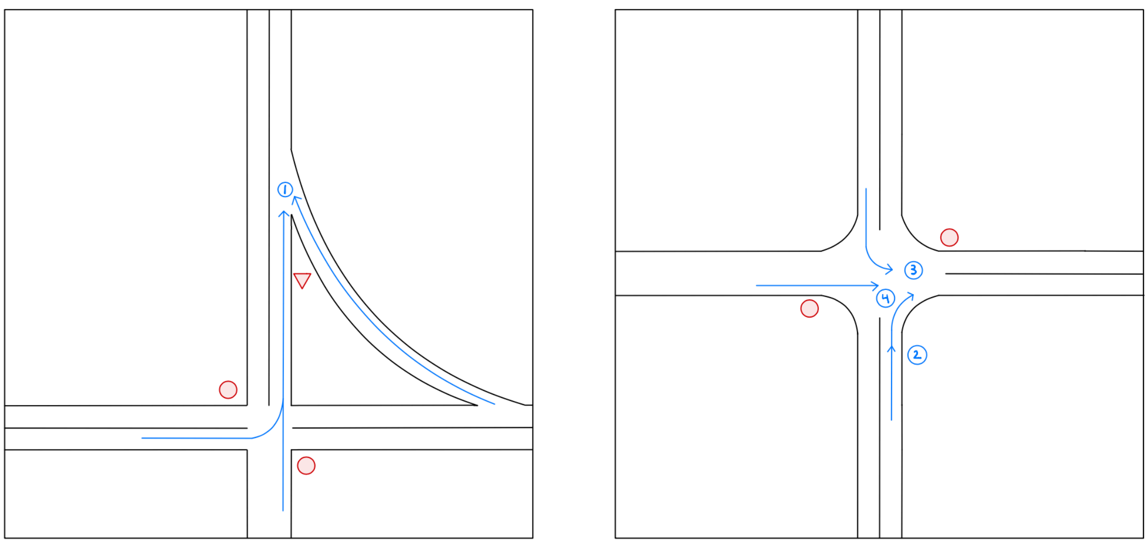


Figure 6.3 Low AADT, 4-Leg Intersections

6.3.3 Category 3: Medium AADT, 3-Leg

The intersection to the left of Figure 6.4 is the FRT ramp located at N-15/N-65 in Butler County. For this case, the only conflict observed was the merging conflict of the right-turning vehicles using the FRT ramp and the crossing-through traffic. The intersection to the right of Figure 6.4 is a non-FRT intersection located at N-22/L-63A in Nance County. Because the FRT ramp is located on the minor approach of the intersection, the right turn located on the non-FRT intersection that was observed is also on the minor approach. Due to this, the only conflict of interest is the RTOR conflict involving the right-turning vehicles at the minor approach and the major through traffic.

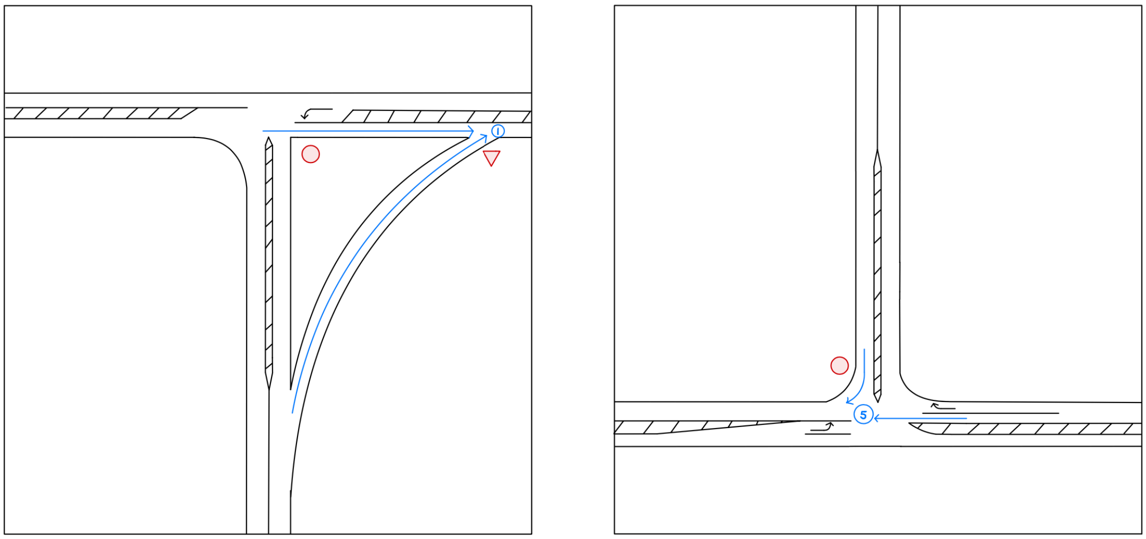


Figure 6.4 Medium AADT, 3-Leg Intersections

6.3.4 Category 4: Medium AADT, 4-Leg

The intersection to the left of Figure 6.5 is the FRT ramp located at N-15/N-92 in Butler County. For this case, the only conflict observed was the merging conflict of the right-turning vehicles using the FRT ramp and the crossing-through traffic. The intersection to the right of Figure 6.5 is a non-FRT intersection located at N-1/N-50 in Cass County. Because the FRT ramp is located on the major approach of the intersection, the right turn located on the non-FRT intersection that was observed is also on the major approach. The right-turning vehicles share a lane with the through traffic, therefore, the conflicts present at this intersection are the right-turn, same direction conflict, opposing left-turn conflict, and through, cross traffic from left conflict.

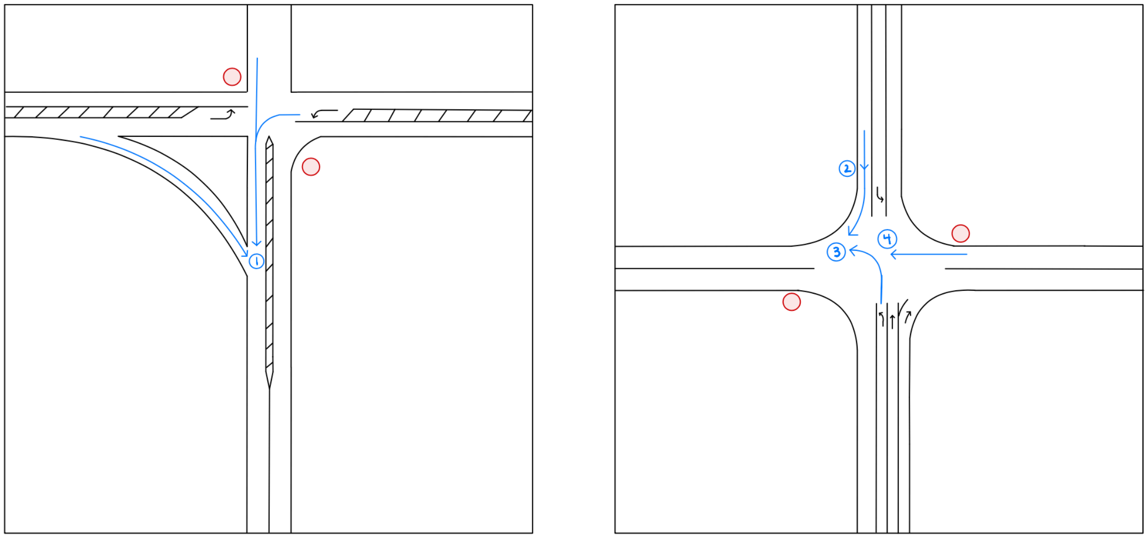


Figure 6.5 Medium AADT, 4-Leg Intersections

6.3.5 Category 5: High AADT, 3-Leg

The intersection to the left of Figure 6.6 is the FRT ramp located at US-77/N-109 in Saunders County. For this case, the only conflict observed was the merging conflict of the right-turning vehicles using the FRT ramp and the crossing-through traffic. The intersection to the right of Figure 6.6 is a non-FRT intersection located at N-15/N-92 in Butler County. Because the FRT ramp is located on the major approach of the intersection, the right turn located on the non-FRT intersection that was observed is also on the major approach. The right-turning vehicles have an exclusive right-turn lane separated from the through traffic, therefore, the only conflict present at this intersection is an opposing left-turn conflict.

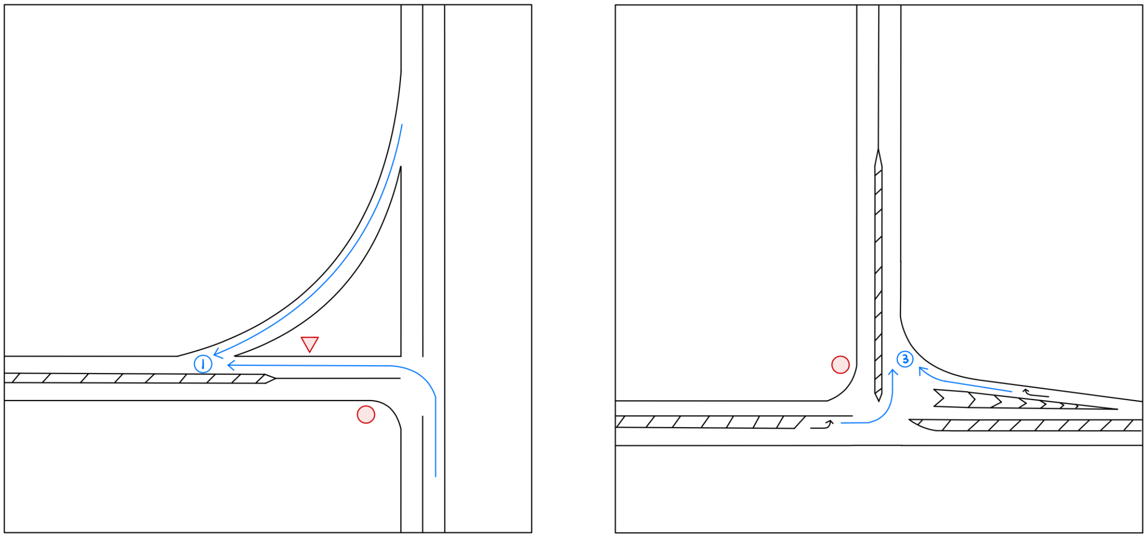


Figure 6.6 High AADT, 3-Leg Intersections

6.3.6 Category 6: High AADT, 4-Leg

The intersection to the left of Figure 6.7 is the FRT ramp located at US-77/N-92 in Saunders County. This intersection has two FRT ramps, but only the FRT ramp on the minor approach was studied. For this case, the only conflict observed was the merging conflict of the right-turning vehicles using the FRT ramp and the crossing-through traffic. The intersection to the right of Figure 6.7 is a non-FRT intersection located at N-1/US-34 in Cass County. Because the FRT ramp of interest is located on the minor approach, the right turn located on the non-FRT intersection that was observed is also on the minor approach. Due to this, the conflicts of interest are the RTOR conflict involving the right-turning vehicles at the minor approach and the major through traffic, as well as an opposing left-turn conflict.

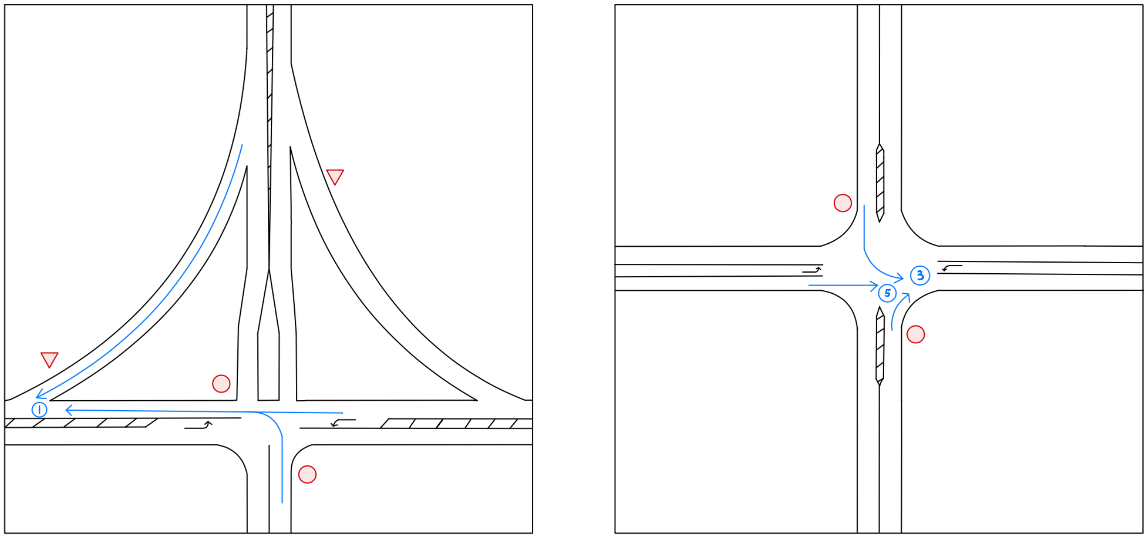


Figure 6.7 High AADT, 4-Leg Intersections

6.4 Analysis and Results

For each intersection, approximately 72 hours of video were reviewed and various data were recorded. This data included: right-turning vehicles on the approach of interest, crossing-through vehicles that could conflict with the right-turning vehicles, potential traffic conflicts, and traffic conflicts. Using 15-minute increments, these variables were recorded and organized in an Excel spreadsheet. The characteristics of these sites and the conflict data are shown in detail in Appendix E. Due to this process being lengthy and spanning several months, each conflict was timestamped and revisited a second time to ensure uniformity in the traffic conflict definitions.

As noted, these intersections span a range of traffic volumes from very high to very low. Using a similar reasoning when utilizing the crash rate in the crash analysis, conflicts per 1000 entering right-turning vehicles was chosen as the primary metric to study. This placed all of the intersections on an even playing field, regardless of the right-turning traffic volume.

Table 6.2 gives the results of the conflict analysis in both conflict per hour and conflict per 1000 entering right-turning vehicles. The values in bold indicate a higher value for viewing ease. As can be seen, in most cases, the non-FRT intersections experience higher values of both conflict metrics.

Table 6.2 Conflict Analysis Results

		RT APPROACH			
		Conflict/Hour		Conflict/1000 entering RT vehicles	
	AADT Range	FRT Site	Non-FRT Site	FRT Site	Non-FRT Site
3-Leg	Low	0.056	**0.818**	3.320	**39.773**
	Medium	**0.048**	0.000	**1.350**	0.000
	High	**0.188**	0.163	2.070	**2.558**
Average:		0.097	**0.327**	1.962	**11.778**
4-Leg	Low	0.000	**0.017**	0.000	**43.478**
	Medium	0.028	**0.167**	0.560	**36.697**
	High	**0.351**	0.116	4.637	**7.601**
Average:		**0.126**	0.100	3.048	**14.342**
Overall Average:		0.112	**0.214**	2.499	**12.275**

When conducting this analysis, in addition to the separation of the FRT and non-FRT intersections by traffic volume and the number of legs, three scenarios were observed that presented interesting findings:

1. FRT ramp located on the minor approach, with the non-FRT right-turn located on the stop-controlled minor approach
2. FRT ramp located on the major approach, with the non-FRT right-turn movement having no exclusive right-turn lane on the major approach
3. FRT ramp located on the major approach, with the non-FRT right-turn approach having an exclusive right-turn lane

Table 6.3 presents these findings. Again, the non-FRT intersections experienced higher conflicts per 1000 right-turning vehicles. Scenario two, which compares the FRT ramp on the major approach and the non-FRT right-turn on the major approach with no exclusive right-turn lane, had the most significant difference. This is believed to be because of the right-turn, same-direction conflict. With the right-turning vehicles and through vehicles sharing a lane, whenever a vehicle slows to turn right, following-through vehicles often traveling at a high rate of speed must suddenly slow down or swerve over the centerline to avoid a rear-end crash.

Table 6.3 Traffic Conflict Scenario Results

Scenario	# of Int. Studied	FRT Conflict/1000 RT vehicles	Non-FRT Conflict/1000 RT vehicles
1	2	3.440	**7.048**
2	3	1.146	**39.297**
3	1	2.070	**2.558**

Chapter 7 Traffic Operations Analysis

7.1 Background

The minor approach traffic at a stop-controlled intersection must stop at the intersection before proceeding with the desired movement. An FRT ramp can accommodate the right-turning traffic from a minor approach, thus avoiding stoppage at the intersection and reducing operational delays and queue generations on the minor approaches. However, FRT ramps requires additional right of way and construction costs compared to the non-FRT intersection. Additionally, AADT of the intersection and turning percentages in different approaches can impact the efficacy of an FRT ramp. Therefore, measurement of operational benefits of FRT ramps requires modeling of traffic operations surrounding the FRT and comparable non-FRT intersections.

McCoy et al. (1995) conducted operational studies of FRT ramps in 1994 for Nebraska conditions. The delay components of FRT and stop-controlled intersections were estimated by the Highway Capacity Manual (HCM, 1994), which is now obsolete. Additionally, the cost components used in that analyses are outdated as well. Note that the HCM delays were estimated from two-way or one-way stop-controlled intersections, and FRT delays were also estimated using the same stop-controlled intersection methodologies. However, the mechanism of right-turning vehicle movement from the stopped condition of the intersection and FRT ramps are different. These operations should be modeled as observed in the real-world. Therefore, this study utilized microsimulation models to more accurately represent traffic conditions for both non-FRT and FRT ramp intersections.

The microscopic model, if calibrated and validated properly, can produce faithful outcomes that represent field conditions (Haque, 2022). The microscopic model allows the stochastic nature of traffic conditions and individual vehicle/driver interactions. These enable microsimulation tools to imitate real-world traffic conditions with greater accuracy and precision.

This chapter presents the development of a microsimulation model to imitate the FRT and non-FRT right-turn operations. The operational data found from this model were used to conduct the benefit cost analysis of whether an FRT ramp is warranted to improve traffic conditions.

The three major objectives of this chapter are as follows.

1. Develop microsimulation models for FRT and non-FRT intersections and calibrate and validate the models using field-observed data
2. Conduct comparative operational analysis between FRT and non-FRT intersections
3. Study the economic feasibility of providing an FRT ramp for various traffic and geometric conditions

7.2 Methodology

There are two main approaches used in this chapter to achieve the objectives. The first approach is to build a microsimulation model and the second approach is to use the model outcomes and integrate them into a benefit cost analysis method.

As previously mentioned, McCoy et al. (1995) used a stop-controlled intersection methodology using the 1994 version of the HCM. The operational studies of the FRT ramp were analyzed by the delay equations developed for the two-way/one-way stop-controlled intersection. However, it is known that the HCM default assumptions may not be applicable to represent local conditions. Note that a macroscopic method like the HCM can be applied in many locations, however, this study was focused on Nebraska drivers' right-turning behaviors.

To study the economic viability of FRT ramps, intersection operational delay comparisons with and without FRT ramps were conducted under similar traffic and geometric conditions. Then the costs and benefits (if any) associated with FRT construction and maintenance incurred by FRT ramp intersections were compared. Benefit cost analysis throughout the design life of the FRT ramp using a discount rate was conducted under different traffic and geometric conditions. Finally, this study determined the feasibility of FRT ramps based on the benefit cost ratio (B/C ratio).

7.3 Data Preparation

7.3.1 Data Collection Site Characteristics

Data from four sites were used to conduct the operational analysis for this project.

7.3.1.1 Site 1: Three-Legged One-way Stop-Controlled Intersection with an FRT Ramp

Located in Bone Creek Township in Butler County, Nebraska, the site is a three-legged one-way stop-controlled intersection as shown in Figure 7.1. The major road approaches are Hwy 64 and Hwy 15 (Rd 41) in the eastbound and westbound directions. The minor road is on Hwy 15 (M N Rd) on the south side of the intersection and is stop-controlled. The FRT ramp starts from the minor road (1,000 feet from the intersection) and joins the major road (950 feet from the intersection).

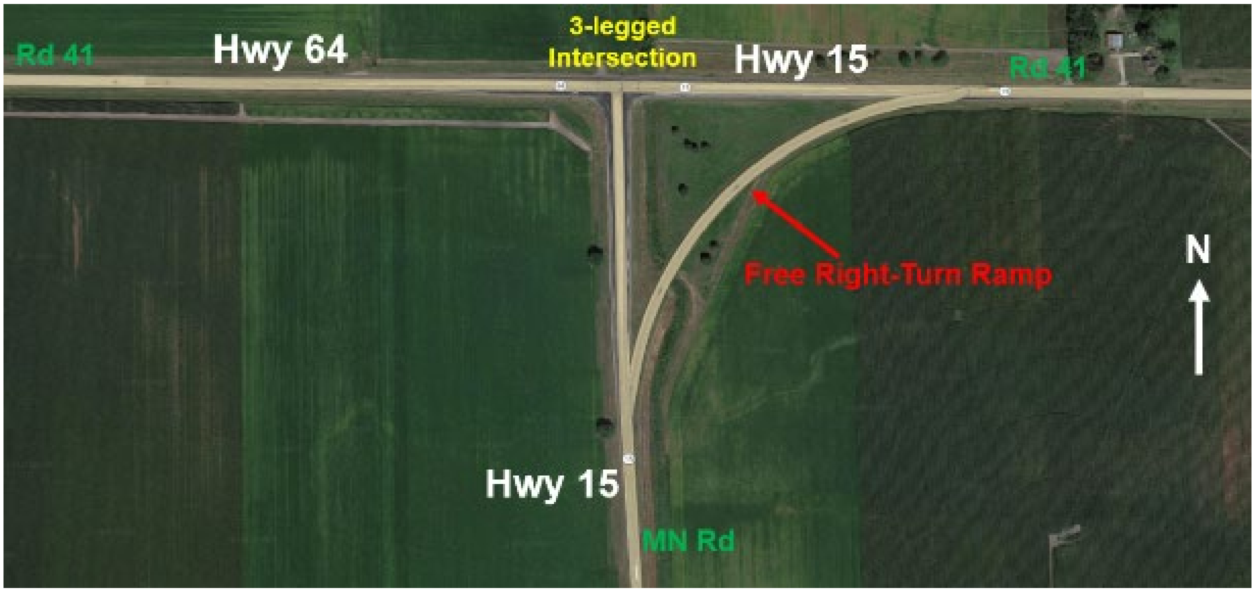


Figure 7.1 Three-Legged One-way Stop-Controlled Intersection with FRT Ramp at Bone Creek, Nebraska (Location coordinates: 41.333405, -97.129290)

All approaches have a 65 mph speed limit. This location has an AADT of 9,975 vehicles. Both the major and minor roads are undivided two-lane highways (single lane in each direction).

In the intersection, the minor approach has a wide single lane for vehicles to turn left on the major road. There is no through movement from the minor as it is 3-legged intersection. The westbound traffic from the major approach has a left-turn bay and yields to the opposing through and right-turning traffic. On the other hand, westbound traffic from the major approach allows through movements that are free-flowing. Also, near the intersection, the westbound major approach has a dedicated lane for right-turning vehicles.

7.3.1.2 Site 2: Four-Legged Two-Way Stop-Controlled Intersection with an FRT Ramp

Located in Marietta, Saunders County, this site is a four-legged unsignalized two-way STOP-controlled intersection as shown in Figure 7.2. The major road approaches are Hwy 77 and Hwy 92 (Co Rd M) in the eastbound and westbound directions. The minor road is on Hwy

77 (Co Rd 11) in the northbound and southbound direction and has two-way STOP-control at the intersection. One FRT ramp starts at the major road from the westbound approach (600 feet from the intersection) and joins the minor road for the northbound approach (600 feet from the intersection). The other FRT ramp starts at the minor road from the southbound approach (650 feet from the intersection) and joins the major road for the westbound approach (700 feet from the intersection).

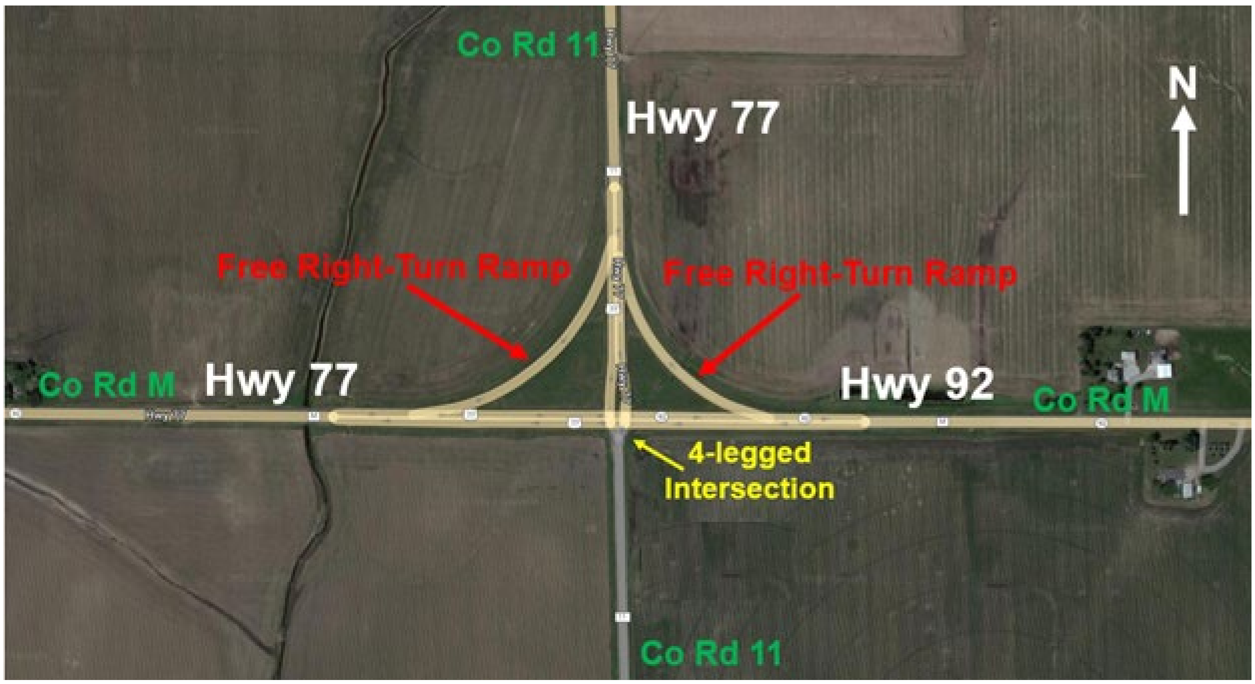


Figure 7.2 Four-legged Unsignalized Intersection with an FRT Ramp at Marietta, Nebraska (Location coordinates: 41.2341865, -96.502896)

All approaches have a 65-mph speed limit. This location has an AADT of 21,614 vehicles. Both the major and minor roads are undivided two-lane highways (single lane in each direction).

At the intersection, the minor approach from the northbound traffic has a wide single lane for vehicles for through, left-turn, and right-turn movements. On the other hand, minor approach from the southbound traffic has the following properties: i) an FRT ramp for right-turn movements, and ii) a wide single lane for left-turn movements at the intersection.

The westbound traffic from the major approach has the following lane distribution properties: i) the through and right-turn movements are shared by a single lane, and ii) a dedicated left-turn bay for left turn movements that yields to the opposing through traffic. The eastbound traffic from the major approach has the following lane distribution properties: i) an FRT ramp for right-turn movements, ii) a dedicated left-turn bay for left-turn movements that yields to the opposing through traffic, and iii) the through movement is free-flowing.

7.3.1.3 Site 3: Three-Legged One-way Stop-Controlled Intersection without an FRT Ramp

The location of this site is in David City, Butler County, Nebraska. It is a three-legged unsignalized at-grade intersection as depicted in Figure 7.3. The major road approaches are Hwy 92 (32 Rd) in the eastbound and westbound directions. The minor road is on Hwy 15 (MN Rd) in the northbound and southbound direction and has STOP-control at the intersection.

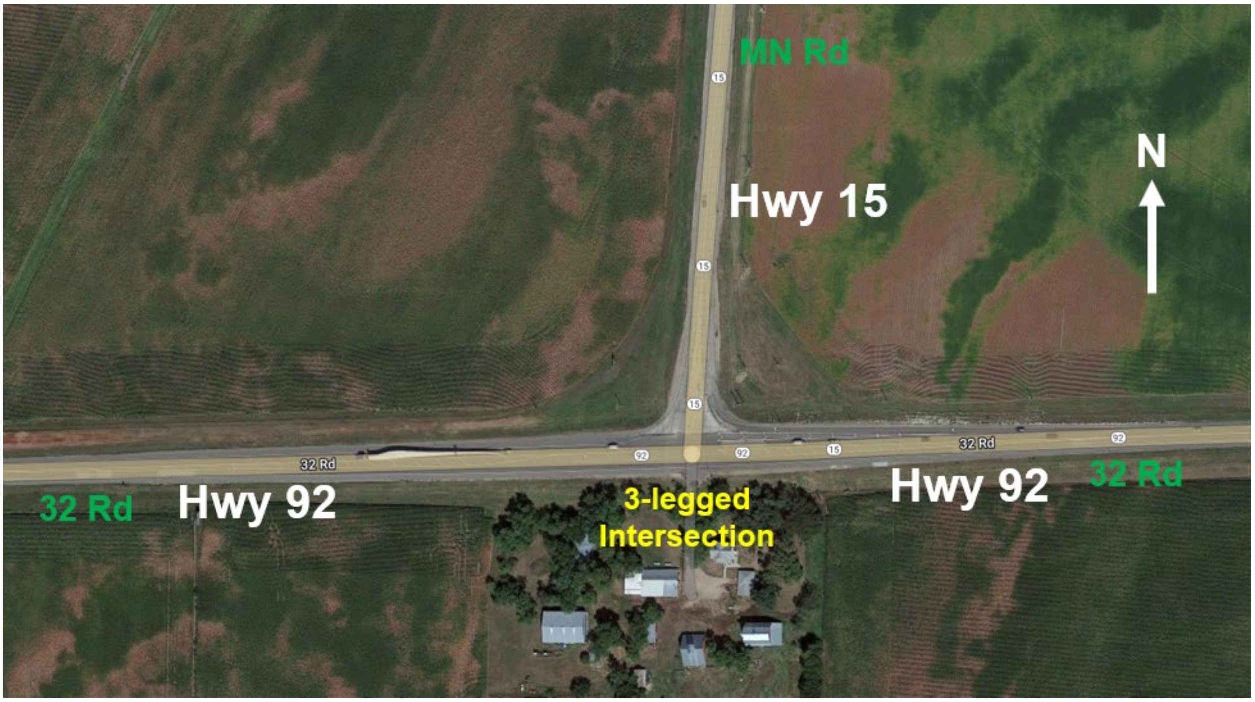


Figure 7.3 Three-legged Unsignalized Regular Intersection at David City, Nebraska (Location coordinates: 41.206305, -97.129958)

All approaches have a 65 mph speed limit. This location has an AADT of 13,891 vehicles. Both the major and minor roads are undivided two-lane highways (single lane in each direction).

At the intersection, the minor approach has a wide single lane for vehicles to turn left and right onto the major road and no through movement, as it is a three-legged intersection. The eastbound traffic from major approach has a left-turn bay and yields to the opposing through and right-turning traffic. On the other hand, westbound traffic from the major approach allows through movements, which are free flowing.

7.3.1.4 Site 4: Four-Legged Two-Way Stop-Controlled Intersection without an FRT Ramp

The location of this site is in Avoca, Cass County, Nebraska. It is a four-legged unsignalized two-way STOP-controlled intersection as shown in Figure 7.4. The major road approaches are Hwy 34 (E O St.) in the eastbound and westbound directions. The minor road is on Hwy 50 in the northbound and southbound direction and has STOP-control at the intersection (i.e., Hwy 34 traffic does not stop).

Figure 7.4 Four-legged Unsignalized Regular intersection at Avoca, Nebraska (Location coordinates: 40.813046, -96.178535)

All approaches have a 65-mph speed limit. This location has an AADT of 12,000 vehicles. Both the major and minor roads are undivided two-lane highways (single lane in each direction). At the intersection, the minor approach from the northbound and southbound traffic has a wide single lane for through, left-turn, and right-turn movements.

The westbound and eastbound traffic from the major approach has the following lane distribution properties: i) the through and right-turn movements are shared by a single lane, and ii) a dedicated left-turn bay for left turn movement that yields to the opposing through traffic.

7.3.2 Data Collection and Processing

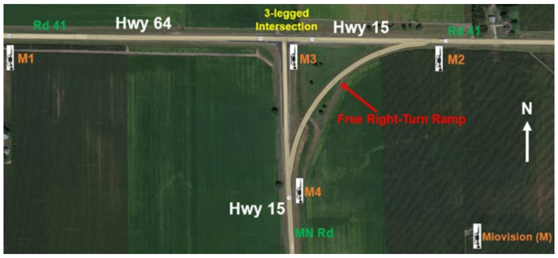
Multiple sets of Miovision scouts (Miovision Scout, 2023) were used to collect traffic data at the four sites. In addition to the Miovision, the research team used radar guns to collect sample data of the approach speed of vehicles entering, exiting, or turning within the intersection and FRT ramp. Figure 7.5 presents the devices used for data collection.

a) Miovision

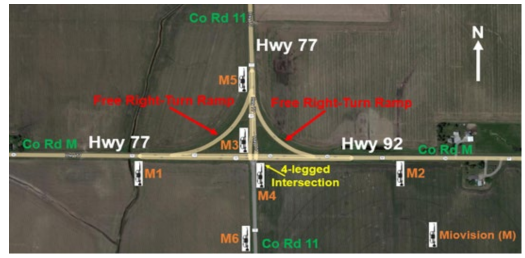
b) Radar gun (Stalker ATS Professional Radar Gun)

Figure 7.5 Data Collection Devices

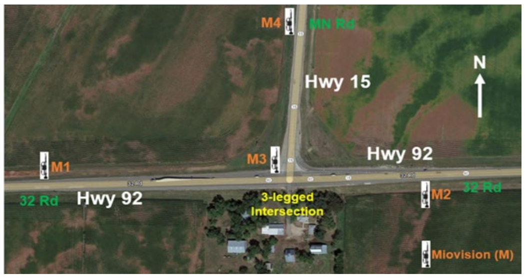
Miovision cameras were set in different locations around each intersection and the FRT ramps to collect traffic operations data. Figure 7.6 shows the setup of the Miovision devices at the four sites.



Site 1: Miovision installed in 3-legged FRT intersection



Site 2: Miovision installed in 4-legged FRT intersection



Site 3: Miovision installed in 3-legged non-FRT intersection

Site 4: Miovision installed in 4-legged non-FRT intersection

Figure 7.6 Miovision Device Locations at the Four Test Sites

Note that the video data collected using Miovision can be used to extract traffic demand, traffic composition, and travel time from one location of Miovision to others. However, the Miovision is equipped with technology to collect media access control (MAC) addresses of devices installed or present in the vehicles. Therefore, in addition to observing video data, the research team gathered the MAC addresses from the Miovision as an “object” and these unique objects were matched using the R coding platform as shown in Figure 7.7. This method was used to find information such as travel times, volumes, and turn percentages. Note that this traffic information was available from equipped vehicles only.

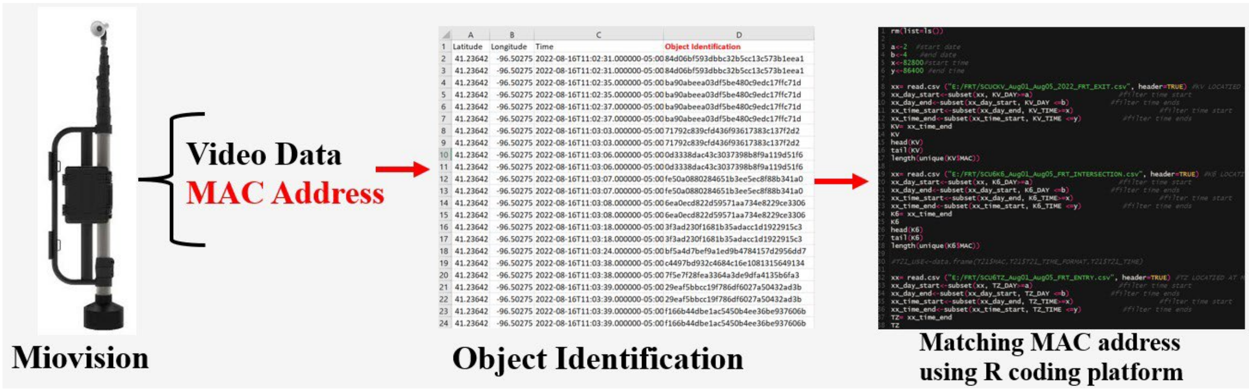
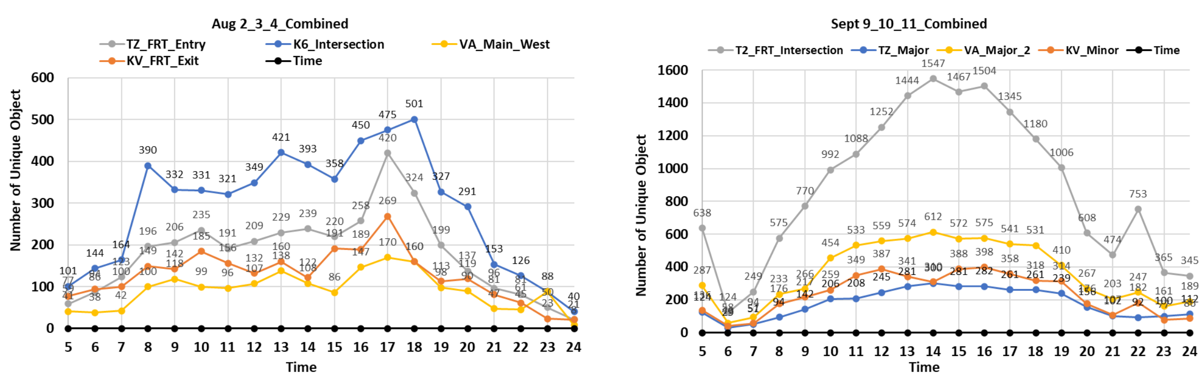


Figure 7.7 Miovision Data Extraction using MAC Addresses

Note that using the unique object information, as shown in Figure 7.7, the volume pattern (not the exact number of vehicles) throughout a day could be found. This method was helpful to identify peak hour periods and relative hourly distribution of vehicles throughout the day. Figure 7.8 shows an example for Site 1 and Site 3 for multiple Miovision sets used in the field.



Site 1 Site 3

Figure 7.8 Vehicle Pattern Observed Using Unique Object from Miovision

Data collected from these four test sites were used to develop the microsimulation model described in the next section.

7.4 Microsimulation Modelling

A microsimulation model requires proper calibration to reflect field-observed driving behaviors and operational outcomes. There are several available traffic microsimulation tools for model development, including TransModeler™, AIMSUN™, TRANSIMS™, PARAMICS™, CORSIM™, and VISSIM™. A comparison of traffic modeling software tools is provided elsewhere (FHWA, 2016; Haque and Sangster, 2018). The research team used VISSIM (PTV VISSIM, 2020) because i) it has the capability of modeling all operational aspects of stop-controlled intersections and ramps, and ii) it has been widely used as an aid in developing many HCM macroscopic models (such as freeway capacity, passenger car equivalence, two-lane highway work zone, etc.) (HCM, 2016).

7.4.1 Microsimulation Model Calibration Method

This study applied a robust calibration technique (Haque et al., 2022) to model the microsimulation model as shown in Figure 7.9.

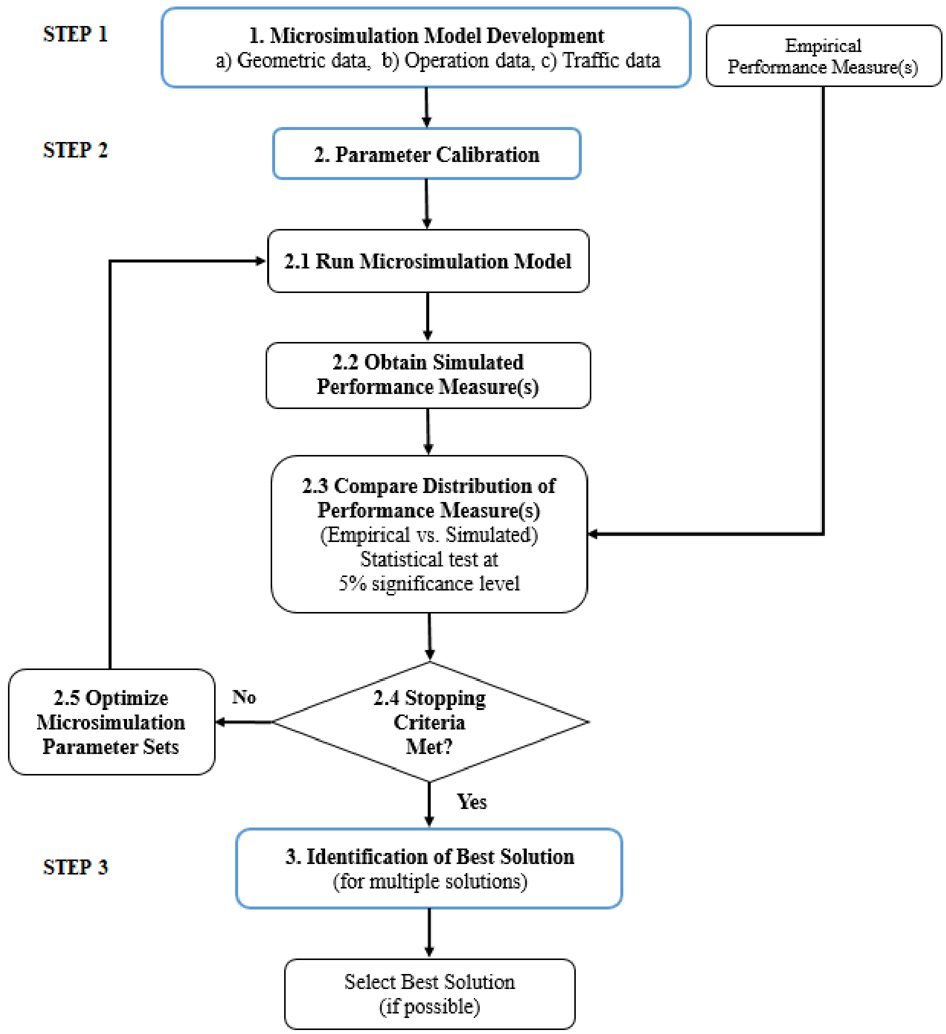


Figure 7.9 Microsimulation Model Calibration Algorithm (Haque et al., 2022)

A description of the three-step process is as follows.

Step 1. An important part of the model development was to obtain local data that represents the stop-controlled intersection and ramp operations. This included geometric data (e.g., horizontal curvature, segment lengths, grades, etc.), operation data (e.g., traffic control technique, signage, speed limits, etc.), and traffic data (e.g., vehicle volumes, truck percentages, etc.).

The two hours (i.e., 4 pm to 6 pm) of empirical traffic data from Site 1 and Stie 3 (in total four hours) were used in developing the VISSIM simulation model. Data including traffic demand and the proportion of heavy trucks were used as input for the microsimulation model. In addition, geometric dimensions of the unsignalized intersection, posted speed limit, and FRT ramp dimensions were used to develop the microsimulation model. Note that performance data, such as travel time, were collected and prepared for use in Step 2.

Step 2. All commercially available microsimulation models have parameters that users can adjust to control internal driver behavior (e.g., car following, lane changing, etc.) to represent the field observed traffic conditions. While default values of these parameters may be used, better results are obtained if the parameters are calibrated to local field data (Spiegelman et al., 2010). This study used two types of parameter sets, which were the driver behavior model and the gap acceptance model.

From VISSIM microsimulation platform, seven parameters were used that are directly related to driver behaviors (Buck et al., 2017; Zhao et al., 2022; Haque et al., 2023). These were CC0 (standstill distance), CC1 (headway time), CC2 (following variation), CC3 (threshold for entering ‘‘following’’ mode), CC4 (negative following threshold), CC5 (positive following threshold), and CC6 (speed dependency of oscillation). A detailed description of these model parameters can be found elsewhere (PTV VISSIM, 2020).

The gap acceptance model was required to accurately model traffic behaviors in the unsignalized intersection. The gap acceptance model included critical headway of vehicle for the intersection and FRT ramp. Critical headway is defined as the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle (HCM, 2016). Therefore, the driver's critical headway was the minimum headway that would be acceptable. A particular driver may reject headways less than the critical headway and may accept headways greater than or equal to the critical headway. From field observation, critical headway can be estimated based on observations of the largest rejected and smallest accepted headway for a given intersection. The VISSIM microsimulation model had two functionalities that could regulate the critical headway aspects (i.e., gap acceptance parameters), which were "Priority Rules" and "Conflict Area" (PTV VISSIM, 2020). In priority rules, the "minimum gap time" parameter was associated with the critical headway. Therefore, parameters from the driver behavior model (CC0, CC1, CC2, CC3, CC4, CC5 and CC6) and gap acceptance model (minimum gap time) were calibrated for passenger cars and heavy vehicles so that the VISSIM simulated performance measure (i.e., travel time) was similar to the field observed data. Note that this calibration method used statistical tests to confirm that the simulated and field observed performance measures were similar.

Step 3. Several optimization algorithms can be used to find optimal solutions for values of different parameters tested in Step 2. These include the simplex method, the genetic algorithm, and simulated annealing (Kochenderfer et al., 2019). In this study, the research team used genetic algorithm with the aid of MATLAB language platform to find suitable parameter values that may produce statistically similar simulated, and field observed results.

Note that the calibration procedure may identify a zero solution, a single solution, or multiple solutions. If the optimization algorithm found multiple sets of parameters that satisfied the statistical test, a further criterion was required to determine the ‘‘best’’ parameter set. Therefore, the parameter set that resulted in the least error when the simulation results were compared to the observed data could be chosen, or the parameter set that best represented the local driver behavior could be selected, or standard guidelines such as the HCM could be used. In this project, video data were available to collect samples that represented many of the important parameters such as CC0, CC1, and minimum gap time. Therefore, the research team chose the final parameter solutions based on the calibration algorithm outcomes complying with the field observed behaviors.

7.4.2 Calibration and Validation Results

The calibration process used travel time data of left-turn movements from a minor road to a major road as shown in Figure 7.10. The left-turn was the most critical movement as it must consider the major and opposing minor road traffic at the intersection. The operational performance of minor traffic movement was impacted by the number of vehicles moving to the FRT ramp since they would have eventually stopped when using the intersection.

Figure 7.10 Critical Left-Turn Movement from Minor Road to Major Road

Empirical travel time data of left-turn traffic from minor movements are input to the calibration algorithm as shown in Figure 7.9. The traffic at the FRT-ramp intersection (Site 1) was northbound left-turn (NBL) and the traffic at the non-FRT-ramp intersection (Site 3) was southbound left-turn (SBL). Table 7.1 presents the analysis results.

Table 7.1 Microsimulation Calibration Results for Intersections with and without FRT Ramp

Calibration Results		
Travel time (TT) Statistics	**FRT Approach: NBL**	**Non-FRT Approach: SBL**
Empirical Mean TT	53.06 seconds	110.10 seconds
Simulated Mean TT	54.02 seconds	108.63 seconds
Mean Absolute Error %	1.79%	1.20%
Welch t-test (P-value) (alpha =5%)	0.33	0.78
Kolmogorov Smirnov (KS) test (P-value) (alpha= 5%)	0.07	0.34

Table 7.1 shows that the empirical mean travel times of the FRT and non-FRT intersections for the left-turn approach were 53.06 and 110.10 seconds, respectively. The calibrated simulation models produced travel times of 54.02 and 108.63 seconds, which were within 1.79% and 1.20% of the mean field observed values. Therefore, the simulated travel times were close to the empirical observations. However, the calibration algorithm aims to find solutions that produce results without any statistically significant difference at the 95% confidence level. The Welch t-test and Kolmogorov–Smirnov (KS) tests showed a p-value higher than 0.05. This implied that there was no statistical evidence of difference in the mean values. The KS test provided evidence that the distribution of the travel time of the simulated and observed were similar. Therefore, it was evident that the simulation model produced the variabilities of the traffic performance occurring in real-world scenarios. This was the major goal of the calibration process.

Furthermore, the calibrated parameters were applied in Site 2 and Site 4 (i.e., four-legged intersection with and without FRT ramp), and the simulation model produced similar field observed travel times to those discussed above. Therefore, the calibrated microsimulation models were also validated using Site 2 and Site 4. Note that the calibration algorithm shown in Figure 7.9 can be directly applied to the Site 2 and Site 4 traffic conditions to find the optimal parameter set.

Table 7.2 shows representative values of the final parameters from the calibration algorithm. Slight variations of the parameter values were used based on different locations to fine-tune desired outcomes. In a broad sense, Table 7.2 represents the calibrated parameters for Nebraska's local conditions.

Table 7.2 Calibrated Microsimulation Parameter Values for Driver Behavior and Gap Acceptance Model

Parameters	**Passenger Car**	**Heavy Trucks**
CC0 (Standstill distance)	10 feet	10 feet
CC1 (headway time)	2.75 s (mean)	3.25 s (mean)
	0.2 s (Standard deviation)	0.2 s (Standard deviation)
CC2 (following variations)	20 feet	20 feet
CC4-CC6	VISSIM default values	VISSIM default values
Minimum gap time	5.1 s (Turn from major approach)	5.6 s (Left turn from minor approach)
	6.6 s (Left turn from minor approach)	7.1 s (Right turn from intersection)
	6.5 s (Right turn from FRT ramp/minor approach)	7.0 s (Right turn from FRT ramp/minor approach)

7.4.3 Sensitivity Analysis

As the VISSIM microsimulation model was calibrated and validated, the models could be used to study different alternative scenarios and different performance measures such as stopped delay, vehicle delay, travel time, and maximum queue length. To test the ability of the simulated model to respond to the variabilities of traffic demand, three example scenarios were tested where the major road volumes were kept at 400 vehicles per hour (vph) and three minor road volumes of 100 vph (Scenario 1), 200 vph (Scenario 2) and 300 vph (Scenario 3) were studied. It was assumed that 40% of traffic from the major road turns on to the minor road and the right turn percentage of the minor road was 50%. Heavy trucks comprised 7.5% of the total traffic volume. Table 7.3 lists the results of the three example scenarios.

Table 7.3 Sensitivity Analysis Results of Three Scenarios

Volume	**Delay (second/vehicle)**			**Maximum Queue (feet)**		
	FRT Minor	Non-FRT Minor	Difference	FRT Minor	Non-FRT Minor	Difference
Scenario 1	35.8	40.7	11.9%	172.1	302.8	43.1%
Scenario 2	85.5	217.4	60.1%	349.6	1899.2	81.5%
Scenario 3	289.6	457.1	36.6%	1469.7	5180.1	71.6%

Table 7.3 shows that the FRT ramp can help reduce vehicular delay and maximum queue length as the minor volume increased from 100 to 300 vph. The maximum queue and delay can be reduced up-to around 60% and 80%, respectively. A 50% right turn percentage was used, which means use of the FRT ramp contributed to the improvement. Therefore, different traffic conditions (combinations of different volume levels and turn percentages) should be studied to measure the potential impacts of FRT ramps. Section 7.5.1 presents a comprehensive study of different traffic and FRT geometric conditions through sensitivity analysis.

7.5 Feasibility Studies of FRT Ramp

It is useful to find whether an FRT ramp is economically viable, given the potential operational benefits. Compared to the right turn movement from the minor approach, an FRT ramp requires additional right of way and substantial construction costs. The financial feasibility of constructing an FRT ramp is therefore examined in this section for any prospective operational benefits.

7.5.1 Scenario Development

An FRT-ramp feasibility study requires consideration of various traffic conditions and FRT geometry. This section determines different scenarios for FRT and non-FRT ramp intersections on a two-lane highway facility. Three FRT ramp dimensions with various speed limits were considered. These were FRT radii of 650, 1,200, and 1,800 feet with respective speed limits of 45, 55, and 65 miles per hour (mph). These FRT radii and speed limits were congruent with the AASHTO Green Book and NDOT Road manual design (AASHTO, 2018; NDOT RDM, 2019). The FRT ramps under consideration directed right-turning traffic from the minor road to the major road. Therefore, traffic using these ramps did not need to stop at the stopped-controlled intersection. Note that an alternative scenario, where FRT ramps emerged from the major road, did not necessarily cause operational issues on either the major or the minor road other than slowing down. This is the reason the FRT ramp from the minor approach was considered for the feasibility studies.

The research team considered three traffic volume levels both for the major approach (5,000, 10,000, and 15,000 AADT) and minor approach (2,500, 5,000, and 7,500 AADT). These volume scenarios applied to both stop-controlled intersections with and without an FRT ramp. The daily traffic was distributed among two hours of peak periods (i.e., morning and evening) and 14 hours of non-peak periods. Eight hours of traffic from 10:00 pm to 6:00 am were assumed negligible. This study assumed that 20% of traffic turned from the major approach to the minor approach for all scenarios. However, three right turning percentages (i.e., 10%, 25%, and 50%) scenarios were assumed to move through the FRT ramp to the major street. The traffic stream was assumed to be 15% heavy vehicles (i.e., combination of single unit truck and tractor trailer) which complied with the average value found from truck AADT records (NDOT AADT, 2023), video data observations, and the previous McCoy et al. study (1995).

Therefore, there were nine combinations of AADT (three each from the major and the minor approaches), three types of ramps (650, 1,200, and 1,800 feet radii) and three levels of right-turning FRT traffic (10%, 25%, and 50%). This setup resulted in 81 scenarios. Furthermore, each of the 81 scenarios required two traffic periods (peak and non-peak hour) and two types of intersections (stopped controlled with and without FRT ramps), making a total 324 scenarios. These 324 scenarios were simulated in the VISSIM microsimulation software. One-third of these scenarios were run 10 times and the rest were run 5 times (using different seed numbers) making a total of 2,160 simulation runs.

Each simulation run generated operational outcomes such as stopped delays (i.e., vehicle stopping at stop-controlled intersections), vehicle delays (stopped delays plus delays due to acceleration and deceleration to respond to surrounding traffic), maximum queue length, and travel times of different sections along the simulated network. The research team processed these results and integrated them into the respective cost components. This procedure enabled feasibility studies for the FRT ramps.

7.5.2 Operational and FRT Construction Costs

Quantification of the operational costs of vehicle movements around intersections required three major components: i) value of time, ii) idling cost, and iii) running cost. The unit value of time was used to quantify the delay or travel time savings costs. Idling costs occurred when vehicles were completely stopped at the intersection. Furthermore, compared to the stopped controlled intersection, right-turning vehicles using the FRT ramp needed to traverse less distance, quantified as 0.429 times the radius of the FRT ramp radius (McCoy et al., 1995). This factor (i.e., distance savings due to FRT ramp) incurred running cost savings for the FRT ramp.

The FRT ramp costs included construction costs, right-of-way costs, and maintenance costs. McCoy et al. (1995) listed different cost components and their values in 1994. This study converted 1994 values to the current year (2023) and estimated the FRT ramp costs.

Based on the literature review of operational cost components for National use and Nebraska-based studies (AASHTO Redbook, 2010; Tufuor et al., 2022) and conversion of prices from the previous year, the costs categories applied are shown in Table 7.4.

Table 7.4 Cost Components and Unit Values for Operation, Construction and Maintenance

Cost Component		**Vehicle Composition**		
		Passenger car	**Single unit truck**	**Tractor-trailer**
Operation costs	Value of time	29.18 ($/hr)	31.55 ($/hr)	33.45 ($/hr)
	Idling cost	1.60 ($/hr)	1.24 ($/hr)	0.87 ($/hr)
	Running cost	0.07 ($/mile)	0.21 ($/mile)	0.21 ($/mile)
Construction & maintenance costs	FRT ramp	**FRT Dimensions (Radius in feet)**		
		1800	**1200**	**650**
		$ 1,161,000	$ 775,000	$ 420,000

7.5.3 Benefit Cost Analysis

The cost items shown in Table 7.4 were applied to the FRT and non-FRT intersections. The research team used operational costs of the non-FRT and FRT intersections under the same traffic and geometric conditions to determine benefits. In addition, vehicles using the FRT ramp aid in benefits due to the distance savings. The combined benefits were compared with the construction and maintenance costs of FRT ramps. A design life of 20 years was assumed for this study. The net benefit and costs were converted to present value using discount rates to conduct a benefit cost analysis. This study used three discount rates, which were 4%, 6%, and 8%.

Table 7.5 lists the benefit/cost ratio (B/C ratio) for different traffic and geometric conditions while applying three discount rates. The table color codes the outcomes based on the B/C ratio. For no benefit or B/C ratio less than one, B/C ratio more than one but less than two, and B/C ratio more than two are coded as red, yellow, and green, respectively. A B/C ratio of more than two may be considered favorable for the FRT ramp alternative.

Table 7.5 Benefit cost ratio (B/C) for FRT Ramp under Different Traffic and Geometric Conditions

Discount rate	Major Road AADT	Right Turn %	FRT R= 1800 feet SL =65 mph: Minor Road AADT 2500	5000	7500	FRT R= 1200 feet SL =55 mph: Minor Road AADT 2500	5000	7500	FRT R= 650 feet SL =45 mph: Minor Road AADT 2500	5000	7500
Discount rate = 4%	5000	10	Red	Red	Green	Red	Yellow	Green	Red	Green	Green
		25	Red	Yellow	Green	Red	Green	Green	Yellow	Green	Green
		50	Yellow	Green	Green	Yellow	Green	Green	Green	Green	Green
	10000	10	Red	Green	Green	Red	Green	Green	Red	Green	Green
		25	Red	Green	Green	Yellow	Green	Green	Green	Green	Green
		50	Yellow	Green	Green	Green	Green	Green	Green	Green	Green
	15000	10	Green	Green	Green	Green	Green	Green	Green	Green	Green
		25	Green	Green	Green	Green	Green	Green	Green	Green	Green
		50	Green	Green	Green	Green	Green	Green	Green	Green	Green
Discount rate = 6%	5000	10	Red	Red	Green	Red	Red	Green	Red	Green	Green
		25	Red	Yellow	Green	Red	Green	Green	Red	Green	Green
		50	Green	Green	Green	Yellow	Green	Green	Yellow	Green	Green
	10000	10	Red	Green	Green	Red	Green	Green	Red	Green	Green
		25	Red	Green	Green	Red	Green	Green	Yellow	Green	Green
		50	Yellow	Green	Green	Green	Green	Green	Green	Green	Green
	15000	10	Green	Green	Green	Green	Green	Green	Green	Green	Green
		25	Green	Green	Green	Green	Green	Green	Green	Green	Green
		50	Green	Green	Green	Green	Green	Green	Green	Green	Green
Discount rate = 8%	5000	10	Red	Red	Green	Red	Red	Green	Red	Yellow	Green
		25	Red	Yellow	Green	Red	Yellow	Green	Red	Green	Green
		50	Green	Green	Green	Yellow	Green	Green	Yellow	Green	Green
	10000	10	Red	Green	Green	Red	Green	Green	Red	Green	Green
		25	Red	Green	Green	Red	Green	Green	Yellow	Green	Green
		50	Yellow	Green	Green	Yellow	Green	Green	Green	Green	Green
	15000	10	Green	Green	Green	Green	Green	Green	Green	Green	Green
		25	Green	Green	Green	Green	Green	Green	Green	Green	Green
		50	Green	Green	Green	Green	Green	Green	Green	Green	Green

Note: SL (Speed Limit), R (Radius), FRT (Free Right Turn)

B/C ratio: less than 1 or no benefit (Red) more than 1 but less than 2 (Yellow) more than 2 (Green)

Under each discount rate, there were 81 scenarios. It can be seen that for 4%, 6%, and 8% discount rates, there were 17, 18, and 21 scenarios, respectively, that have a B/C ratio lower than two. Not surprisingly, a higher discount rate tended to reduce the economic feasibility of the FRT ramp.

The authors would like to recommend the feasibility of the FRT ramp alternative using the 8% discount rate. It was found that when the major road had 15,000 or more AADT and the minor road had 2,500 or more AADT with a right-turning to major road volume of 10% or higher, the FRT ramp was warranted (i.e., B/C ratio is higher than two). On the other hand, if the major road had 10,000 AADT and the minor road had 5,000 or more AADT, the FRT ramp was warranted for 10% or more right-turning vehicles from the minor to the major road. Similarly, if the major road had 5,000 AADT and the minor road had 7,500 or more AADT, the FRT ramp was warranted for 10% or more right-turning vehicle from the minor to the major road.

In case of a high right-turn percentage such as 50% from minor to major approach, a scenario comprising of a major road with 5,000 or more AADT and a minor road with 2,500 or more AADT should be considered as a candidate of the FRT ramp alternative.

Even though a shorter FRT ramp reduces construction costs (compared to a large FRT ramp) and may be a viable option to gain benefits, the maximum queue length of peak hour period traffic may extend upstream higher than the FRT entrance location. Therefore, it can hinder traffic that intends to make a right-turn to the major road via an FRT ramp. Therefore, caution should be exercised along with B/C ratio results before choosing to use short FRT ramps.

Chapter 8 Summary and Conclusions

This chapter first presents a summary of the research, including the data used and tests that were conducted, followed by their results. Then, based on the research findings, conclusions, limitations, and recommendations for future research are given.

8.1 Research Summary and Results

The primary objectives of this research were to: identify rural free right-turn (FRT) ramp intersections in Nebraska and similar non-FRT-ramp intersections for comparison testing purposes, perform a safety analysis using police-reported crashes from 2010 to 2019, and perform a conflict analysis using Miovision Scout video recording equipment.

8.1.1 Inventory of FRT and non-FRT Intersections

In total, 68 FRT ramp intersections were identified, with 57 intersections containing one FRT ramp and 11 intersections containing two FRT ramps. Intersection characteristics, such as intersection legs, presence of skew, and lighting were recorded for inventory purposes. Additionally, specific data relating to the FRT ramps themselves were recorded, such as signage, FRT length, FRT radius, island type, and the presence of acceleration and deceleration lanes. AADT ranges of low, medium and high were created using quartiles of the FRT intersection traffic volumes from 2018 to ensure that non-FRT intersections that were identified had a wide range of traffic volumes. The year 2018 was chosen, as it was the latest traffic volume data available before the COVID-19 pandemic, in hopes of avoiding potentially "abnormal" values thereafter. 24 non-FRT intersections were identified—12 three-legged and 12 four-legged—and further divided into the low, medium, and high AADT categories. Similar recorded intersection characteristics were obtained for both the non-FRT intersections and the FRT intersections.

8.1.2 Safety Analysis

For the safety analysis, a comparison of FRT and non-FRT crash frequencies, crash rates, severity, and crash types over the ten-year period (2010–2019) was performed to identify differences. The raw data of the crashes reported during the period were first compared to search for trends. Regarding crash severity, there were no evident differences between intersections with and without FRT ramps; the most notable finding was that the FRT ramp intersections (1.41%) experienced 0.40% more fatal crashes from 2010 to 2019 than the non-FRT intersections (1.01%). Regarding the crash type, the FRT-ramp intersections had 7.53% fewer rear-end crashes than the non-FRT-ramp intersections. Also, the FRT-ramp intersections had 9.35% more sideswipe crashes than non-FRT-ramp intersections. However, there were no large differences amongst the different crash types.

Crash frequency and crash rate were calculated for each FRT-ramp and non-FRT-ramp intersection and several comparisons were made between the two groups to see how traffic volume, intersection type, and the presence of the FRT ramp on the major or minor approach affect the values. For crash frequency, 20 comparisons were made between the FRT-ramp and non-FRT-ramp intersections, with the FRT-ramp intersections having a higher crash frequency in 14 cases. For crash rates, the same comparisons were reviewed, with FRT intersections having a higher crash rate in 19 of the 20 comparisons. A two-sample t-test was performed for these comparisons using an alpha value of 0.05, to identify any statistically significant differences among mean crash frequencies and rates. For the crash frequency comparisons, no statistically significant findings were determined. For crash rate, there was only one statistically significant finding: For FRT-ramp intersections that have an FRT ramp on the major approach, either at three-leg or four-leg intersections, a statistically significant higher crash rate was observed when compared to non-FRT-ramp intersections of all-leg types.

8.1.3 Conflict Analysis

For the conflict analysis, Miovision Scout video recording equipment was used to record vehicle interactions at several FRT and non-FRT intersections. The intersections were chosen based on AADT and the number of intersection legs. In total, 12 intersections were chosen: six three-legged and six four-legged, with one FRT and one non-FRT per low, medium, and high AADT category. For the FRT intersections, conflicts were recorded between the vehicles using the FRT ramp and the crossing-through vehicles. For the non-FRT intersections, the observed right-turn movement was chosen based on the location of its FRT intersection counterpart. For example, for the low AADT category for three-legged intersections, the FRT ramp was located on the major approach, therefore for the non-FRT comparison, the right-turn movement of interest was also on the major approach. For the non-FRT intersections, several conflicts were observed, including right-turn, same direction, opposing left-turn, through, cross traffic from left, and right-turn-on-red (RTOR). The location of the right-turn movement on the major or minor approach, the number of intersection legs, and the presence of an exclusive right-turn lane determined what specific conflicts existed.

For the 12 intersections, with six being FRT intersections and six being non-FRT intersections, conflict per hour and conflict per 1000 entering right-turning vehicles were compared. For conflict per hour, it was split evenly with three FRT intersections having a higher value in some cases, and three non-FRT intersections having higher values in the other cases. However, across all tested intersections, the non-FRT intersections had higher conflicts per hour. For conflict per 1000 entering right-turning vehicles, five of the non-FRT intersections had higher values than their FRT intersection counterpart, and the non-FRT intersections had a much higher value when considering all the tested sites. The choice to use conflict per 1000 entering right-turning vehicles as the primary metric was made for a similar reason the crash rate was chosen for the safety analysis—the differences in traffic volume are no longer a significant factor when using this method.

To look at these intersections in a different way besides AADT and the number of intersection legs, the intersections were categorized into three major scenarios:

1. FRT ramp located on the minor approach, with the non-FRT right-turn located on the stop-controlled minor approach
2. FRT ramp located on the major approach, with the non-FRT right-turn movement having no exclusive right-turn lane on the major approach
3. FRT ramp located on the major approach, with the non-FRT right-turn approach having an exclusive right-turn lane

Comparing these scenarios, the non-FRT intersections all had higher conflicts per 1000 entering right-turning vehicles, with the most significant difference in scenario two. When vehicles turn on the major approach of a rural highway with no exclusive right-turn lane present, the following-through vehicles, traveling at a high rate of speed, must suddenly slow down and brake or swerve across the painted centerline to avoid a rear-end collision. The FRT ramp eliminates this conflict as right-turning and through traffic are separated at the intersection. In scenario three, where there is an exclusive right-turn lane present on the major approach, there are more similarities in conflicts per 1000 entering right-turning vehicles, but the FRT intersections still produce lower values. Scenario one also has less of a difference between FRT and non-FRT intersections, where the FRT ramp is located on the minor approach and the non-

FRT right-turn is located on the minor approach which is stop-controlled. For the non-FRT intersections, it can be inferred that drivers are less likely to disobey the stop sign and impede on the major traffic's right-of-way, but other conflicts are still present even when the vehicles make their right-turn because there is still interaction with the major traffic. Because of these other conflicts, the non-FRT intersections have a higher conflict per 1000 entering right-turning vehicles.

8.1.4 Operational Analysis

Four sites in Nebraska were studied to build a microsimulation model using VISSIM to model traffic operations in FRT and non-FRT stop-controlled intersections. A robust calibration algorithm was used to make sure the performance measures simulated by VISSIM were not statistically different compared to the field observed measures.

The simulation model was used to study different traffic conditions and various geometry of FRT ramps. A total of 324 scenarios were studied to conduct a comparison study between non-FRT and FRT intersections in terms of operational benefits. With a 20-year design life and 4%, 6%, and 8% discount rates, the operational value in terms of cost savings and FRT construction costs were calculated. The resulting B/C ratios obtained for all traffic and geometry conditions were used to determine the economic feasibility of FRT ramp.

Based on the B/C ratio analysis, the FRT ramp can be justified based on the following observations.

- When the major road has 15,000 or more AADT and the minor road has 2,500 or more AADT with 10% or higher left-turning volume from major to minor, an FRT ramp is warranted.

- If the major road has 10,000 AADT and the minor road has 5,000 or more AADT with 10% or higher right-turning volume from major to minor, an FRT ramp is warranted.
- If the major road has 5,000 AADT and the minor road has 7,500 or more AADT with 10% or higher right-turning volume from major to minor, an FRT ramp is warranted.
- If the major road has 5,000 or more AADT and the minor road has 2,500 or more AADT, with a high right-turn percentage (i.e., 50%) from minor to major approach, an FRT ramp alternative should be considered.
- Short FRT's construction costs are lower. However, during peak hour, vehicle queues may grow longer and may block the entrance of the FRT ramp. This scenario can block the right turning traffic from using the FRT ramp without being stopped. Therefore, along with B/C ratio outcomes, extra care should be taken before deciding in favor of a relatively shorter FRT ramp.

8.2 Conclusions

After analyzing the findings of the safety and conflict analyses, the following conclusions were made:

- The presence of an FRT ramp at an intersection does not affect the crash frequency, rate, severity, or type of crash. Although the results indicated higher values for both crash frequency and crash rate, only one statistically significant finding was observed.
- Conflicts reduced between right-turning vehicles and the other traffic at the intersection when an FRT ramp was present. This was especially true when no exclusive right-turn lanes existed at non-FRT-ramp intersections.
- For 10% or more right-turning traffic from minor to major roads, FRT ramps are justified in minor approaches in terms of operational benefit for the following three traffic

conditions: i) major road with 15,000 and minor road with 2,500 AADT, ii) major road with 10,000 and minor road with 5,000 AADT, and iii) major road with 5,000 and minor road with 7,500 AADT.

Revisiting McCoy's (1995) research study, similar findings were reported. McCoy stated that "the presence of an FRT lane does not affect the frequency, severity, or types of accidents that occur." Regarding conflict, McCoy's study focused on the need for acceleration lanes, stating that "the absence of acceleration lanes increases conflict in the merge area." For this research, scenario three of the conflict analysis represents this finding as well. All FRT-ramp intersections had an acceleration lane, while the non-FRT intersections with exclusive right-turn lanes did not have acceleration lanes. In this case, the FRT intersections had a lower conflict per 1000 entering right-turning vehicles.

8.3 Limitations and Future Research

This research conducted its safety analysis assuming several factors. For example, because the construction dates of the FRT ramps were not known, the FRT intersections were assumed to have similar geometric and traffic characteristics for the ten-year period of interest (2010–2019). If a particular FRT-ramp intersection had an FRT ramp constructed within that period, the changes in that intersection's crash frequency and crash rate were not known. Additionally, with limited traffic volume data (i.e., missing odd years), assumptions were made that interpolation of the known data to find the missing data was sufficient.

Another limitation of this research was the use of the two-sample t-tests to test the statistical significance of the safety analysis. First, crashes were Poisson distributed, while the t-test was to be used for normal distributions, so typically the t-test would not be accepted. However, with the available data and testing of two populations, it was chosen as the best method. An Empirical-Bayes before-after test would be preferred, however, due to the lack of data detailing the construction of each FRT ramp and the potential need for much older crash data for older FRT ramps, sufficient and precise data for a "before" and "after" period would be hard to obtain. For future research, if these dates and many more years of crash data could be obtained, it would presumably offer more precise results.

Also, regarding the use of t-tests in traffic studies, it has been argued that the term "not significant" can often be confused with "not important" (Hauer, 2004). Although the findings of the t-test in the case of this research, found only one statistical finding out of 40 comparisons that were tested at the 95% confidence level, these findings are not irrelevant and do not entirely indicate that there was no change in safety observed. This paired with relatively few populations (68 FRT intersections and 24 non-FRT intersections) in the statistical sense, the results may not be fully indicative of what is true about the FRT ramp's effect on safety. Therefore, in future research, a study of FRT-ramp intersections and non-FRT-ramp intersections across several states may provide more telling results.

The conflict behaviors from the field data should be incorporated into a microsimulation platform so that more conflict data can be produced for different traffic situations using the surrogate safety assessment model (SSAM).

References

AASHTO Green Book. 2018. A Policy on Geometric Design of Highway and Streets. Edition 2018.

AASHTO Red Book. 2010. User and Non-User Benefit Analysis for Highways.

Achtemeier, J., Craig, C. M., & Morris, N. L. (2019, November). The effects of restricted sight distances on drivers at simulated rural intersections. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 63, No. 1, pp. 2122-2123). Sage CA: Los Angeles, CA: SAGE Publications.

Ale, G. B., Varma, A., & Gage, B. (2014). Safety impacts of right-turn lanes at unsignalized intersections and driveways on two-lane roadways: Crash analysis. *Journal of Transportation Engineering*, *140*(2), 04013001.

Ale, G. B., Varma, A., Gage, B., & Gyawali, S. (2014). Safety-based volume warrants for right-turn lanes at unsignalized intersections and driveways on two-lane roadways. *Journal of Transportation Engineering*, *140*(12), 04014064.

Bared, J., Giering, G. L., & Warren, D. L. (1999). Safety evaluation of acceleration and deceleration lane lengths. *ITE journal*, *69*, 50-54.

Biancardo, S. A., Russo, F., Zhang, W., & Veropalumbo, R. (2019). Design criteria for improving safety performance of rural intersections. *Journal of Advanced Transportation*, *2019*, 1-11.

Biancardo, S. A., Russo, F., Žilionienė, D., & Zhang, W. (2017). Rural two-lane two-way three-leg and four-leg stop-controlled intersections: predicting road safety effects. *The Baltic Journal of Road and Bridge Engineering*, *12*(2), 117-126.

Buck, H. S., N. Mallig, and P. Vortisch. Calibrating VISSIM to analyze delay at signalized intersections. Transportation Research Record: Journal of the Transportation Research Board, 2017. 2615: 73–81.

Calvi, A., & De Blasiis, M. R. (2011). Driver behavior on acceleration lanes: Driving simulator study. Transportation Research Record, Journal of the Transportation Research Board, 2248(1), 96-103.

Calvi, A., Benedetto, A., & De Blasiis, M. R. (2012). A driving simulator study of driver performance on deceleration lanes. *Accident Analysis & Prevention*, *45*, 195-203.

Cottrell Jr, B. H. (1982). Guidelines for treatment of right-turn movements on rural roads (abridgment, No. HS-034 645).

Cottrell, B. H. (1981). The development of criteria for the treatment of right turn movements on rural roads (No. VHTRC 81-R45). Virginia Transportation Research Council.

Crowe, E. C. (1990). Traffic conflict values for three-leg, unsignalized intersections. Transportation Research Record, Journal of the Transportation Research Board,1287.

Dabbour, E., Easa, S. M., & Dabbour, O. (2021). Minimum lengths of acceleration lanes based on actual driver behavior and vehicle capabilities. *Journal of Transportation Engineering, Part A: Systems*, *147*(3), 04020162.

Dixon, K. K., Hibbard, J. L., & Nyman, H. (1999, June). Right-turn treatment for signalized intersections. In *Urban Street Symposium, Transportation Research Circular E-C019* (Vol. 3, No. 5556, p. 036).

Fazio, J., Holden, J., & Rouphail, N. M. (1993). Use of freeway conflict rates as an alternative to crash rates in weaving section safety analyses. Transportation Research Record, Journal of the Transportation Research Board, 1401.

Federal Highway Administration. Office of Safety Research and Development. Surrogate safety measures from traffic simulation models. Updated March 8, 2016.

https:\www.fhwa.dot.gov\publications\research\safety\03050\04.cfm. Accessed March 30, 2023.
Fitzpatrick, K., Schneider IV, W. H., & Park, E. S. (2006). Operation and safety of right-turn lane designs. Transportation Research Record, Journal of the Transportation Research Board, 1961(1), 55-64.
Gemar, M. D., Wafa, Z., & Forecaster, T. D. Developing design guidelines for right-turn slip lanes. Submitted for consideration for the 2016 TexITE Technical Paper Award.
Hadi, M. A., & Thakkar, J. (2003). Speed differential as a measure to evaluate the need for right-turn deceleration lanes at unsignalized intersections. Transportation Research Record, Journal of the Transportation Research Board, 1847(1), 58-65.
Haleem, K., & Abdel-Aty, M. (2010). Examining traffic crash injury severity at unsignalized intersections. *Journal of Safety Research*, *41*(4), 347-357.
Hall, D. L., Sinha, K. C., & Michael, H. (1978). Comprehensive evaluation of nonsignalized control at low volume intersections. Transportation Research Record, Journal of the Transportation Research Board, 681, 10-12.
Haque, M. S. 2022. Improved traffic analysis methodology for lane closure on two-lane highway work zone. Doctoral Dissertation, The University of Nebraska-Lincoln.
Haque, M. S., and J. D. Sangster. 2018. Best practices for modeling light rail at intersections. University Transportation Center for Railway Safety. No. 26-1121-0018-009.
Haque, M. S., L. Rilett., L. Zhao, and E. Tufuor. 2022. Calibration and validation of a microsimulation model of lane closures on two-lane highway work zone. Transportation Research Record, Journal of the Transportation Research Board. https://doi.org/10.1177/03611981221119456
Haque, M. S., L. R. Rilett, and L. Zhao. 2023. Impact of platooning of connected and automated heavy vehicles on interstate freeway work zone operations. *Journal of Transportation Engineering, Part A: Systems*, 149(3). https://ascelibrary.org/doi/full/10.1061/JTEPBS.TEENG-7434
Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Rabbani, E. R., & Griffith, M. S. (2003). Safety effectiveness of intersection left-and right-turn lanes. Transportation Research Record, Journal of the Transportation Research Board, *1840*(1), 131-139.
Hauer, E. (1997). Observational before/after studies in road safety. Estimating the effect of highway and traffic engineering measures on road safety, Elsevier Science, Tarrytown, NY.
Hauer, E. (2004). The harm done by tests of significance. *Accident Analysis & Prevention*, *36*(3), 495-500.
HCM. (1994). Highway Capacity Manual. Chapter 10: Unsignalized Intersection. Special Report 209, 3rd Edition. Transportation Research Board. Washington, DC.
HCM. 2016. Highway Capacity Manual, 6th Edition. Transportation Research Board, Washington, D.C.
Hochstein, J. L., Maze, T. H., Preston, H., Storm, R., & Welch, T. M. (2007). Safety effects of offset right-turn lanes at rural expressway intersections. In *Mid-Continent Transportation Research Symposium, Ames, Iowa*.
Khattak, A. J., & Jovanis, P. P. (1990). Capacity and delay estimation for priority unsignalized intersections: Conceptual and empirical issues. Transportation Research Record, Journal of the Transportation Research Board, (1287).
Khattak, A., & Kang, Y. (2018). Offset Right-Turn Lanes on State Highway Systems (No. 26-1121-0030-001), Nebraska Department of Transportation.

Kim, D. G., Washington, S., & Oh, J. (2006). Modeling crash types: New insights into the effects of covariates on crashes at rural intersections. *Journal of Transportation Engineering*, *132*(4), 282-292.
Kochenderfer, M. J., and T. A. 2019. Wheeler. Algorithms for Optimization. MIT Press, Cambridge, MA.
Kou, C. C., & Machemehl, R. B. (1997). Modeling vehicle acceleration deceleration behavior during merge maneuvers. *Canadian Journal of Civil Engineering*, *24*(3), 350-358.
Leckrone, S. J., Tarko, A. P., & Anastasopoulos, P. C. (2011). Improving safety at high-speed rural intersections. In *3rd International Conference on Road Safety and Simulation, September* (pp. 14-16).
Macfarlane, G. S., Saito, M., & Schultz, G. G. (2011). Delay underestimation at free right-turn channelized intersections. *Procedia-Social and Behavioral Sciences*, *16*, 560-567.
Macfarlane, G. S., Saito, M., & Schultz, G. G. (2011). Driver perceptions at free right-turn channelized intersections. In *Transportation and Development Institute Congress 2011: Integrated Transportation and Development for a Better Tomorrow* (pp. 1128-1137).
Maze, T. H., Hawkins, N. R., & Burchett, G. (2004). *Rural expressway intersection synthesis of practice and crash analysis* (No. CTRE Project 03-157). Ames: Center for Transportation Research and Education, Iowa State University.
McCoy, P. T., & Hoppe, W. J. (1986). Traffic operations study of the turning lanes on uncontrolled approaches of rural intersections. Transportation Research Record, Journal of the Transportation Research Board, 1100, l-9.
McCoy, P. T., & Tobin, J. R. (1982). Use of additional through lanes at signalized intersections. Transportation Research Record, Journal of the Transportation Research Board,, *869*, 1-5.
McCoy, P. T., Bishu, R. R., Bonneson, J. A., Fitts, J. W., Fowler, M. D., Gaber, S. L., & Sicking, D. L. (1995). Guidelines for free right-turn lanes at unsignalized intersections on rural two-lane highways. Final Report (No. RES1 (0099) P603).
McCoy, P. T., Bonneson, J. A., Ataullah, S., & Eitel, D. S. (1994). Guidelines for right-turn lanes on urban roadways. Transportation Research Record, Journal of the Transportation Research Board, 1445, 130-137.
McCoy, P. T., Hoppe, W. J., & Dvorak, D. V. (1985). Benefit-cost evaluation of left-turn lanes on uncontrolled approaches of rural intersections. Transportation Research Record, Journal of the Transportation Research Board, 1026, 40-43.
Menon, A., & Donath, M. (2014). Minnesota Department of Transportation Rural Intersection Conflict Warning System (RICWS) Reliability Evaluation.
Meuleners, L. B., Fraser, M. L., & Roberts, P. (2020). Impact of the rural intersection active warning system (RIAWS) on driver speed: A driving simulator study. *Accident Analysis & Prevention*, *141*, 105541.
Miovision Scout. 2023. https://www2.miovision.com/get-scout. Accessed March 30, 2023.
NDOT AADT. 2023. Nebraska Department of Transportation. Annual Average Daily Traffic. https://gis.ne.gov/portal/apps/webappviewer/index.html?id=8ed4b009b0d546f19f0284e5bba0f972. Accessed March 30, 2023.
NDOT RDM. 2019. Nebraska Road Design Manual. Nebraska Department of Transportation.
Nebraska Department of Transportation, Roadway Design Manual, Chapter 4: Intersections, Driveways, and Channelization, May 2012. https://dot.nebraska.gov/media/11484/g-chap-4-intersections-and-driveways.pdf

Oh, J., Washington, S., & Choi, K. (2004). Development of accident prediction models for rural highway intersections. Transportation Research Record, Journal of the Transportation Research Board, 1897(1), 18-27.

Parker Jr, M. R., & Zegeer, C. V. (1989). Traffic conflict techniques for safety and operations: Observer's manual (No. FHWA-IP-88-027, NCP 3A9C0093). Federal Highway Administration, US DOT.

Pawar, D. S., & Patil, G. R. (2017). Minor-street vehicle dilemma while maneuvering at unsignalized intersections. *Journal of Transportation Engineering, Part A: Systems*, *143*(8), 04017039.

Perkins, S. R., & Harris, J. L. (1968). Traffic conflict characteristics-accident potential at intersections. *Highway Research Record*, (225).

Potts, I. B., Harwood, D. W., Bauer, K. M., Gilmore, D. K., Hutton, J. M., Torbic, D. J., ... & Barlow, J. M. (2014). Design guidance for channelized right-turn lanes (NCHRP Project 03-89).

Potts, I. B., Ringert, J. F., Harwood, D. W., & Bauer, K. M. (2007). Operational and safety effects of right-turn deceleration lanes on urban and suburban arterials. Transportation Research Record, Journal of the Transportation Research Board, *2023*(1), 52-62.

Preston, H., & Storm, R. (2003, August). Reducing crashes at rural thru-stop controlled intersections. In *Mid-Continent Transportation Research Symposium* (pp. 21-22).

PTV VISSIM. 2020. Software. User Manual. https://www.ptvgroup.com/en/solutions/products/ptv-vissim/. Accessed March 30, 2023.

Ring, J. B., & Sadek, A. W. (2012). Predicting lane utilization and merge behavior at signalized intersections with auxiliary lanes in Buffalo, New York. *Journal of Transportation Engineering*, *138*(9), 1143-1150.

Salman, N. K., & Al-Maita, K. J. (1995). Safety evaluation at three-leg, unsignalized intersections by traffic conflict technique. Transportation Research Record, Journal of the Transportation Research Board, 1485(28), 177-185.

Schattler, K. L., Hanson, T., & Maillacheruvu, K. (2016). Effectiveness evaluation of a modified right-turn lane design at intersections. *Illinois Center for Transportation Series No. 16-013; Research Report No. FHWA-ICT-16-012*.

Schurr, K., & Foss Jr, T. J. (2010). Offset right-turn lanes for improved intersection sight distance. Final Report SPR-P1(06) P592. Nebraska Department of Transportation.

Spiegelman, C., E. S. Park, and L. R. Rilett. 2010. Transportation Statistics and Microsimulation. CRC Press, Boca Raton, FL, 2010.

Tufuor, E., L. Zhao, M. S. Haque, L. R. Rilett, J. E. Anderson, and E. C. Thompson. 2022. Estimating system and traveler costs due to lane closures during construction and maintenance operations. Final Report, Nebraska Department of Transportation. No. FY21-008. 2022.

Wolfe, F. A., & Lane, W. (2000, June). Effect of radius of curvature for right turning vehicles on through traffic delay. In *Proceedings of Fourth International Symposium on Highway Capacity,* Maui, Hawaii.

Yan, X., & Richards, S. H. (2009). Influence of restricted sight distances on gap-acceptance and non-gap-acceptance RTOR driving behaviors. *The University of Tennessee*.

Yang, J. (2008). Risk-based volume warrants for free right-turn lanes on two-lane roadways. *Journal of Transportation Engineering*, *134*(4), 155-162.

Zegeer, C. V., & Deen, R. C. (1977). Traffic conflicts as a diagnostic tool in highway safety. Kentucky Transportation Center Research Report.
Zeidan, G. R., & McCoy, P. T. (2000). Effects of right-turn lanes on driveway sight distance. Transportation Research Record, Journal of the Transportation Research Board, *1737*(1), 78-83.
Zhao, Li., L. Rilett., M. S. Haque. 2022. Calibration and validation methodology for simulation models of intelligent work zones. Transportation Research Record, Journal of the Transportation Research Board, 2676 (5): 500-513. https://doi.org/10.1177/03611981221082591
Zhou, H., Chen, H., & Baratian-Ghorghi, F. (2017). Prediction of intermittent sight distance obstruction at unsignalized intersections with conventional right-turn lanes. *Journal of Transportation Safety & Security*, *9*(1), 64-81.

Appendix A

Table A.1 FRT Ramp Intersection Characteristics (1 of 13)

Variable	Description	Coding (if applicable)	Source of Information
FRT_ID	FRT ramp ID		
INT_ID	FRT ramp intersection ID		
ITEM_NO	Number of ramp in order of when listed in the logbook		
COORDINATE	Coordinates via pathweb, based on reference post that was associated with the ramp		Pathweb
HWY_MAIN	Main highway, as stated		Nebraska Highway Reference Logbook
COUNTY	County, as stated		
HWY_POINT	Short description of the point on the highway where the ramp is located		
RAMP_DIR	Direction of the ramp from the reference post given (logbook travels from west to east or south to north)		
REF_POST	Reference post listed		
MILES	Copied directly; typically, similar to the reference post number		
HWY_NO	Highway number given in existing FRT inventory spreadsheet		From "IntegratedHighwayInventory_IHIP0108" spreadsheet provided by NDOT
REF_BEG	Reference post number at the beginning of the ramp		
REF_END	Reference post number at the end of the ramp		
RAMP_ID	ID number given to each ramp		
RAMP_LOC	Short description of the location of the ramp; typically includes intersecting roads and city		
INT	Intersecting roadways where the ramp exists		
BEG_END	Beginning or end of the ramp indicator, for highway segment:	Beginning = 1 End = 0	Pathweb/Google Earth
CITY	City (or village) the ramp is located in		Pathweb
AREA_TYPE	Rural or urban area, based off of population (population of 5,000 or more is urban, per AASHTO)	Rural = 1 Urban = 0	Nebraska Census website

Table A.1 FRT Ramp Intersection Characteristics (2 of 13)

Variable	Description	Coding (if applicable)	Source of Information
LEGS	Number of Intersection legs	4-leg intersection = 4 3-leg intersection = 3	Pathweb/Google Earth
SKEW	Presence of intersection skew	Yes = 1 No = 0	Pathweb/Google Earth
NAME_ENTR	Highway name of the road where the ramp entrance is located		Pathweb/Google Earth
LN_ENTR	Number of lanes on the road approaching the ramp		Pathweb/Google Earth
SHLDR_ENTR	Type of shoulder on the road approaching the ramp entrance	Paved = 2 Unpaved = 1 None = 0	Pathweb/Google Earth
DH_ENTR	Is the road approaching the ramp a divided highway?	Yes = 1 No = 0	Pathweb/Google Earth
DECEL_LN	Presence of a deceleration lane approaching the ramp entrance	Yes = 1 No = 0	Pathweb/Google Earth
MED_ENTR	Presence of a median on the road approaching the ramp entrance	Raised grass = 3 Raised pavement = 2 Painted = 1 None = 0	Pathweb/Google Earth
SL_ENTR	Speed limit (mph) of the road approaching the ramp entrance		Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (3 of 13)

Variable	Description	Coding (if applicable)	Source of Information
SL_SIGN_ENTR	Speed limit sign type	R2-1 = 1  R2-1 W13-1P = 0  W13-1P	Pathweb/Google Earth
SL_LOC_ENTR	Speed limit sign location (coordinates) on the road approaching the ramp entrance		Pathweb
SURF_ENTR	Surface type of road approaching ramp entrance	Gravel = 2 Asphalt = 1 Concrete = 0	Pathweb/Google Earth
CNTRL_THRU	Traffic control of through traffic for road approaching FRT ramp	Traffic signals = 3 STOP sign = 2 YIELD sign = 1 None = 0	Pathweb/Google Earth
NAME_EXIT	Highway name of the road where the ramp exits to		Pathweb/Google Earth
LN_EXT	Number of lanes on the road where the ramp exits to		Pathweb/Google Earth
SHLDR_EXIT	Type of shoulder on the road the ramp exits to	Paved = 2 Unpaved = 1 None = 0	Pathweb/Google Earth
DH_EXIT	Is the road the ramp exits to a divided highway?	Yes = 1 No = 0	Pathweb/Google Earth
ACCEL_LN	Presence of an acceleration lane after the ramp exit	Yes = 1	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (4 of 13)

Variable	Description	Coding (if applicable)	Source of Information
CNTRL_THRU	Traffic control of through traffic for road approaching FRT ramp	Traffic signals = 3 STOP sign = 2 YIELD sign = 1 None = 0	Pathweb/Google Earth
NAME_EXIT	Highway name of the road where the ramp exits to		Pathweb/Google Earth
LN_EXT	Number of lanes on the road where the ramp exits to		Pathweb/Google Earth
SHLDR_EXIT	Type of shoulder on the road the ramp exits to	Paved = 2 Unpaved = 1 None = 0	Pathweb/Google Earth
DH_EXIT	Is the road the ramp exits to a divided highway?	Yes = 1 No = 0	Pathweb/Google Earth
ACCEL_LN	Presence of an acceleration lane after the ramp exit	Yes = 1 No = 0	Pathweb/Google Earth
MED_EXIT	Presence of a median on the road exiting from the ramp	Raised grass = 3 Raised pavement = 2 Painted = 1 None = 0	Pathweb/Google Earth
SL_EXIT	Speed limit (mph) of the road exiting from the ramp		Pathweb/Google Earth
SL_SIGN_EXIT	Speed limit sign type	R2-1 = 1 W13-1P = 0	Pathweb/Google Earth
SL_LOC_EXIT	Speed limit sign location (coordinates) on the road exiting from the ramp		Pathweb/Google Earth
SURF_EXIT	Surface type of road after the ramp exit	Gravel = 2 Asphalt = 1 Concrete = 0	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (5 of 13)

Variable	Description	Coding (if applicable)	Source of Information
LENGTH	Length of FRT ramp (ft)		Google Earth
RADIUS	Radius of FRT ramp (ft)		Google Earth
ISLAND	Type of island present at the ramp	Grass island = 3 Raised pavement island = 2 Painted island = 1 None = 0	Pathweb/Google Earth
SHLDR_RAMP	Type of shoulder on the ramp	Paved = 2 Unpaved = 1 None = 0	Pathweb/Google Earth
SL_RAMP	Speed limit (mph) of the ramp, if applicable		Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (6 of 13)

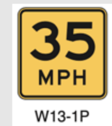
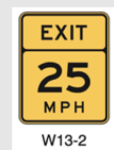
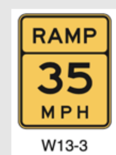
Variable	Description	Coding (if applicable)	Source of Information
SL_SIGN_RAMP	Speed limit sign on ramp	W13-1P w/ W1-6 = 4   R2-1 = 3  W13-2 = 2  W13-3 = 1  None = 0	Pathweb/Google Earth
DELIN	Presence of delineators on ramp roadway edge	Yes = 1 No = 0	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (7 of 13)

Variable	Description	Coding (if applicable)	Source of Information
HAW_SIGN_1	Number of W1-8 horizontal alignment warning signs present on the ramp		Pathweb/Google Earth
HAW_SIGN_2	Presence of W1-2 horizontal alignment warning sign on ramp	Yes = 1  No = 0	Pathweb/Google Earth
SURF_RAMP	Surface type of the ramp	Gravel = 2 Asphalt = 1 Concrete = 0	Pathweb/Google Earth
CNTRL_RAMP	Traffic control at the exit of the ramp	STOP sign = 2  YIELD sign = 1  None = 0	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (8 of 13)

Variable	Description	Coding (if applicable)	Source of Information
ADV_TC_1	Presence of W3-2 advanced traffic control signing	Yes = 1 No = 0 	Pathweb/Google Earth
ADV_TC_2	Presence of W3-2a advanced traffic control signing	Yes = 1 No = 0 	Pathweb/Google Earth
JCT_SIGN	Presence of an M2-2 combination junction sign	Yes = 1 No = 0 	Pathweb/Google Earth
US_SIGN	Quantity of M1-4 U.S. route signs	Two = 2 One = 1 None = 0 	Pathweb/Google Earth
STATE_SIGN	Quantity of M1-5 state route signs	Two = 2 One = 1 None = 0 	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (9 of 13)

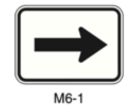
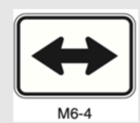
Variable	Description	Coding (if applicable)	Source of Information
DIR_SIGN_1	Quantity of M6-1 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0 	Pathweb/Google Earth
DIR_SIGN_2	Quantity of M6-2 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0 	Pathweb/Google Earth
DIR_SIGN_3	Quantity of M6-3 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0 	Pathweb/Google Earth
DIR_SIGN_4	Quantity of M6-4 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0 	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (10 of 13)

Variable	Description	Coding (if applicable)	Source of Information
DIR_SIGN_5	Quantity of M6-5 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0  M6-5	Pathweb/Google Earth
DIR_SIGN_6	Quantity of M6-6 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0  M6-6	Pathweb/Google Earth
DIR_SIGN_7	Quantity of M6-7 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0  M6-7	Pathweb/Google Earth
DIR_SIGN_8	Quantity of M5-1 advance turn and directional arrow auxiliary signs	Two = 2 One = 1 None = 0  M5-1	Pathweb/Google Earth
WARN_DA	Presence of a W12-1 double arrow sign	Yes = 1 No = 0  W12-1	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (11 of 13)

Variable	Description	Coding (if applicable)	Source of Information
OBJ_1	Presence of an OM1-3 object marker for obstruction sign	Yes = 1 No = 0 	Pathweb/Google Earth
OBJ_2	Presence of an OM1-2 object marker for obstruction sign	Yes = 1 No = 0 	Pathweb/Google Earth
MERGE_1	Presence of a W4-1 merge sign	Yes = 1 No = 0 	Pathweb/Google Earth
MERGE_2	Presence of a W4-5 merge sign	Yes = 1 No = 0 	Pathweb/Google Earth
EXCLSN_1	Presence of R5-1 selective exclusion signing at the exit of the ramp, from the opposing direction	Yes = 1 No = 0 	Pathweb/Google Earth

Table A.1 FRT Ramp Intersection Characteristics (12 of 13)

Variable	Description	Coding (if applicable)	Source of Information
EXCLSN_2	Presence of R5-1a selective exclusion signing at the exit of the ramp, from the opposing direction	Yes = 1 No = 0  R5-1a	Pathweb/Google Earth
LIGHT	Presence of light posts in the area	Yes = 1 No = 0	Pathweb/Google Earth
RAIL	Presence of a railroad crossing near the intersection	Yes = 1 No = 0	Pathweb/Google Earth
BLDG	Presence of residential or commercial buildings near the intersection	Yes = 1 No = 0	Pathweb/Google Earth
COORD_CNTR_ID	Unique ID given for Google Earth labeling purposes		Google Earth
COORD_CNTR	Coordinates of the center of the intersection		
COORD_N_ID	Unique ID given for Google Earth labeling purposes		
COORD_N	Coordinates of the leg north of the intersection, 1/4 quarter mile from center		
COORD_E_ID	Unique ID given for Google Earth labeling purposes		
COORD_E	Coordinates of the leg east of the intersection, 1/4 quarter mile from center		
COORD_S_ID	Unique ID given for Google Earth labeling purposes		
COORD_S	Coordinates of the leg south of the intersection, 1/4 quarter mile from center		
COORD_W_ID	Unique ID given for Google Earth labeling purposes		
COORD_W	Coordinates of the leg west of the intersection, 1/4 quarter mile from center		

Table A.1 FRT Ramp Intersection Characteristics (13 of 13)

Variable	Description	Coding (if applicable)	Source of Information
RAMP_BEG	Intersection leg where the ramp begins	North = 0 East = 1 South = 2 West = 3	Pathweb/Google Earth
RAMP_END	Intersection leg where the ramp ends	North = 0 East = 1 South = 2 West = 3	Pathweb/Google Earth

Table A.2 FRT Intersection Basic Characteristics (1 of 2)

Note 1: items shaded in gray indicate two ramps of the same intersection

Note 2: FRT ramp 'FRT11' was removed, so although the last ramp is 'FRT80' there are 79 total ramps

Note 3: if an FRT radius is indicated as 'N/A' the ramp is a straight segment

Note 4: FRT length and FRT radius are rounded to the nearest 50 ft

SITE_ID	FRT_ID	COUNTY	INTERSECTION	LEGS	SKEW	LIGHT	FRT LENGTH (ft)	FRT RADIUS (ft)
FRT1	FRT1	BOX BUTTE	N-2/L-7E	3	Yes	Yes	150	350
FRT2	FRT2	BOX BUTTE	N-2/US-385	3	No	Yes	450	350
FRT3	FRT3	CUSTER	N-2/N-92	4	Yes	Yes	200	350
FRT4_5	FRT4	HAMILTON	N-2/US-34	4	Yes	Yes	100	150
	FRT5	HAMILTON	N-2/US-34	4	Yes	Yes	550	350
FRT6	FRT6	WEBSTER	N-4/US-281	3	Yes	No	550	N/A
FRT7	FRT7	GAGE	N-4/N-103	3	Yes	Yes	350	450
FRT8	FRT8	PAWNEE	N-4/N-99	4	No	No	100	150
FRT9	FRT9	PAWNEE	N-4/N-50	3	No	No	2000	1550
FRT10	FRT10	RICHARDSON	N-4/N-105	3	No	Yes	200	200
FRT12_13	FRT12	KEARNEY	US-6/34/N-44	4	Yes	Yes	800	600
	FRT13	KEARNEY	US-6/34/N-44	4	Yes	Yes	400	300
FRT14	FRT14	SALINE	US-6/N-33	3	No	Yes	1300	N/A
FRT15	FRT15	JEFFERSON	N-8/N-15	3	Yes	No	500	400
FRT16	FRT16	PAWNEE	N-8/N-99	4	No	No	100	250
FRT17	FRT17	CUMING	N-9/US-275	3	No	Yes	600	N/A
FRT18	FRT18	THURSTON	N-9/N-16	3	Yes	Yes	350	450
FRT19	FRT19	LINE	N-9/N-35	4	No	Yes	300	300
FRT20	FRT20	DIXON	N-9/N-35	4	No	Yes	1200	650
FRT21	FRT21	SHERMAN	N-10/L-82A	4	No	Yes	300	150
FRT22	FRT22	CEDAR	N-12/N-57	4	No	No	2000	1150
FRT23	FRT23	BOONE	N-14/N-39	3	Yes	No	850	1250
FRT24	FRT24	SALINE	N-14/N-41	4	No	No	300	250
FRT25	FRT25	BUTLER	N-15/N-92	4	No	Yes	200	150
FRT26	FRT26	BUTLER	N-15/N-64	3	Yes	Yes	1500	1100
FRT27	FRT27	STANTON	N-15/US-275	3	No	Yes	200	250
FRT28	FRT28	CEDAR	N-15/US-20	3	Yes	Yes	1150	N/A
FRT29	FRT29	CEDAR	N-15/N-59	4	No	No	1400	1150
FRT30	FRT30	DAWES	US-20/N-71	3	No	Yes	500	350
FRT31	FRT31	HOLT	US-20/US-281	4	No	Yes	150	200
FRT32	FRT32	HOLT	US-20/US-275	4	Yes	Yes	950	1700
FRT33_34	FRT33	PIERCE	US-20/US-81	4	No	Yes	750	600
	FRT34	PIERCE	US-20/US-81	4	No	Yes	200	200
FRT35	FRT35	NANCE	N-22/N-39	4	No	Yes	600	500
FRT36	FRT36	PERKINS	N-23/N-61	4	No	Yes	950	550
FRT37	FRT37	FRONTIER	N-23/US-83	4	Yes	Yes	150	100
FRT38_39	FRT38	HITCHCOCK	N-25/US-34	4	Yes	Yes	250	150
	FRT39	HITCHCOCK	N-25/US-34	4	Yes	Yes	250	250
FRT40	FRT40	MORRILL	US-26/L-62A	3	Yes	Yes	500	900

Table A.2 FRT Intersection Basic Characteristics (2 of 2)

Note 1: items shaded in gray indicate two ramps of the same intersection

Note 2: FRT ramp 'FRT11' was removed, so although the last ramp is 'FRT80' there are 79 total ramps

Note 3: if an FRT radius is indicated as 'N/A' the ramp is a straight segment

Note 4: FRT length and FRT radius are rounded to the nearest 50 ft

SITE_ID	FRT_ID	COUNTY	INTERSECTION	LEGS	SKEW	LIGHT	FRT LENGTH (ft)	FRT RADIUS (ft)
FRT41	FRT41	MORRILL	US-26/N-92	3	No	Yes	200	200
FRT42	FRT42	CUMING	N-32/US-275	3	No	Yes	200	150
FRT43	FRT43	DUNDY	US-34/N-61	3	No	Yes	700	450
FRT44	FRT44	LANCASTER	US-34/S-55M	3	Yes	No	350	950
FRT45_46	FRT45	CASS	US-34/US-75	4	No	Yes	600	550
	FRT46	CASS	US-34/US-75	4	No	Yes	400	350
FRT47	FRT47	WAYNE	N-16/N-35	4	No	Yes	500	400
FRT48	FRT48	DOUGLAS	RD	3	No	Yes	250	200
FRT49	FRT49	BOONE	N-39/N-56	3	Yes	Yes	700	1000
FRT50	FRT50	FILLMORE	N-41/S-30H	4	No	Yes	200	200
FRT51	FRT51	FURNAS	N-46/N-89	3	No	Yes	600	950
FRT52	FRT52	CEDAR	N-57/N-59	4	No	No	1400	1200
FRT53_54	FRT53	KEITH	N-61/N SPRUCE ST	4	No	Yes	1350	1100
	FRT54	KEITH	N-61/N SPRUCE ST	4	No	Yes	1350	1200
FRT55	FRT55	SAUNDERS	N-64/S-78J	3	No	No	650	450
FRT56	FRT56	PAWNEE	N-65/S-67C	4	No	No	300	250
FRT57	FRT57	KIMBALL	N-71/OLD N-71	3	No	Yes	1450	1150
FRT58_59	FRT58	RICHARDSON	US-73/US-75	4	Yes	Yes	1400	1900
	FRT59	RICHARDSON	US-73/US-75	4	Yes	Yes	500	350
FRT60	FRT60	ADAMS	N-74/US-281	3	Yes	Yes	550	N/A
FRT61	FRT61	ADAMS	N-74/US-281	4	No	No	550	500
FRT62	FRT62	GAGE	US-77/W LOCUST RD	4	No	No	400	300
FRT63_64	FRT63	SAUNDERS	US-77/N-92	4	No	Yes	950	800
	FRT64	SAUNDERS	US-77/N-92	4	No	Yes	900	650
FRT65	FRT65	SAUNDERS	US-77N-109	3	Yes	Yes	400	300
FRT66	FRT66	SAUNDERS	AVE	3	No	Yes	400	400
FRT67_68	FRT67	POLK	US-81/N-92	4	No	Yes	850	700
	FRT68	POLK	US-81/N-92	4	No	Yes	850	700
FRT69_70	FRT69	POLK	US-81/N-92	4	No	Yes	1100	700
	FRT70	POLK	US-81/N-92	4	No	Yes	950	700
FRT71_72	FRT71	DODGE	N-91/US-275	3	Yes	Yes	350	250
	FRT72	DODGE	N-91/US-275	3	Yes	Yes	250	250
FRT73	FRT73	MADISON	N-121/US-275	4	No	Yes	350	50
FRT74	FRT74	HARLAN	N-89/US-136	4	Yes	Yes	250	500
FRT75	FRT75	GAGE	ROAD	3	Yes	Yes	750	1800
FRT76	FRT76	DOUGLAS	N-92/US-275	4	Yes	Yes	1100	550
FRT77	FRT77	MORRILL	N-92/US-385	3	Yes	Yes	850	750
FRT78	FRT78	MORRILL	US-385/L-62A	3	No	Yes	450	300
FRT79	FRT79	BUFFALO	L-10D/9TH ST	4	No	No	1000	800
FRT80	FRT80	CLAY	S-18A	4	No	No	550	450

Table A.3 FRT Intersections and Ramps by County (1 of 2)

County	No. of FRT Ramp Intersections	No. of FRT Ramps
Adams	2	2
Boone	2	2
Box Butte	2	2
Buffalo	1	1
Butler	2	2
Cass	1	2
Cedar	4	4
Clay	1	1
Cuming	2	2
Custer	1	1
Dawes	1	1
Line	1	1
Dixon	1	1
Dodge	1	2
Douglas	2	2
Dundy	1	1
Fillmore	1	1
Frontier	1	1
Furnas	1	1
Gage	3	3
Hamilton	1	2
Harlan	1	1

Table A.3 FRT Intersections and Ramps by County (2 of 2)

County	No. of FRT Ramp Intersections	No. of FRT Ramps
Hitchcock	1	2
Holt	2	2
Jefferson	1	1
Kearney	1	2
Keith	1	2
Kimball	1	1
Lancaster	1	1
Madison	1	1
Morrill	4	4
Nance	1	1
Pawnee	4	4
Perkins	1	1
Pierce	1	2
Polk	2	4
Richardson	2	3
Saline	2	2
Saunders	4	5
Sherman	1	1
Stanton	1	1
Thurston	1	1
Wayne	1	1
Webster	1	1
Total	**68**	**79**

Table A.4 FRT Intersection AADT from 2010-2019 (1 of 2)

Site	2010 AADT	2011 AADT	2012 AADT	2013 AADT	2014 AADT	2015 AADT	2016 AADT	2017 AADT	2018 AADT	2019 AADT	AVERAGE 10 YR AADT
FRT1	3370	3348	3325	3510	3695	3745	3795	3755	3715	3945	3620
FRT2	6665	6628	6590	6925	7260	7213	7165	6858	6550	6523	6838
FRT3	5717	5736	5755	6072	6389	6955	7520	7107	6693	6334	6428
FRT4_5	12480	13100	13720	13500	13280	13425	13570	15373	17175	15960	14158
FRT6	3860	4103	4345	4278	4210	4158	4105	4280	4455	4680	4247
FRT7	5125	5075	5025	5260	5495	5498	5500	5480	5460	5555	5347
FRT8	2080	2075	2070	2003	1935	2020	2105	2163	2220	2390	2106
FRT9	3830	3828	3825	3763	3700	3945	4190	4059	3927	4002	3907
FRT10	4790	4698	4605	4800	4995	4863	4730	4645	4560	4725	4741
FRT12_13	12189	12327	12465	12331	12196	12241	12285	13087	13888	14612	12762
FRT14	8255	8805	9355	8953	8550	8863	9175	7968	6760	6860	8354
FRT15	4151	4088	4025	4325	4624	4547	4470	4580	4689	4441	4394
FRT16	1150	1060	970	1025	1080	1195	1310	1308	1305	1580	1198
FRT17	16625	16263	15900	16238	16575	17268	17960	18260	18560	16910	17056
FRT18	5110	5498	5885	6008	6130	6305	6480	6580	6680	6550	6123
FRT19	8255	8585	8915	9088	9260	9788	10315	10838	11360	9328	9573
FRT20	8090	8058	8025	8850	9675	9593	9510	10058	10605	9595	9206
FRT21	2295	2318	2340	2268	2195	2293	2390	2408	2425	2370	2330
FRT22	5481	5663	5845	5737	5628	5694	5760	5372	4984	4975	5514
FRT23	8115	8235	8355	7745	7135	7505	7875	8050	8225	7923	7916
FRT24	3457	3476	3495	3499	3503	3679	3855	3674	3493	3886	3602
FRT25	10827	10866	10905	10898	10890	11090	11290	11828	12366	12267	11323
FRT26	9420	9110	8800	8848	8895	9356	9818	9896	9975	9229	9335
FRT27	16085	15815	15545	15768	15990	16633	17275	17268	17260	16450	16409
FRT28	6780	6955	7130	6953	6775	7238	7700	8647	9593	9582	7735
FRT29	6040	6648	7255	7013	6770	7085	7400	7543	7685	6645	7008
FRT30	3020	3010	3000	3023	3045	3565	4085	4420	4755	4755	3668
FRT31	12355	11295	10235	10650	11065	12625	14185	15470	16755	15869	13050
FRT32	5298	5349	5400	5441	5482	5271	5060	5694	6328	5976	5530
FRT33_34	13390	13780	14170	14705	15240	14968	14695	14795	14895	13634	14427
FRT35	4350	4983	5615	5603	5590	5593	5595	5780	5965	5661	5473
FRT36	4983	5299	5615	5505	5394	5440	5485	5596	5706	5323	5434
FRT37	6175	6060	5945	6288	6630	6505	6380	6393	6405	6195	6298

Table A.4 FRT Intersection AADT from 2010-2019 (2 of 2)

Site	2010 AADT	2011 AADT	2012 AADT	2013 AADT	2014 AADT	2015 AADT	2016 AADT	2017 AADT	2018 AADT	2019 AADT	AVERAGE 10 YR AADT
FRT38_39	5830	5848	5865	6305	6745	6085	5425	6433	7440	7090	6307
FRT40	8475	8708	8940	8888	8835	9915	10995	10510	10025	9405	9470
FRT41	8035	7823	7610	7680	7750	8370	8990	8435	7880	7275	7985
FRT42	18430	18310	18190	18470	18750	21425	24100	25575	27050	25195	21550
FRT43	3175	3393	3610	3578	3545	3558	3570	3473	3375	3718	3499
FRT44	12545	13123	13700	13285	12870	12095	11320	12603	13885	13275	12870
FRT45_46	17465	16420	15375	16278	17180	14583	11985	11166	10347	10830	14163
FRT47	9580	9493	9405	9990	10575	10660	10745	11578	12411	11416	10585
FRT48	565	565	565	565	565	565	565	565	565	565	565
FRT49	4780	4760	4740	4643	4545	4790	5035	5129	5223	4902	4855
FRT50	2605	2438	2270	2180	2090	2235	2380	2525	2670	2885	2428
FRT51	2175	2073	1970	1973	1975	2175	2375	1923	1470	1520	1963
FRT52	2645	2735	2825	2985	3145	3390	3635	3565	3495	3450	3187
FRT53_54	7945	7918	7890	7615	7340	6443	5545	5130	4714	4815	6535
FRT55	2725	2663	2600	2810	3020	3380	3740	4143	4545	4503	3413
FRT56	585	573	560	623	685	738	790	588	385	365	589
FRT57	5480	5913	6345	6260	6175	6208	6240	6615	6989	7052	6328
FRT58_59	7663	7732	7800	7855	7909	8287	8665	8867	9068	8615	8246
FRT60	5770	6015	6260	6253	6245	6135	6025	6180	6335	6550	6177
FRT61	6525	6718	6910	6748	6585	6918	7250	7033	6815	6863	6836
FRT62	9780	9303	8825	9110	9395	9625	9855	10106	10357	9816	9617
FRT63_64	12322	12396	12470	12802	13133	15919	18705	20160	21614	21458	16098
FRT65	17060	17388	17715	17423	17130	17263	17395	18893	20390	18183	17884
FRT66	2845	2908	2970	3078	3185	3188	3190	3230	3270	3133	3100
FRT67_68	8865	9565	10265	10430	10595	11065	11535	11438	11340	11275	10637
FRT69_70	12530	12650	12770	13175	13580	14150	14720	15233	15745	15330	13988
FRT71_72	14730	15553	16375	16258	16140	16428	16715	17673	18630	17170	16567
FRT73	12866	13548	14230	14186	14142	14956	15770	15565	15360	14982	14560
FRT74	2660	2703	2745	2711	2676	2516	2355	2449	2543	2664	2602
FRT75	6635	6475	6315	6549	6782	6404	6025	6410	6794	6570	6496
FRT76	21385	22110	22835	21333	19830	20445	21060	22199	23338	22924	21746
FRT77	6405	6225	6045	6325	6605	6245	5885	5975	6065	5685	6146
FRT78	9020	9383	9745	9350	8954	9182	9410	9864	10317	9987	9521
FRT79	900	973	1045	958	870	870	870	913	955	965	932
FRT80	1045	1025	1005	950	895	950	1005	970	935	1003	978

Appendix B

Table B.1 Non-FRT Comparison Intersection Basic Characteristics

SITE_ID	COUNTY	INTERSECTION	LEGS	SKEW	LIGHT
COMP1	BOX BUTTE	US-385/L-7E	4	No	Yes
COMP2	WEBSTER	N-4/US-281	3	No	Yes
COMP3	HOWARD	N-11/N-92	4	No	Yes
COMP4	HARLAN	N-4/US-183	4	No	Yes
COMP5	CLAY	US-6/N-14	4	No	Yes
COMP6	BUTLER	N-15/N-92	3	No	Yes
COMP7	NANCE	N-22/L-63A	3	No	Yes
COMP8	THURSTON	N-9/N-16	4	No	Yes
COMP9	NEMAHA	N-105/US-136	3	No	Yes
COMP10	CUSTER	N-2/US-183	3	Yes	Yes
COMP11	CUMING	N-51/US-275	3	No	Yes
COMP12	CEDAR	N-15/N-116	3	No	No
COMP13	CEDAR	N-12/US-81	4	No	Yes
COMP14	SAUNDERS	N-109/S-78H	3	No	Yes
COMP15	GAGE	N-41/N-43	3	No	Yes
COMP16	WASHINGTON	US-30/N-31	3	No	Yes
COMP17	SARPY	N-31/N-50	3	No	Yes
COMP18	JOHNSON	N-50/US-136	4	No	Yes
COMP19	CASS	N-1/US-34	4	No	Yes
COMP20	GAGE	N-4/N-136	3	No	Yes
COMP21	SAUNDERS	N-79/N-92	4	No	Yes
COMP22	NEMAHA	N-67/US-75	4	No	Yes
COMP23	CASS	US-34/N-50	4	No	Yes
COMP24	CASS	N-1/N-50	4	No	Yes

Table B.2 Non-FRT Comparison Intersections by County

County	No. of Non-FRT Ramp Intersections
Box Butte	1
Butler	1
Cass	3
Cedar	2
Clay	1
Cuming	1
Custer	1
Gage	2
Harlan	1
Howard	1
Johnson	1
Nance	1
Nemaha	2
Sarpy	1
Saunders	2
Thurston	1
Washington	1
Webster	1
Total	**24**

Table B.3 Non-FRT Intersection AADT from 2010-2019

Site	2010 AADT	2011 AADT	2012 AADT	2013 AADT	2014 AADT	2015 AADT	2016 AADT	2017 AADT	2018 AADT	2019 AADT	AVERAGE 10 YR AADT
COMP1	5360	5158	4955	5078	5200	4715	4230	4595	4960	4834	4908
COMP2	4316	4456	4595	4318	4040	4093	4145	4566	4986	5016	4453
COMP3	6610	6633	6655	6850	7045	7070	7095	7346	7596	7351	7025
COMP4	7180	7350	7520	7893	8265	8393	8520	8725	8930	8948	8172
COMP5	8255	8288	8320	7322	6324	7310	8295	8793	9290	9210	8141
COMP6	12705	12625	12545	12703	12860	13458	14055	13973	13891	13716	13253
COMP7	7385	7808	8230	8193	8155	7773	7390	7950	8510	8068	7946
COMP8	4905	5060	5215	5315	5415	6148	6880	6937	6994	6507	5938
COMP9	4765	4780	4795	4833	4870	5728	6585	5870	5155	5180	5256
COMP10	6730	6660	6590	6963	7335	6908	6480	6910	7340	7200	6912
COMP11	14640	14058	13475	13710	13945	13613	13280	13613	13945	13450	13773
COMP12	5090	5125	5160	5108	5055	5230	5405	5363	5320	5175	5203
COMP13	12580	13008	13435	13713	13990	13630	13270	12963	12655	13195	13244
COMP14	7455	7650	7845	7868	7890	7858	7825	7793	7760	7195	7714
COMP15	6385	6323	6260	6010	5760	6810	7860	7740	7620	7295	6806
COMP16	11640	12120	12600	12850	13100	13855	14610	13941	13272	12683	13067
COMP17	18425	18908	19390	19665	19940	20001	20063	20124	20185	20163	19686
COMP18	9252	9576	9900	10389	10878	12104	13329	14555	15780	15378	12114
COMP19	17465	16420	15375	16278	17180	17385	17590	18608	19625	18005	17393
COMP20	4739	4382	4025	3984	3943	4509	5075	5212	5349	5078	4630
COMP21	7370	7660	7950	8095	8240	8520	8800	9328	9855	9283	8510
COMP22	12675	12395	12115	12635	13155	13355	13555	13755	13955	13938	13153
COMP23	11795	11458	11120	11123	11125	11986	12848	13709	14570	13920	12365
COMP24	11520	10928	10335	11253	12170	13140	14110	13853	13595	13303	12421

Appendix C

Table C.1 FRT Intersection Crashes by Year from 2010-2019

CRASH BY YEAR	
Year	No. of Crashes
2010	96
2011	92
2012	77
2013	83
2014	87
2015	82
2016	77
2017	67
2018	90
2019	91
Total	**842**

Table C.2 Non-FRT Intersection Crashes by Year from 2010-2019

CRASH BY YEAR	
Year	No. of Crashes
2010	28
2011	24
2012	26
2013	21
2014	24
2015	37
2016	23
2017	33
2018	41
2019	40
Total	**297**

Table C.3 FRT Intersection Crashes by Site (1 of 2)

CRASH BY SITE	
Site	No. of Crashes
FRT1	25
FRT2	7
FRT3	11
FRT4_5	34
FRT6	8
FRT7	10
FRT8	7
FRT9	18
FRT10	5
FRT11	0
FRT12_13	16
FRT14	7
FRT15	11
FRT16	1
FRT17	34
FRT18	5
FRT19	12
FRT20	14
FRT21	1
FRT22	7
FRT23	10
FRT24	18
FRT25	12
FRT26	7
FRT27	21
FRT28	7
FRT29	6
FRT30	7
FRT31	34
FRT32	11
FRT33_34	15
FRT35	5
FRT36	3
FRT37	11

Table C.3 FRT Intersection Crashes by Site (2 of 2)

CRASH BY SITE	
Site	No. of Crashes
FRT38_39	14
FRT40	7
FRT41	13
FRT42	63
FRT43	3
FRT44	6
FRT45_46	15
FRT47	17
FRT48	18
FRT49	7
FRT50	4
FRT51	3
FRT52	1
FRT53_54	6
FRT55	3
FRT56	0
FRT57	7
FRT58_59	8
FRT60	7
FRT61	2
FRT62	18
FRT63_64	21
FRT65	42
FRT66	10
FRT67_68	9
FRT69_70	28
FRT71_72	27
FRT73	15
FRT74	7
FRT75	3
FRT76	27
FRT77	8
FRT78	18
FRT79	2
FRT80	3
Total	**842**

Table C.4 Non-FRT Intersection Crashes by Site

CRASH BY SITE	
Site	No. of Crashes
COMP1	6
COMP2	6
COMP3	9
COMP4	15
COMP5	13
COMP6	20
COMP7	8
COMP8	7
COMP9	5
COMP10	5
COMP11	6
COMP12	2
COMP13	13
COMP14	19
COMP15	9
COMP16	25
COMP17	26
COMP18	17
COMP19	28
COMP20	8
COMP21	3
COMP22	6
COMP23	31
COMP24	10
Total	**297**

Table C.5 FRT Intersection Crash Rates by Year (2010)

Site	2010 Crash	2010 AADT	2010 Crash Rate
FRT1	6	3370	4.878
FRT2	2	6665	0.822
FRT3	0	5717	0.000
FRT4_5	5	12480	1.098
FRT6	2	3860	1.420
FRT7	0	5125	0.000
FRT8	1	2080	1.317
FRT9	2	3830	1.431
FRT10	1	4790	0.572
FRT12_13	2	12189	0.450
FRT14	2	8255	0.664
FRT15	0	4151	0.000
FRT16	0	1150	0.000
FRT17	3	16625	0.494
FRT18	0	5110	0.000
FRT19	3	8255	0.996
FRT20	1	8090	0.339
FRT21	0	2295	0.000
FRT22	0	5481	0.000
FRT23	1	8115	0.338
FRT24	3	3457	2.378
FRT25	3	10827	0.759
FRT26	1	9420	0.291
FRT27	3	16085	0.511
FRT28	0	6780	0.000
FRT29	2	6040	0.907
FRT30	0	3020	0.000
FRT31	4	12355	0.887
FRT32	1	5298	0.517
FRT33_34	1	13390	0.205
FRT35	0	4350	0.000
FRT36	1	4983	0.550
FRT37	0	6175	0.000
FRT38_39	0	5830	0.000
FRT40	0	8475	0.000
FRT41	1	8035	0.341
FRT42	6	18430	0.892
FRT43	1	3175	0.863
FRT44	1	12545	0.218
FRT45_46	5	17465	0.784
FRT47	1	9580	0.286
FRT48	0	565	0.000
FRT49	1	4780	0.573
FRT50	0	2605	0.000
FRT51	0	2175	0.000
FRT52	0	2645	0.000
FRT53_54	1	7945	0.345
FRT55	1	2725	1.005
FRT56	0	585	0.000
FRT57	0	5480	0.000
FRT58_59	1	7663	0.358
FRT60	1	5770	0.475
FRT61	0	6525	0.000
FRT62	3	9780	0.840
FRT63_64	1	12322	0.222
FRT65	4	17060	0.642
FRT66	1	2845	0.963
FRT67_68	1	8865	0.309
FRT69_70	5	12530	1.093
FRT71_72	2	14730	0.372
FRT73	3	12866	0.639
FRT74	1	2660	1.030
FRT75	0	6635	0.000
FRT76	3	21385	0.384
FRT77	0	6405	0.000
FRT78	2	9020	0.607
FRT79	0	900	0.000
FRT80	0	1045	0.000
Total	96	501859	0.524

Table C.6 FRT Intersection Crash Rates by Year (2011)

Site	2011 Crash	2011 AADT	2011 Crash Rate
FRT1	2	3348	1.637
FRT2	0	6628	0.000
FRT3	2	5736	0.955
FRT4_5	7	13100	1.464
FRT6	0	4103	0.000
FRT7	1	5075	0.540
FRT8	1	2075	1.320
FRT9	1	3828	0.716
FRT10	0	4698	0.000
FRT12_13	6	12327	1.334
FRT14	0	8805	0.000
FRT15	2	4088	1.340
FRT16	1	1060	2.585
FRT17	5	16263	0.842
FRT18	0	5498	0.000
FRT19	2	8585	0.638
FRT20	1	8058	0.340
FRT21	0	2318	0.000
FRT22	0	5663	0.000
FRT23	2	8235	0.665
FRT24	0	3476	0.000
FRT25	0	10866	0.000
FRT26	0	9110	0.000
FRT27	2	15815	0.346
FRT28	0	6955	0.000
FRT29	1	6648	0.412
FRT30	0	3010	0.000
FRT31	3	11295	0.728
FRT32	0	5349	0.000
FRT33_34	3	13780	0.596
FRT35	1	4983	0.550
FRT36	0	5299	0.000
FRT37	1	6060	0.452
FRT38_39	2	5848	0.937
FRT40	0	8708	0.000
FRT41	2	7823	0.700
FRT42	8	18310	1.197
FRT43	0	3393	0.000
FRT44	0	13123	0.000
FRT45_46	2	16420	0.334
FRT47	0	9493	0.000
FRT48	5	565	24.245
FRT49	1	4760	0.576
FRT50	0	2438	0.000
FRT51	0	2073	0.000
FRT52	0	2735	0.000
FRT53_54	0	7918	0.000
FRT55	0	2663	0.000
FRT56	0	573	0.000
FRT57	0	5913	0.000
FRT58_59	1	7732	0.354
FRT60	1	6015	0.455
FRT61	0	6718	0.000
FRT62	0	9303	0.000
FRT63_64	6	12396	1.326
FRT65	6	17388	0.945
FRT66	0	2908	0.000
FRT67_68	2	9565	0.573
FRT69_70	3	12650	0.650
FRT71_72	3	15553	0.528
FRT73	1	13548	0.202
FRT74	1	2703	1.014
FRT75	0	6475	0.000
FRT76	2	22110	0.248
FRT77	0	6225	0.000
FRT78	1	9383	0.292
FRT79	1	973	2.817
FRT80	0	1025	0.000
Total	92	507547	0.497

Table C.7 FRT Intersection Crash Rates by Year (2012)

Site	2012 Crash	2012 AADT	2012 Crash Rate
FRT1	3	3325	2.472
FRT2	0	6590	0.000
FRT3	0	5755	0.000
FRT4_5	1	13720	0.200
FRT6	1	4345	0.631
FRT7	0	5025	0.000
FRT8	0	2070	0.000
FRT9	6	3825	4.298
FRT10	0	4605	0.000
FRT12_13	2	12465	0.440
FRT14	0	9355	0.000
FRT15	1	4025	0.681
FRT16	0	970	0.000
FRT17	3	15900	0.517
FRT18	0	5885	0.000
FRT19	1	8915	0.307
FRT20	1	8025	0.341
FRT21	1	2340	1.171
FRT22	0	5845	0.000
FRT23	1	8355	0.328
FRT24	3	3495	2.352
FRT25	1	10905	0.251
FRT26	0	8800	0.000
FRT27	1	15545	0.176
FRT28	0	7130	0.000
FRT29	0	7255	0.000
FRT30	0	3000	0.000
FRT31	5	10235	1.338
FRT32	2	5400	1.015
FRT33_34	0	14170	0.000
FRT35	1	5615	0.488
FRT36	1	5615	0.488
FRT37	2	5945	0.922
FRT38_39	3	5865	1.401
FRT40	0	8940	0.000
FRT41	1	7610	0.360
FRT42	3	18190	0.452
FRT43	0	3610	0.000
FRT44	1	13700	0.200
FRT45_46	2	15375	0.356
FRT47	3	9405	0.874
FRT48	3	565	14.547
FRT49	0	4740	0.000
FRT50	0	2270	0.000
FRT51	0	1970	0.000
FRT52	0	2825	0.000
FRT53_54	2	7890	0.694
FRT55	0	2600	0.000
FRT56	0	560	0.000
FRT57	2	6345	0.864
FRT58_59	1	7800	0.351
FRT60	0	6260	0.000
FRT61	0	6910	0.000
FRT62	3	8825	0.931
FRT63_64	1	12470	0.220
FRT65	3	17715	0.464
FRT66	0	2970	0.000
FRT67_68	2	10265	0.534
FRT69_70	1	12770	0.215
FRT71_72	4	16375	0.669
FRT73	0	14230	0.000
FRT74	1	2745	0.998
FRT75	0	6315	0.000
FRT76	0	22835	0.000
FRT77	2	6045	0.906
FRT78	2	9745	0.562
FRT79	0	1045	0.000
FRT80	0	1005	0.000
Total	77	513235	0.411

Table C.8 FRT Intersection Crash Rates by Year (2013)

Site	2013 Crash	2013 AADT	2013 Crash Rate
FRT1	0	3510	0.000
FRT2	0	6925	0.000
FRT3	1	6072	0.451
FRT4_5	6	13500	1.218
FRT6	1	4278	0.640
FRT7	2	5260	1.042
FRT8	0	2003	0.000
FRT9	1	3763	0.728
FRT10	0	4800	0.000
FRT12_13	0	12331	0.000
FRT14	0	8953	0.000
FRT15	1	4325	0.634
FRT16	0	1025	0.000
FRT17	2	16238	0.337
FRT18	0	6008	0.000
FRT19	0	9088	0.000
FRT20	2	8850	0.619
FRT21	0	2268	0.000
FRT22	1	5737	0.478
FRT23	1	7745	0.354
FRT24	1	3499	0.783
FRT25	0	10898	0.000
FRT26	0	8848	0.000
FRT27	3	15768	0.521
FRT28	0	6953	0.000
FRT29	0	7013	0.000
FRT30	1	3023	0.906
FRT31	4	10650	1.029
FRT32	1	5441	0.504
FRT33_34	1	14705	0.186
FRT35	0	5603	0.000
FRT36	0	5505	0.000
FRT37	1	6288	0.436
FRT38_39	2	6305	0.869
FRT40	0	8888	0.000
FRT41	2	7680	0.713
FRT42	10	18470	1.483
FRT43	0	3578	0.000
FRT44	1	13285	0.206
FRT45_46	1	16278	0.168
FRT47	1	9990	0.274
FRT48	3	565	14.547
FRT49	0	4643	0.000
FRT50	0	2180	0.000
FRT51	1	1973	1.389
FRT52	1	2985	0.918
FRT53_54	0	7615	0.000
FRT55	0	2810	0.000
FRT56	0	623	0.000
FRT57	1	6260	0.438
FRT58_59	1	7855	0.349
FRT60	0	6253	0.000
FRT61	0	6748	0.000
FRT62	1	9110	0.301
FRT63_64	4	12802	0.856
FRT65	3	17423	0.472
FRT66	2	3078	1.780
FRT67_68	0	10430	0.000
FRT69_70	2	13175	0.416
FRT71_72	6	16258	1.011
FRT73	2	14186	0.386
FRT74	0	2711	0.000
FRT75	1	6549	0.418
FRT76	4	21333	0.514
FRT77	0	6325	0.000
FRT78	2	9350	0.586
FRT79	0	958	0.000
FRT80	2	950	5.768
Total	83	516476	0.440

Table C.9 FRT Intersection Crash Rates by Year (2014)

Site	2014 Crash	2014 AADT	2014 Crash Rate
FRT1	4	3695	2.966
FRT2	2	7260	0.755
FRT3	2	6389	0.858
FRT4_5	2	13280	0.413
FRT6	0	4210	0.000
FRT7	0	5495	0.000
FRT8	0	1935	0.000
FRT9	3	3700	2.221
FRT10	1	4995	0.548
FRT12_13	0	12196	0.000
FRT14	2	8550	0.641
FRT15	2	4624	1.185
FRT16	0	1080	0.000
FRT17	2	16575	0.331
FRT18	1	6130	0.447
FRT19	1	9260	0.296
FRT20	2	9675	0.566
FRT21	0	2195	0.000
FRT22	0	5628	0.000
FRT23	0	7135	0.000
FRT24	3	3503	2.346
FRT25	3	10890	0.755
FRT26	1	8895	0.308
FRT27	2	15990	0.343
FRT28	3	6775	1.213
FRT29	1	6770	0.405
FRT30	2	3045	1.799
FRT31	3	11065	0.743
FRT32	1	5482	0.500
FRT33_34	3	15240	0.539
FRT35	1	5590	0.490
FRT36	0	5394	0.000
FRT37	3	6630	1.240
FRT38_39	0	6745	0.000
FRT40	1	8835	0.310
FRT41	1	7750	0.354
FRT42	3	18750	0.438
FRT43	0	3545	0.000
FRT44	0	12870	0.000
FRT45_46	1	17180	0.159
FRT47	1	10575	0.259
FRT48	0	565	0.000
FRT49	1	4545	0.603
FRT50	0	2090	0.000
FRT51	0	1975	0.000
FRT52	0	3145	0.000
FRT53_54	1	7340	0.373
FRT55	0	3020	0.000
FRT56	0	685	0.000
FRT57	2	6175	0.887
FRT58_59	0	7909	0.000
FRT60	1	6245	0.439
FRT61	0	6585	0.000
FRT62	1	9395	0.292
FRT63_64	1	13133	0.209
FRT65	4	17130	0.640
FRT66	2	3185	1.720
FRT67_68	0	10595	0.000
FRT69_70	3	13580	0.605
FRT71_72	1	16140	0.170
FRT73	2	14142	0.387
FRT74	0	2676	0.000
FRT75	0	6782	0.000
FRT76	8	19830	1.105
FRT77	0	6605	0.000
FRT78	3	8954	0.918
FRT79	0	870	0.000
FRT80	0	895	0.000
Total	87	519717	0.459

Table C.10 FRT Intersection Crash Rates by Year (2015)

Site	2015 Crash	2015 AADT	2015 Crash Rate
FRT1	0	3745	0.000
FRT2	0	7213	0.000
FRT3	3	6955	1.182
FRT4_5	4	13425	0.816
FRT6	0	4158	0.000
FRT7	4	5498	1.993
FRT8	1	2020	1.356
FRT9	1	3945	0.694
FRT10	1	4863	0.563
FRT12_13	2	12241	0.448
FRT14	0	8863	0.000
FRT15	1	4547	0.603
FRT16	0	1195	0.000
FRT17	0	17268	0.000
FRT18	1	6305	0.435
FRT19	2	9788	0.560
FRT20	0	9593	0.000
FRT21	0	2293	0.000
FRT22	0	5694	0.000
FRT23	0	7505	0.000
FRT24	3	3679	2.234
FRT25	1	11090	0.247
FRT26	1	9356	0.293
FRT27	4	16633	0.659
FRT28	0	7238	0.000
FRT29	0	7085	0.000
FRT30	2	3565	1.537
FRT31	6	12625	1.302
FRT32	1	5271	0.520
FRT33_34	2	14968	0.366
FRT35	0	5593	0.000
FRT36	0	5440	0.000
FRT37	2	6505	0.842
FRT38_39	0	6085	0.000
FRT40	1	9915	0.276
FRT41	1	8370	0.327
FRT42	6	21425	0.767
FRT43	0	3558	0.000
FRT44	1	12095	0.227
FRT45_46	0	14583	0.000
FRT47	0	10660	0.000
FRT48	1	565	4.849
FRT49	1	4790	0.572
FRT50	1	2235	1.226
FRT51	0	2175	0.000
FRT52	0	3390	0.000
FRT53_54	0	6443	0.000
FRT55	0	3380	0.000
FRT56	0	738	0.000
FRT57	0	6208	0.000
FRT58_59	0	8287	0.000
FRT60	0	6135	0.000
FRT61	1	6918	0.396
FRT62	2	9625	0.569
FRT63_64	2	15919	0.344
FRT65	3	17263	0.476
FRT66	1	3188	0.860
FRT67_68	3	11065	0.743
FRT69_70	5	14150	0.968
FRT71_72	3	16428	0.500
FRT73	1	14956	0.183
FRT74	0	2516	0.000
FRT75	1	6404	0.428
FRT76	1	20445	0.134
FRT77	2	6245	0.877
FRT78	2	9182	0.597
FRT79	0	870	0.000
FRT80	1	950	2.884
Total	82	533310	0.421

Table C.11 FRT Intersection Crash Rates by Year (2016)

Site	2016 Crash	2016 AADT	2016 Crash Rate
FRT1	2	3795	1.444
FRT2	2	7165	0.765
FRT3	1	7520	0.364
FRT4_5	3	13570	0.606
FRT6	0	4105	0.000
FRT7	0	5500	0.000
FRT8	0	2105	0.000
FRT9	1	4190	0.654
FRT10	1	4730	0.579
FRT12_13	1	12285	0.223
FRT14	0	9175	0.000
FRT15	3	4470	1.839
FRT16	0	1310	0.000
FRT17	8	17960	1.220
FRT18	0	6480	0.000
FRT19	0	10315	0.000
FRT20	2	9510	0.576
FRT21	0	2390	0.000
FRT22	1	5760	0.476
FRT23	2	7875	0.696
FRT24	1	3855	0.711
FRT25	0	11290	0.000
FRT26	0	9817.5	0.000
FRT27	3	17275	0.476
FRT28	0	7700	0.000
FRT29	0	7400	0.000
FRT30	0	4085	0.000
FRT31	3	14185	0.579
FRT32	0	5060	0.000
FRT33_34	0	14695	0.000
FRT35	1	5595	0.490
FRT36	0	5485	0.000
FRT37	1	6380	0.429
FRT38_39	0	5425	0.000
FRT40	1	10995	0.249
FRT41	2	8990	0.610
FRT42	9	24100	1.023
FRT43	2	3570	1.535
FRT44	0	11320	0.000
FRT45_46	0	11985	0.000
FRT47	1	10745	0.255
FRT48	1	565	4.849
FRT49	1	5035	0.544
FRT50	1	2380	1.151
FRT51	0	2375	0.000
FRT52	0	3635	0.000
FRT53_54	1	5545	0.494
FRT55	0	3740	0.000
FRT56	0	790	0.000
FRT57	1	6240	0.439
FRT58_59	3	8665	0.949
FRT60	0	6025	0.000
FRT61	0	7250	0.000
FRT62	1	9855	0.278
FRT63_64	4	18705	0.586
FRT65	5	17395	0.788
FRT66	1	3190	0.859
FRT67_68	1	11535	0.238
FRT69_70	0	14720	0.000
FRT71_72	0	16715	0.000
FRT73	1	15770	0.174
FRT74	1	2355	1.163
FRT75	0	6025	0.000
FRT76	3	21060	0.390
FRT77	1	5885	0.466
FRT78	0	9410	0.000
FRT79	0	870	0.000
FRT80	0	1005	0.000
Total	77	546902.5	0.386

Table C.12 FRT Intersection Crash Rates by Year (2017)

Site	2017 Crash	2017 AADT	2017 Crash Rate
FRT1	5	3755	3.648
FRT2	0	6858	0.000
FRT3	1	7107	0.386
FRT4_5	2	15373	0.356
FRT6	0	4280	0.000
FRT7	2	5480	1.000
FRT8	1	2163	1.267
FRT9	0	4059	0.000
FRT10	0	4645	0.000
FRT12_13	0	13087	0.000
FRT14	0	7968	0.000
FRT15	0	4580	0.000
FRT16	0	1308	0.000
FRT17	3	18260	0.450
FRT18	1	6580	0.416
FRT19	0	10838	0.000
FRT20	3	10058	0.817
FRT21	0	2408	0.000
FRT22	0	5372	0.000
FRT23	0	8050	0.000
FRT24	2	3674	1.491
FRT25	2	11828	0.463
FRT26	3	9896	0.831
FRT27	1	17268	0.159
FRT28	1	8647	0.317
FRT29	1	7543	0.363
FRT30	0	4420	0.000
FRT31	2	15470	0.354
FRT32	1	5694	0.481
FRT33_34	1	14795	0.185
FRT35	0	5780	0.000
FRT36	0	5596	0.000
FRT37	0	6393	0.000
FRT38_39	1	6433	0.426
FRT40	0	10510	0.000
FRT41	0	8435	0.000
FRT42	4	25575	0.429
FRT43	0	3473	0.000
FRT44	0	12603	0.000
FRT45_46	1	11166	0.245
FRT47	4	11578	0.947
FRT48	2	565	9.698
FRT49	0	5129	0.000
FRT50	2	2525	2.170
FRT51	0	1923	0.000
FRT52	0	3565	0.000
FRT53_54	1	5130	0.534
FRT55	2	4143	1.323
FRT56	0	588	0.000
FRT57	0	6615	0.000
FRT58_59	0	8867	0.000
FRT60	2	6180	0.887
FRT61	0	7033	0.000
FRT62	2	10106	0.542
FRT63_64	0	20160	0.000
FRT65	0	18893	0.000
FRT66	1	3230	0.848
FRT67_68	0	11438	0.000
FRT69_70	6	15233	1.079
FRT71_72	2	17673	0.310
FRT73	0	15565	0.000
FRT74	2	2449	2.237
FRT75	0	6410	0.000
FRT76	0	22199	0.000
FRT77	0	5975	0.000
FRT78	3	9864	0.833
FRT79	0	913	0.000
FRT80	0	970	0.000
Total	67	562330	0.326

Table C.13 FRT Intersection Crash Rates by Year (2018)

Site	2018 Crash	2018 AADT	2018 Crash Rate
FRT1	0	3715	0.000
FRT2	0	6550	0.000
FRT3	1	6693	0.409
FRT4_5	3	17175	0.479
FRT6	0	4455	0.000
FRT7	0	5460	0.000
FRT8	1	2220	1.234
FRT9	1	3927	0.698
FRT10	1	4560	0.601
FRT12_13	2	13888	0.395
FRT14	0	6760	0.000
FRT15	0	4689	0.000
FRT16	0	1305	0.000
FRT17	3	18560	0.443
FRT18	1	6680	0.410
FRT19	1	11360	0.241
FRT20	2	10605	0.517
FRT21	0	2425	0.000
FRT22	3	4984	1.649
FRT23	3	8225	0.999
FRT24	2	3493	1.569
FRT25	0	12366	0.000
FRT26	1	9975	0.275
FRT27	2	17260	0.317
FRT28	0	9593	0.000
FRT29	1	7685	0.357
FRT30	1	4755	0.576
FRT31	1	16755	0.164
FRT32	4	6328	1.732
FRT33_34	2	14895	0.368
FRT35	1	5965	0.459
FRT36	1	5706	0.480
FRT37	0	6405	0.000
FRT38_39	5	7440	1.841
FRT40	2	10025	0.547
FRT41	2	7880	0.695
FRT42	10	27050	1.013
FRT43	0	3375	0.000
FRT44	0	13885	0.000
FRT45_46	0	10347	0.000
FRT47	4	12411	0.883
FRT48	1	565	4.849
FRT49	1	5223	0.525
FRT50	0	2670	0.000
FRT51	2	1470	3.728
FRT52	0	3495	0.000
FRT53_54	0	4714	0.000
FRT55	0	4545	0.000
FRT56	0	385	0.000
FRT57	0	6989	0.000
FRT58_59	1	9068	0.302
FRT60	0	6335	0.000
FRT61	1	6815	0.402
FRT62	2	10357	0.529
FRT63_64	1	21614	0.127
FRT65	6	20390	0.806
FRT66	1	3270	0.838
FRT67_68	0	11340	0.000
FRT69_70	2	15745	0.348
FRT71_72	1	18630	0.147
FRT73	1	15360	0.178
FRT74	1	2543	1.077
FRT75	1	6794	0.403
FRT76	2	23338	0.235
FRT77	2	6065	0.903
FRT78	3	10317	0.797
FRT79	0	955	0.000
FRT80	0	935	0.000
Total	90	577757	0.427

Table C.14 FRT Intersection Crash Rates by Year (2019)

Site	2019 Crash	2019 AADT	2019 Crash Rate
FRT1	3	3945	2.083
FRT2	1	6523	0.420
FRT3	0	6334	0.000
FRT4_5	1	15960	0.172
FRT6	4	4680	2.342
FRT7	1	5555	0.493
FRT8	2	2390	2.293
FRT9	2	4002	1.369
FRT10	0	4725	0.000
FRT12_13	1	14612	0.188
FRT14	3	6860	1.198
FRT15	1	4441	0.617
FRT16	0	1580	0.000
FRT17	5	16910	0.810
FRT18	1	6550	0.418
FRT19	2	9328	0.587
FRT20	0	9595	0.000
FRT21	0	2370	0.000
FRT22	2	4975	1.102
FRT23	0	7923	0.000
FRT24	0	3886	0.000
FRT25	2	12267	0.447
FRT26	0	9229	0.000
FRT27	0	16450	0.000
FRT28	3	9582	0.858
FRT29	0	6645	0.000
FRT30	1	4755	0.576
FRT31	3	15869	0.518
FRT32	0	5976	0.000
FRT33_34	2	13634	0.402
FRT35	0	5661	0.000
FRT36	0	5323	0.000
FRT37	1	6195	0.442
FRT38_39	1	7090	0.386
FRT40	2	9405	0.583
FRT41	1	7275	0.377
FRT42	4	25195	0.435
FRT43	0	3718	0.000
FRT44	2	13275	0.413
FRT45_46	3	10830	0.759
FRT47	2	11416	0.480
FRT48	2	565	9.698
FRT49	1	4902	0.559
FRT50	0	2885	0.000
FRT51	0	1520	0.000
FRT52	0	3450	0.000
FRT53_54	0	4815	0.000
FRT55	0	4503	0.000
FRT56	0	365	0.000
FRT57	1	7052	0.389
FRT58_59	0	8615	0.000
FRT60	2	6550	0.837
FRT61	0	6863	0.000
FRT62	3	9816	0.837
FRT63_64	1	21458	0.128
FRT65	8	18183	1.205
FRT66	1	3133	0.875
FRT67_68	0	11275	0.000
FRT69_70	1	15330	0.179
FRT71_72	5	17170	0.798
FRT73	4	14982	0.731
FRT74	0	2664	0.000
FRT75	0	6570	0.000
FRT76	4	22924	0.478
FRT77	1	5685	0.482
FRT78	0	9987	0.000
FRT79	1	965	2.839
FRT80	0	1003	0.000
Total	91	556153	0.448

Table C.15 FRT Intersection Crash Rates by Year (Ten-Year Total)

Site	TOTAL CRASH	TOTAL AADT	TOTAL CRASH RATE
FRT1	25	36203	1.892
FRT2	7	68375	0.280
FRT3	11	64277	0.469
FRT4_5	34	141583	0.658
FRT6	8	42473	0.516
FRT7	10	53473	0.512
FRT8	7	21060	0.911
FRT9	18	39068	1.262
FRT10	5	47410	0.289
FRT12_13	16	127619	0.343
FRT14	7	83543	0.230
FRT15	11	43939	0.686
FRT16	1	11983	0.229
FRT17	34	170558	0.546
FRT18	5	61225	0.224
FRT19	12	95731	0.343
FRT20	14	92058	0.417
FRT21	1	23300	0.118
FRT22	7	55138	0.348
FRT23	10	79163	0.346
FRT24	18	36017	1.369
FRT25	12	113226	0.290
FRT26	7	93346	0.205
FRT27	21	164088	0.351
FRT28	7	77351	0.248
FRT29	6	70083	0.235
FRT30	7	36678	0.523
FRT31	34	130504	0.714
FRT32	11	55299	0.545
FRT33_34	15	144271	0.285
FRT35	5	54734	0.250
FRT36	3	54345	0.151
FRT37	11	62975	0.479
FRT38_39	14	63065	0.608
FRT40	7	94695	0.203
FRT41	13	79848	0.446
FRT42	63	215495	0.801
FRT43	3	34993	0.235
FRT44	6	128700	0.128
FRT45_46	15	141628	0.290
FRT47	17	105852	0.440
FRT48	18	5650	8.728
FRT49	7	48546	0.395
FRT50	4	24278	0.451
FRT51	3	19628	0.419
FRT52	1	31870	0.086
FRT53_54	6	65354	0.252
FRT55	3	34128	0.241
FRT56	0	5890	0.000
FRT57	7	63276	0.303
FRT58_59	8	82460	0.266
FRT60	7	61768	0.310
FRT61	2	68363	0.080
FRT62	18	96171	0.513
FRT63_64	21	160978	0.357
FRT65	42	178838	0.643
FRT66	10	30995	0.884
FRT67_68	9	106373	0.232
FRT69_70	28	139883	0.548
FRT71_72	27	165670	0.447
FRT73	15	145605	0.282
FRT74	7	26021	0.737
FRT75	3	64958	0.127
FRT76	27	217459	0.340
FRT77	8	61460	0.357
FRT78	18	95210	0.518
FRT79	2	9318	0.588
FRT80	3	9783	0.840
Total	842	5335286	0.432

Table C.16 Non-FRT Intersection Crash Rates by Year (2010)

Site	2010 Crash	2010 AADT	2010 Crash Rate
COMP1	0	5360	0.000
COMP2	1	4316	0.635
COMP3	1	6610	0.414
COMP4	0	7180	0.000
COMP5	0	8255	0.000
COMP6	0	12705	0.000
COMP7	2	7385	0.742
COMP8	0	4905	0.000
COMP9	0	4765	0.000
COMP10	2	6730	0.814
COMP11	0	14640	0.000
COMP12	0	5090	0.000
COMP13	3	12580	0.653
COMP14	2	7455	0.735
COMP15	1	6385	0.429
COMP16	5	11640	1.177
COMP17	3	18425	0.446
COMP18	0	9252	0.000
COMP19	2	17465	0.314
COMP20	0	4739	0.000
COMP21	0	7370	0.000
COMP22	0	12675	0.000
COMP23	1	11795	0.232
COMP24	5	11520	1.189
Total	28	219242	0.350

Table C.17 Non-FRT Intersection Crash Rates by Year (2011)

Site	2011 Crash	2011 AADT	2011 Crash Rate
COMP1	0	5158	0.000
COMP2	1	4456	0.615
COMP3	1	6633	0.413
COMP4	4	7350	1.491
COMP5	0	8288	0.000
COMP6	2	12625	0.434
COMP7	1	7808	0.351
COMP8	1	5060	0.541
COMP9	0	4780	0.000
COMP10	0	6660	0.000
COMP11	0	14058	0.000
COMP12	0	5125	0.000
COMP13	0	13008	0.000
COMP14	1	7650	0.358
COMP15	0	6323	0.000
COMP16	1	12120	0.226
COMP17	1	18908	0.145
COMP18	2	9576	0.572
COMP19	3	16420	0.501
COMP20	1	4382	0.625
COMP21	0	7660	0.000
COMP22	1	12395	0.221
COMP23	3	11458	0.717
COMP24	1	10928	0.251
Total	24	218824	0.300

Table C.18 Non-FRT Intersection Crash Rates by Year (2012)

Site	2012 Crash	2012 AADT	2012 Crash Rate
COMP1	1	4955	0.553
COMP2	1	4595	0.596
COMP3	1	6655	0.412
COMP4	1	7520	0.364
COMP5	1	8320	0.329
COMP6	4	12545	0.874
COMP7	1	8230	0.333
COMP8	1	5215	0.525
COMP9	0	4795	0.000
COMP10	1	6590	0.416
COMP11	0	13475	0.000
COMP12	0	5160	0.000
COMP13	3	13435	0.612
COMP14	4	7845	1.397
COMP15	1	6260	0.438
COMP16	1	12600	0.217
COMP17	3	19390	0.424
COMP18	0	9900	0.000
COMP19	1	15375	0.178
COMP20	0	4025	0.000
COMP21	0	7950	0.000
COMP22	0	12115	0.000
COMP23	1	11120	0.246
COMP24	0	10335	0.000
Total	26	218405	0.326

Table C.19 Non-FRT Intersection Crash Rates by Year (2013)

Site	2013 Crash	2013 AADT	2013 Crash Rate
COMP1	0	5078	0.000
COMP2	0	4318	0.000
COMP3	1	6850	0.400
COMP4	1	7893	0.347
COMP5	2	7322	0.748
COMP6	2	12703	0.431
COMP7	1	8193	0.334
COMP8	0	5315	0.000
COMP9	0	4833	0.000
COMP10	0	6963	0.000
COMP11	3	13710	0.600
COMP12	1	5108	0.536
COMP13	0	13713	0.000
COMP14	1	7868	0.348
COMP15	1	6010	0.456
COMP16	1	12850	0.213
COMP17	3	19665	0.418
COMP18	2	10389	0.527
COMP19	1	16278	0.168
COMP20	0	3984	0.000
COMP21	0	8095	0.000
COMP22	0	12635	0.000
COMP23	1	11123	0.246
COMP24	0	11253	0.000
Total	21	222143	0.259

Table C.20 Non-FRT Intersection Crash Rates by Year (2014)

Site	2014 Crash	2014 AADT	2014 Crash Rate
COMP1	0	5200	0.000
COMP2	0	4040	0.000
COMP3	0	7045	0.000
COMP4	0	8265	0.000
COMP5	4	6324	1.733
COMP6	3	12860	0.639
COMP7	0	8155	0.000
COMP8	1	5415	0.506
COMP9	1	4870	0.563
COMP10	1	7335	0.374
COMP11	1	13945	0.196
COMP12	0	5055	0.000
COMP13	0	13990	0.000
COMP14	2	7890	0.694
COMP15	0	5760	0.000
COMP16	2	13100	0.418
COMP17	3	19940	0.412
COMP18	0	10878	0.000
COMP19	1	17180	0.159
COMP20	0	3943	0.000
COMP21	0	8240	0.000
COMP22	1	13155	0.208
COMP23	2	11125	0.493
COMP24	2	12170	0.450
Total	24	225880	0.291

Table C.21 Non-FRT Intersection Crash Rates by Year (2015)

Site	2015 Crash	2015 AADT	2015 Crash Rate
COMP1	1	4715	0.581
COMP2	1	4093	0.669
COMP3	0	7070	0.000
COMP4	0	8393	0.000
COMP5	1	7310	0.375
COMP6	1	13458	0.204
COMP7	2	7773	0.705
COMP8	1	6148	0.446
COMP9	1	5728	0.478
COMP10	0	6908	0.000
COMP11	1	13613	0.201
COMP12	1	5230	0.524
COMP13	0	13630	0.000
COMP14	0	7858	0.000
COMP15	3	6810	1.207
COMP16	3	13855	0.593
COMP17	3	20001	0.411
COMP18	2	12104	0.453
COMP19	6	17385	0.946
COMP20	4	4509	2.430
COMP21	0	8520	0.000
COMP22	1	13355	0.205
COMP23	5	11986	1.143
COMP24	0	13140	0.000
Total	37	233587	0.434

Table C.22 Non-FRT Intersection Crash Rates by Year (2016)

Site	2016 Crash	2016 AADT	2016 Crash Rate
COMP1	1	4230	0.648
COMP2	0	4145	0.000
COMP3	2	7095	0.772
COMP4	3	8520	0.965
COMP5	1	8295	0.330
COMP6	0	14055	0.000
COMP7	1	7390	0.371
COMP8	0	6880	0.000
COMP9	0	6585	0.000
COMP10	0	6480	0.000
COMP11	0	13280	0.000
COMP12	0	5405	0.000
COMP13	1	13270	0.206
COMP14	1	7825	0.350
COMP15	1	7860	0.349
COMP16	1	14610	0.188
COMP17	0	20063	0.000
COMP18	2	13329	0.411
COMP19	5	17590	0.779
COMP20	0	5075	0.000
COMP21	0	8800	0.000
COMP22	1	13555	0.202
COMP23	2	12848	0.426
COMP24	1	14110	0.194
Total	23	241294	0.261

Table C.23 Non-FRT Intersection Crash Rates by Year (2017)

Site	2017 Crash	2017 AADT	2017 Crash Rate
COMP1	2	4595	1.192
COMP2	0	4566	0.000
COMP3	2	7346	0.746
COMP4	2	8725	0.628
COMP5	3	8793	0.935
COMP6	2	13973	0.392
COMP7	0	7950	0.000
COMP8	1	6937	0.395
COMP9	0	5870	0.000
COMP10	1	6910	0.396
COMP11	0	13613	0.000
COMP12	0	5363	0.000
COMP13	2	12963	0.423
COMP14	4	7793	1.406
COMP15	0	7740	0.000
COMP16	4	13941	0.786
COMP17	1	20124	0.136
COMP18	1	14555	0.188
COMP19	2	18608	0.294
COMP20	0	5212	0.000
COMP21	2	9328	0.587
COMP22	0	13755	0.000
COMP23	4	13709	0.799
COMP24	0	13853	0.000
Total	33	246216	0.367

Table C.24 Non-FRT Intersection Crash Rates by Year (2018)

Site	2018 Crash	2018 AADT	2018 Crash Rate
COMP1	0	4960	0.000
COMP2	2	4986	1.099
COMP3	1	7596	0.361
COMP4	0	8930	0.000
COMP5	1	9290	0.295
COMP6	4	13891	0.789
COMP7	0	8510	0.000
COMP8	0	6994	0.000
COMP9	2	5155	1.063
COMP10	0	7340	0.000
COMP11	0	13945	0.000
COMP12	0	5320	0.000
COMP13	1	12655	0.216
COMP14	3	7760	1.059
COMP15	0	7620	0.000
COMP16	1	13272	0.206
COMP17	7	20185	0.950
COMP18	5	15780	0.868
COMP19	4	19625	0.558
COMP20	2	5349	1.024
COMP21	0	9855	0.000
COMP22	0	13955	0.000
COMP23	8	14570	1.504
COMP24	0	13595	0.000
Total	41	251138	0.447

Table C.25 Non-FRT Intersection Crash Rates by Year (2019)

Site	2019 Crash	2019 AADT	2019 Crash Rate
COMP1	1	4834	0.567
COMP2	0	5016	0.000
COMP3	0	7351	0.000
COMP4	4	8948	1.225
COMP5	0	9210	0.000
COMP6	2	13716	0.400
COMP7	0	8068	0.000
COMP8	2	6507	0.842
COMP9	1	5180	0.529
COMP10	0	7200	0.000
COMP11	1	13450	0.204
COMP12	0	5175	0.000
COMP13	3	13195	0.623
COMP14	1	7195	0.381
COMP15	2	7295	0.751
COMP16	6	12683	1.296
COMP17	2	20163	0.272
COMP18	3	15378	0.534
COMP19	3	18005	0.456
COMP20	1	5078	0.540
COMP21	1	9283	0.295
COMP22	2	13938	0.393
COMP23	4	13920	0.787
COMP24	1	13303	0.206
Total	40	244085	0.449

Table C.26 Non-FRT Intersection Crash Rates by Year (Ten-Year Total)

Site	TOTAL CRASH	TOTAL AADT	TOTAL CRASH RATE
COMP1	6	49084	0.335
COMP2	6	44529	0.369
COMP3	9	70250	0.351
COMP4	15	81723	0.503
COMP5	13	81406	0.438
COMP6	20	132530	0.413
COMP7	8	79460	0.276
COMP8	7	59376	0.323
COMP9	5	52560	0.261
COMP10	5	69115	0.198
COMP11	6	137728	0.119
COMP12	2	52030	0.105
COMP13	13	132438	0.269
COMP14	19	77138	0.675
COMP15	9	68063	0.362
COMP16	25	130671	0.524
COMP17	26	196863	0.362
COMP18	17	121140	0.384
COMP19	28	173930	0.441
COMP20	8	46296	0.473
COMP21	3	85100	0.097
COMP22	6	131533	0.125
COMP23	31	123653	0.687
COMP24	10	124205	0.221
Total	297	2320813	0.351

Appendix D

Table D.1 T Table

t Table

cum. prob	$t_{.50}$	$t_{.75}$	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.99}$	$t_{.995}$	$t_{.999}$	$t_{.9995}$
one-tail	**0.50**	**0.25**	**0.20**	**0.15**	**0.10**	**0.05**	**0.025**	**0.01**	**0.005**	**0.001**	**0.0005**
two-tails	**1.00**	**0.50**	**0.40**	**0.30**	**0.20**	**0.10**	**0.05**	**0.02**	**0.01**	**0.002**	**0.001**
df											
1	0.000	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.000	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.000	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.000	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.000	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.000	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.000	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.000	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.000	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.000	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.000	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.000	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.000	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.000	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.000	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										

Table D.2 Crash Frequency Comparison (alpha = 0.05)

Comparison1	Comparison2	n1	n2	CrashFreq1	CrashFreq2	Critical F-Value	F-Statistic	Variance	df	T-Statistic	Critical T-Value (alpha = 0.05)	Significance?
Low AADT, 3-Leg FRT	Low AADT, 3-Leg Non-FRT	16	4	**0.856**	0.525	5.20	5.31	unequal	18	1.74	2.101	NO
Low AADT, 4-Leg FRT	Low AADT, 4-Leg Non-FRT	22	4	0.664	**0.925**	5.18	1.73	equal	24	0.93	2.064	NO
Low AADT, All Legs FRT	Low AADT, All Legs Non-FRT	38	8	**0.760**	0.725	2.56	2.14	equal	44	0.10	1.960	NO
Medium AADT, 3-Leg FRT	Medium AADT, 3-Leg Non-FRT	8	4	0.763	**1.025**	3.07	4.47	unequal	10	0.82	2.228	NO
Medium AADT, 4-Leg FRT	Medium AADT, 4-Leg Non-FRT	8	4	**1.413**	0.975	3.07	2.48	equal	10	1.98	2.228	NO
Medium AADT, All Legs FRT	Medium AADT, All Legs Non-FRT	16	8	**1.088**	1.000	2.16	1.32	equal	22	0.44	2.074	NO
High AADT, 3-Leg FRT	High AADT, 3-Leg Non-FRT	7	4	**3.014**	1.925	5.29	4.04	equal	9	1.08	2.262	NO
High AADT, 4-Leg FRT	High AADT, 4-Leg Non-FRT	7	4	**2.486**	2.050	3.29	1.99	equal	9	0.75	2.262	NO
High AADT, All Legs FRT	High AADT, All Legs Non-FRT	14	8	**2.750**	1.988	2.66	2.12	equal	20	1.36	2.066	NO
All 3-Leg FRT	All AADT, 3-Leg Non-FRT	31	12	**1.319**	1.158	2.08	2.43	unequal	41	0.47	1.960	NO
All 4-Leg FRT	All AADT, 4-Leg Non-FRT	37	12	1.170	**1.317**	2.06	1.06	equal	47	0.50	1.960	NO
All FRT	All AADT, All Legs Non-FRT	68	24	**1.245**	1.238	1.62	1.71	unequal	90	0.00	1.960	NO
FRT on Major Road, 3-Leg	All 3-Leg Non-FRT	26	12	1.112	**1.158**	2.10	1.29	equal	36	0.14	1.960	NO
FRT on Minor Road, 3-Leg	All 3-Leg Non-FRT	4	12	**2.625**	1.158	2.66	10.19	unequal	14	1.07	2.145	NO
FRT on Major Road, 4-Leg	All 4-Leg Non-FRT	19	12	1.095	**1.317**	2.14	1.13	equal	29	0.67	2.045	NO
FRT on Minor Road, 4-Leg	All 4-Leg Non-FRT	8	12	0.738	**1.317**	2.68	2.31	equal	18	1.66	2.101	NO
FRT on Both Major and Minor Road , 4-Leg	All 4-Leg Non-FRT	10	12	**1.660**	1.317	2.28	1.05	equal	20	0.91	2.086	NO
FRT on Major Road, All Legs	All Non-FRT	45	24	**1.104**	1.238	1.65	1.23	equal	67	0.58	1.960	NO
FRT on Minor Road, All Legs	All Non-FRT	12	24	**1.367**	1.238	1.87	4.32	unequal	34	0.24	1.960	NO
FRT on Both Major and Minor Road, All Leg	All Non-FRT	11	24	**1.755**	1.238	1.89	1.14	equal	33	1.65	1.960	NO

Table D.3 Crash Frequency Comparison (alpha = 0.10)

Comparison1	Comparison2	n1	n2	CrashFreq1	CrashFreq2	Critical F-Value	F-Statistic	Variance	df	T-Statistic	Critical T-Value (alpha = 0.10)	Significance?
Low AADT, 3-Leg FRT	Low AADT, 3-Leg Non-FRT	16	4	**0.856**	0.525	5.20	5.31	unequal	18	1.74	1.734	YES
Low AADT, 4-Leg FRT	Low AADT, 4-Leg Non-FRT	22	4	0.664	**0.925**	5.18	1.73	equal	24	0.93	1.711	NO
Low AADT, All Legs FRT	Low AADT, All Legs Non-FRT	38	8	**0.760**	0.725	2.56	2.14	equal	44	0.10	1.645	NO
Medium AADT, 3-Leg FRT	Medium AADT, 3-Leg Non-FRT	8	4	0.763	**1.025**	3.07	4.47	unequal	10	0.82	1.812	NO
Medium AADT, 4-Leg FRT	Medium AADT, 4-Leg Non-FRT	8	4	**1.413**	0.975	3.07	2.48	equal	10	1.98	1.812	YES
Medium AADT, All Legs FRT	Medium AADT, All Legs Non-FRT	16	8	**1.088**	1.000	2.16	1.32	equal	22	0.44	1.717	NO
High AADT, 3-Leg FRT	High AADT, 3-Leg Non-FRT	7	4	**3.014**	1.925	5.29	4.04	equal	9	1.08	1.833	NO
High AADT, 4-Leg FRT	High AADT, 4-Leg Non-FRT	7	4	**2.486**	2.050	3.29	1.99	equal	9	0.75	1.833	NO
High AADT, All Legs FRT	High AADT, All Legs Non-FRT	14	8	**2.750**	1.988	2.66	2.12	equal	20	1.36	1.725	NO
All 3-Leg FRT	All AADT, 3-Leg Non-FRT	31	12	**1.319**	1.158	2.08	2.43	unequal	41	0.47	1.645	NO
All 4-Leg FRT	All AADT, 4-Leg Non-FRT	37	12	1.170	**1.317**	2.06	1.06	equal	47	0.50	1.645	NO
All FRT	All AADT, All Legs Non-FRT	68	24	**1.245**	1.238	1.62	1.71	unequal	90	0.00	1.645	NO
FRT on Major Road, 3-Leg	All 3-Leg Non-FRT	26	12	1.112	**1.158**	2.10	1.29	equal	36	0.14	1.645	NO
FRT on Minor Road, 3-Leg	All 3-Leg Non-FRT	4	12	**2.625**	1.158	2.66	10.19	unequal	14	1.07	1.761	NO
FRT on Major Road, 4-Leg	All 4-Leg Non-FRT	19	12	1.095	**1.317**	2.14	1.13	equal	29	0.67	1.699	NO
FRT on Minor Road, 4-Leg	All 4-Leg Non-FRT	8	12	0.738	**1.317**	2.68	2.31	equal	18	1.66	1.734	NO
FRT on Both Major and Minor Road , 4-Leg	All 4-Leg Non-FRT	10	12	**1.660**	1.317	2.28	1.05	equal	20	0.91	1.725	NO
FRT on Major Road, All Legs	All Non-FRT	45	24	**1.104**	1.238	1.65	1.23	equal	67	0.58	1.645	NO
FRT on Minor Road, All Legs	All Non-FRT	12	24	**1.367**	1.238	1.87	4.32	unequal	34	0.24	1.645	NO
FRT on Both Major and Minor Road, All Leg	All Non-FRT	11	24	**1.755**	1.238	1.89	1.14	equal	33	1.65	1.645	YES

Table D.4 Crash Rate Comparison (alpha = 0.05)

Comparison1	Comparison2	n1	n2	CrashRate1	CrashRate2	Critical F-Value	F-Statistic	Variance	df	T-Statistic	Critical T-Value (alpha = 0.05)	Significance?
Low AADT, 3-Leg FRT	Low AADT, 3-Leg Non-FRT	16	4	0.546	0.294	5.20	177.03	unequal	18	1.38	2.101	NO
Low AADT, 4-Leg FRT	Low AADT, 4-Leg Non-FRT	22	4	0.428	0.389	5.18	19.44	unequal	24	0.99	2.064	NO
Low AADT, All Legs FRT	Low AADT, All Legs Non-FRT	38	8	0.478	0.349	2.54	126.47	unequal	44	1.59	1.960	NO
Medium AADT, 3-Leg FRT	Medium AADT, 3-Leg Non-FRT	8	4	0.263	0.382	3.05	4.46	unequal	10	1.04	2.228	NO
Medium AADT, 4-Leg FRT	Medium AADT, 4-Leg Non-FRT	8	4	0.352	0.253	3.05	2.33	equal	10	1.53	2.228	NO
Medium AADT, All Legs FRT	Medium AADT, All Legs Non-FRT	16	8	0.315	0.306	2.16	2.87	unequal	22	0.09	2.074	NO
High AADT, 3-Leg FRT	High AADT, 3-Leg Non-FRT	7	4	0.517	0.353	5.29	1.58	equal	9	1.08	2.262	NO
High AADT, 4-Leg FRT	High AADT, 4-Leg Non-FRT	7	4	0.441	0.408	3.29	1.61	equal	9	0.36	2.262	NO
High AADT, All Legs FRT	High AADT, All Legs Non-FRT	14	8	0.480	0.379	2.65	1.02	equal	20	1.07	2.066	NO
All 3-Leg FRT	All AADT, 3-Leg Non-FRT	31	12	0.459	0.350	2.08	83.64	unequal	41	1.32	1.960	NO
All 4-Leg FRT	All AADT, 4-Leg Non-FRT	37	12	0.410	0.351	2.06	3.36	unequal	47	1.37	1.960	NO
All FRT	All AADT, All Legs Non-FRT	68	24	0.432	0.351	1.62	42.50	unequal	90	1.65	1.960	NO
FRT on Major Road, 3-Leg	All 3-Leg Non-FRT	26	12	0.417	0.350	2.10	4.27	unequal	36	1.24	1.960	NO
FRT on Minor Road, 3-Leg	All 3-Leg Non-FRT	4	12	0.547	0.350	2.66	626.18	unequal	14	1.03	2.145	NO
FRT on Major Road, 4-Leg	All 4-Leg Non-FRT	19	12	0.448	0.351	2.14	4.90	unequal	29	1.60	2.045	NO
FRT on Minor Road, 4-Leg	All 4-Leg Non-FRT	8	12	0.360	0.351	2.34	2.71	unequal	18	0.24	2.101	NO
FRT on Both Major and Minor Road , 4-Leg	All 4-Leg Non-FRT	10	12	0.388	0.351	2.43	1.05	equal	20	0.52	2.086	NO
FRT on Major Road, All Legs	All Non-FRT	45	24	0.429	0.351	1.65	4.67	unequal	67	2.00	1.960	YES
FRT on Minor Road, All Legs	All Non-FRT	12	24	0.448	0.351	1.87	225.72	unequal	34	1.05	1.960	NO
FRT on Both Major and Minor Road, All Leg	All Non-FRT	11	24	0.395	0.351	2.18	1.12	equal	33	0.75	1.960	NO

Table D.5 Crash Rate Comparison (alpha = 0.10)

Comparison1	Comparison2	n1	n2	CrashRate1	CrashRate2	Critical F-Value	F-Statistic	Variance	df	T-Statistic	Critical T-Value (alpha = 0.10)	Significance?
Low AADT, 3-Leg FRT	Low AADT, 3-Leg Non-FRT	16	4	0.546	0.294	5.20	177.03	unequal	18	1.38	1.734	NO
Low AADT, 4-Leg FRT	Low AADT, 4-Leg Non-FRT	22	4	0.428	0.389	5.18	19.44	unequal	24	0.99	1.711	NO
Low AADT, All Legs FRT	Low AADT, All Legs Non-FRT	38	8	0.478	0.349	2.54	126.47	unequal	44	1.59	1.645	NO
Medium AADT, 3-Leg FRT	Medium AADT, 3-Leg Non-FRT	8	4	0.263	0.382	3.05	4.46	unequal	10	1.04	1.812	NO
Medium AADT, 4-Leg FRT	Medium AADT, 4-Leg Non-FRT	8	4	0.352	0.253	3.05	2.33	equal	10	1.53	1.812	NO
Medium AADT, All Legs FRT	Medium AADT, All Legs Non-FRT	16	8	0.315	0.306	2.16	2.87	unequal	22	0.09	1.717	NO
High AADT, 3-Leg FRT	High AADT, 3-Leg Non-FRT	7	4	0.517	0.353	5.29	1.58	equal	9	1.08	1.833	NO
High AADT, 4-Leg FRT	High AADT, 4-Leg Non-FRT	7	4	0.441	0.408	3.29	1.61	equal	9	0.36	1.833	NO
High AADT, All Legs FRT	High AADT, All Legs Non-FRT	14	8	0.480	0.379	2.65	1.02	equal	20	1.07	1.725	NO
All 3-Leg FRT	All AADT, 3-Leg Non-FRT	31	12	0.459	0.350	2.08	83.64	unequal	41	1.32	1.645	NO
All 4-Leg FRT	All AADT, 4-Leg Non-FRT	37	12	0.410	0.351	2.06	3.36	unequal	47	1.37	1.645	NO
All FRT	All AADT, All Legs Non-FRT	68	24	0.432	0.351	1.62	42.50	unequal	90	1.65	1.645	YES
FRT on Major Road, 3-Leg	All 3-Leg Non-FRT	26	12	0.417	0.350	2.10	4.27	unequal	36	1.24	1.645	NO
FRT on Minor Road, 3-Leg	All 3-Leg Non-FRT	4	12	0.547	0.350	2.66	626.18	unequal	14	1.03	1.761	NO
FRT on Major Road, 4-Leg	All 4-Leg Non-FRT	19	12	0.448	0.351	2.14	4.90	unequal	29	1.60	1.699	NO
FRT on Minor Road, 4-Leg	All 4-Leg Non-FRT	8	12	0.360	0.351	2.34	2.71	unequal	18	0.24	1.734	NO
FRT on Both Major and Minor Road , 4-Leg	All 4-Leg Non-FRT	10	12	0.388	0.351	2.43	1.05	equal	20	0.52	1.725	NO
FRT on Major Road, All Legs	All Non-FRT	45	24	0.429	0.351	1.65	4.67	unequal	67	2.00	1.645	YES
FRT on Minor Road, All Legs	All Non-FRT	12	24	0.448	0.351	1.87	225.72	unequal	34	1.05	1.645	NO
FRT on Both Major and Minor Road, All Leg	All Non-FRT	11	24	0.395	0.351	2.18	1.12	equal	33	0.75	1.645	NO

Appendix E

Table E.1 FRT Intersection Test Site Summary Data

SITE	FRT7	FRT61	FRT26	FRT25	FRT65	FRT63
AADT RANGE	LOW	LOW	MEDIUM	MEDIUM	HIGH	HIGH
2018 AADT	5,460	6,815	9,975	12,366	20,390	21,614
INTERSECTION LEGS	3	4	3	4	3	4
RT APPROACH THRU CONTROL	UNCONTROLLED	UNCONTROLLED	STOP-CONTROLLED	UNCONTROLLED	UNCONTROLLED	STOP-CONTROLLED
VIDEO HRS	72	69	104	72	64	85.5
TOTAL THRU	588	89	1282	472	660	10432
THRU/HR	8.17	1.29	12.33	6.56	10.31	122.01
TOTAL RT	1205	460	3704	3569	5797	6470
RT/HR	16.74	6.67	35.62	49.57	90.58	75.67
TOTAL CONFLICT	4	0	5	2	12	30
TOTAL POT CONFLICT	8	1	64	12	49	632

Table E.2 Non-FRT Intersection Test Site Summary Data

SITE	COMP20	COMP8	COMP7	COMP24	COMP6	COMP23
AADT RANGE	LOW	LOW	MEDIUM	MEDIUM	HIGH	HIGH
2018 AADT	5,349	6,994	8,510	13,595	13,891	14,570
INTERSECTION LEGS	3	4	3	4	3	4
RT APPROACH THRU CONTROL	UNCONTROLLED	UNCONTROLLED	STOP-CONTROLLED	UNCONTROLLED	UNCONTROLLED	STOP-CONTROLLED
VIDEO HRS	77	59.5	69	71.75	73.75	77.75
TOTAL THRU	256	889	3306	690	1398	2454
THRU/HR	3.32	14.94	47.91	9.62	18.96	31.56
TOTAL RT	1584	23	93	327	4691	1184
RT/HR	20.57	0.39	1.35	4.56	63.61	15.23
TOTAL CONFLICT	63	1	0	12	12	9
TOTAL POT CONFLICT	44	4	3	17	192	135
CONFLICT/HR	0.82	0.02	0.00	0.17	0.16	0.12

Table E.3 Low AADT, 3-Leg Sites

	LOW AADT, 3-LEG					
	FRT SITE (FRT7)			NON-FRT SITE (COMP20)		
Time Period	Conflicts	Hours of Data	RT Vehicles	Conflicts	Hours of Data	RT Vehicles
12AM-1AM	0	3	3	0	3	2
1AM-2AM	0	3	3	0	3	4
2AM-3AM	0	3	2	0	3	2
3AM-4AM	0	3	3	0	3	3
4AM-5AM	0	3	17	0	3	5
5AM-6AM	0	3	54	0	3	10
6AM-7AM	1	3	97	1	3	51
7AM-8AM	0	3	80	5	3	128
8AM-9AM	1	3	51	3	3	77
9AM-10AM	0	3	63	5	3	75
10AM-11AM	1	3	62	1	3	84
11AM-12PM	0	3	50	2	3	87
12PM-1PM	0	3	68	1	3	91
1PM-2PM	0	3	66	2	3	93
2PM-3PM	0	3	80	1	3	95
3PM-4PM	1	3	96	8	3	107
4PM-5PM	0	3	105	14	3	160
5PM-6PM	0	3	77	17	3	166
6PM-7PM	0	3	60	0	3	91
7PM-8PM	0	3	55	2	4	99
8PM-9PM	0	3	36	0	4	64
9PM-10PM	0	3	37	1	4	45
10PM-11PM	0	3	20	0	4	32
11PM-12AM	0	3	20	0	4	13
Total	4	72	1205	63	77	1584
Conflict/hr	0.056			0.818		
Conflict/1000 RT vehicles	3.320			39.773		

Table E.4 Low AADT, 4-Leg Sites

	LOW AADT, 4-LEG					
	FRT SITE (FRT61)			NON-FRT SITE (COMP8)		
Time Period	Conflicts	Hours of Data	RT Vehicles	Conflicts	Hours of Data	RT Vehicles
12AM-1AM	0	3	0	0	2	0
1AM-2AM	0	3	0	0	2	0
2AM-3AM	0	3	1	0	2	0
3AM-4AM	0	3	2	0	2	0
4AM-5AM	0	3	3	0	2	0
5AM-6AM	0	3	19	0	2	0
6AM-7AM	0	3	18	0	3	0
7AM-8AM	0	3	69	0	3	0
8AM-9AM	0	3	29	0	3	2
9AM-10AM	0	3	23	0	3	2
10AM-11AM	0	3	24	0	3	3
11AM-12PM	0	3	32	0	3	2
12PM-1PM	0	2	13	0	3	2
1PM-2PM	0	2	17	0	3	1
2PM-3PM	0	2	18	1	3	3
3PM-4PM	0	3	34	0	3	1
4PM-5PM	0	3	30	0	3	3
5PM-6PM	0	3	41	0	2.5	2
6PM-7PM	0	3	35	0	2	1
7PM-8PM	0	3	13	0	2	1
8PM-9PM	0	3	18	0	2	0
9PM-10PM	0	3	11	0	2	0
10PM-11PM	0	3	7	0	2	0
11PM-12AM	0	3	3	0	2	0
Total	0	69	460	1	59.5	23
Conflict/hr	0.000			0.017		
Conflict/1000 RT vehicles	0.000			43.478		

Table E.5 Medium AADT, 3-Leg Sites

	MEDIUM AADT, 3-LEG					
	FRT SITE (FRT26)			NON-FRT SITE (COMP7)		
Time Period	Conflicts	Hours of Data	RT Vehicles	Conflicts	Hours of Data	RT Vehicles
12AM-1AM	0	4	7	0	3	0
1AM-2AM	0	4	3	0	3	0
2AM-3AM	0	4	22	0	3	0
3AM-4AM	0	4	37	0	3	0
4AM-5AM	0	4	80	0	3	0
5AM-6AM	0	4	78	0	3	0
6AM-7AM	0	4	148	0	2.25	3
7AM-8AM	0	4	175	0	2.75	18
8AM-9AM	0	4	165	0	3	6
9AM-10AM	0	4	202	0	3	5
10AM-11AM	1	4	200	0	3	4
11AM-12PM	0	4	211	0	3	6
12PM-1PM	0	4	175	0	3	3
1PM-2PM	0	4	202	0	2.25	7
2PM-3PM	0	4	207	0	2.75	8
3PM-4PM	0	4.75	241	0	3	2
4PM-5PM	2	5	634	0	3	8
5PM-6PM	1	5	345	0	3	8
6PM-7PM	1	5	197	0	3	6
7PM-8PM	0	5	127	0	3	4
8PM-9PM	0	5	95	0	2.25	1
9PM-10PM	0	5	87	0	2.75	4
10PM-11PM	0	5	49	0	3	0
11PM-12AM	0	4.25	17	0	3	0
Total	5	104	3704	0	69	93
Conflict/hr	0.048			0.000		
Conflict/1000 RT vehicles	1.350			0.000		

Table E.6 Medium AADT, 4-Leg Sites

	MEDIUM AADT, 4-LEG					
	FRT SITE (FRT25)			NON-FRT SITE (COMP24)		
Time Period	Conflicts	Hours of Data	RT Vehicles	Conflicts	Hours of Data	RT Vehicles
12AM-1AM	0	3	6	0	3	2
1AM-2AM	0	3	5	0	3	1
2AM-3AM	0	3	5	0	3	0
3AM-4AM	0	3	10	0	3	0
4AM-5AM	0	3	30	0	3	0
5AM-6AM	0	3	84	0	3	3
6AM-7AM	0	3	91	0	3	6
7AM-8AM	1	3	130	0	3	17
8AM-9AM	1	3	190	1	3	17
9AM-10AM	0	3	209	0	3	25
10AM-11AM	0	3	237	0	3	17
11AM-12PM	0	3	268	0	3	13
12PM-1PM	0	3	285	0	3	15
1PM-2PM	0	3	246	0	3	12
2PM-3PM	0	3	219	3	2.75	30
3PM-4PM	0	3	288	0	3	38
4PM-5PM	0	3	313	0	3	38
5PM-6PM	0	3	245	7	3	35
6PM-7PM	0	3	211	1	3	27
7PM-8PM	0	3	155	0	3	8
8PM-9PM	0	3	121	0	3	12
9PM-10PM	0	3	92	0	3	5
10PM-11PM	0	3	85	0	3	5
11PM-12AM	0	3	44	0	3	1
Total	2	72	3569	12	71.75	327
Conflict/hr	0.028			0.167		
Conflict/1000 RT vehicles	0.560			36.697		

Table E.7 High AADT, 3-Leg Sites

	HIGH AADT, 3-LEG					
	FRT SITE (FRT65)			NON-FRT SITE (COMP6)		
Time Period	Conflicts	Hours of Data	RT Vehicles	Conflicts	Hours of Data	RT Vehicles
12AM-1AM	0	2	5	0	3	122
1AM-2AM	0	2	6	0	3	25
2AM-3AM	0	2	1	0	3	13
3AM-4AM	0	2	6	0	3	11
4AM-5AM	0	2	11	0	3	27
5AM-6AM	0	2	52	0	3	69
6AM-7AM	0	3	162	1	3	115
7AM-8AM	3	3	387	3	3	249
8AM-9AM	0	3	245	0	3	248
9AM-10AM	0	3	254	0	3	227
10AM-11AM	0	3	290	0	3	239
11AM-12PM	1	3	307	0	3	275
12PM-1PM	1	3	329	0	3	271
1PM-2PM	0	3	341	0	3	292
2PM-3PM	1	3	385	0	3	314
3PM-4PM	1	3	540	3	3	343
4PM-5PM	3	3	634	2	4	553
5PM-6PM	1	3	624	2	3.75	453
6PM-7PM	0	3	427	0	3	305
7PM-8PM	0	3	297	0	3	198
8PM-9PM	1	3	259	0	3	134
9PM-10PM	0	3	148	0	3	103
10PM-11PM	0	2	56	0	3	64
11PM-12AM	0	2	31	1	3	41
Total	12	64	5797	12	73.75	4691
Conflict/hr		0.188			0.163	
Conflict/1000 RT vehicles		2.070			2.558	

Table E.8 High AADT, 4-Leg Sites

	HIGH AADT, 4-LEG					
	FRT SITE (FRT63)			NON-FRT SITE (COMP23)		
Time Period	Conflicts	Hours of Data	RT Vehicles	Conflicts	Hours of Data	RT Vehicles
12AM-1AM	0	3	20	0	3	4
1AM-2AM	0	3	23	0	3	1
2AM-3AM	0	3	21	0	3	2
3AM-4AM	0	3	32	0	3	1
4AM-5AM	0	3	49	0	3	12
5AM-6AM	0	3	138	0	3	30
6AM-7AM	1	3	188	3	3	61
7AM-8AM	0	3	341	1	3	66
8AM-9AM	3	3	327	0	2.75	88
9AM-10AM	2	3	301	0	2	60
10AM-11AM	1	3.5	338	1	2	53
11AM-12PM	1	4	420	1	2	60
12PM-1PM	1	4	424	0	3	60
1PM-2PM	4	4	437	0	3	68
2PM-3PM	4	4	493	0	3	58
3PM-4PM	3	4	510	1	4	115
4PM-5PM	4	4	662	2	4	142
5PM-6PM	3	4	569	0	4	145
6PM-7PM	2	4	368	0	4	67
7PM-8PM	0	4	285	0	4	25
8PM-9PM	0	4	185	0	4	33
9PM-10PM	0	4	139	0	4	20
10PM-11PM	0	4	124	0	4	9
11PM-12AM	1	4	76	0	4	4
Total	30	85.5	6470	9	77.75	1184
Conflict/hr	0.351			0.116		
Conflict/1000 RT vehicles	4.637			7.601		