

Evaluation of J-turn Intersection Design Performance in Missouri Final Report

Praveen Edara, Ph.D., P.E., PTOE
Associate Professor
Department of Civil Engineering
University of Missouri-Columbia

Carlos Sun, Ph.D., P.E., JD
Associate Professor
Department of Civil Engineering
University of Missouri-Columbia

Sawyer Breslow
Graduate Research Assistant
Department of Civil Engineering
University of Missouri-Columbia

A Report on Research Sponsored by
Missouri Department of Transportation and
Mid-America Transportation Center
University of Nebraska–Lincoln

December 2013

Technical Report Documentation Page 1

1. Report No.:	2. Government Accession No.:	3. Recipient's Catalog No.:	
4. Title and Subtitle: Evaluation of J-turn Intersection Design Performance in Missouri		5. Report Date: December 2013	
		6. Performing Organization Code:	
7. Author(s) Edara, P., Sun, C., Breslow, S.		8. Performing Organization Report No.:	
9. Performing Organization Name and Address: Missouri Department of Transportation Organizational Results PO BOX 270, JEFFERSON CITY MO 65102		10. Work Unit No.:	
		11. Contract or Grant No.:	
12. Sponsoring Agency Name and Address: Missouri Department of Transportation Research, Development and Technology PO BOX 270, JEFFERSON CITY MO 65102		13. Type of Report and Period Covered: Final Report. July 2012 – December 2013	
		14. Sponsoring Agency Code:	
15. Supplementary Notes: The investigation was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.			
16. Abstract: Research shows that a high percentage of crashes that take place on high-speed rural expressways occur at intersections with minor roads. One low-cost alternative design for improving the safety of at-grade intersections on such expressways is the J-turn. In the last few years, the Missouri Department of Transportation has converted some two-way stop controlled (TWSC) intersections into J-turns. This study evaluated the effectiveness of the J-turn intersection design in Missouri utilizing field studies, a public survey, crash analysis, and traffic conflict analysis. The field studies collected detailed video data at a J-turn site and a control site. The crash analysis included a statistically rigorous empirical Bayes before-after safety evaluation of five J-turn sites in Missouri. The J-turn design resulted in a 34.8% reduction in crash frequency for all crashes and a 53.7% reduction in crash frequency for all injury and fatal crashes. Both reductions were significant at the 95% confidence level. Annual disabling injury crashes and minor injury crashes decreased by 86% and 50%, respectively. None of the five sites exhibited a fatal crash following J-turn implementation. This five-site analysis showed that annual right angle crashes decreased from 6.3 to 1.3, a 80% reduction. One of the most severe crash types, the left turn, right angle crash, was completely eliminated by the J-turn. One conflict measure, average time to collision, was found to be four times higher at the J-turn site compared to the control TWSC site among minor road turning vehicles, indicating greater safety at the J-turn site. The average wait time at the J-turn site was half the wait time at the control site, while the average travel time at the J-turn site was approximately one minute greater than at the TWSC site. When the public was surveyed regarding trip time perceptions resulting from the J-turn, the majority said there was no adverse effect. A high percentage of minor road left turning and through movements at the J-turn site merged into the travel lanes within the first 400 feet of the acceleration lane. Public opinion regarding the J-turn at US 63 and Deer Park Rd was mixed. Frequent concerns raised by respondents included difficulty merging following the U-turn, improper use of acceleration and deceleration lanes, insufficient U-turn radius to accommodate large vehicles, and driver confusion.			
17. Key Words: J-turns, RCUT, Superstreet, Unsignalized rural expressway design, Alternative intersection designs		18. Distribution Statement: No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161.	
19. Security Classification (of this report): Unclassified.	20. Security Classification (of this page): Unclassified.	21. No of Pages: 89	22. Price:

Form DOT F 1700.7 (06/98).

Technical Report Documentation Page

1. Report No. 25-1121-0003-179	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Evaluation of J-turn Intersection Design Performance in Missouri		5. Report Date December 2013	
		6. Performing Organization Code	
7. Author(s) Edara, P., Sun, C., Breslow, S.		8. Performing Organization Report No. 25-1121-0003-179	
9. Performing Organization Name and Address Mid-America Transportation Center 2200 Vine Street PO Box 830851 Lincoln, NE 68583-0851		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address Research and Innovative Technology Administration 1200 New Jersey Ave., SE Washington, D.C. 20590		13. Type of Report and Period Covered July 2012 – December 2013	
		14. Sponsoring Agency Code MATC TRB RiP No. 1250775	
15. Supplementary Notes			
16. Abstract Research shows that a high percentage of crashes that take place on high-speed rural expressways occur at intersections with minor roads. One low-cost alternative design for improving the safety of at-grade intersections on such expressways is the J-turn. In the last few years, the Missouri Department of Transportation has converted some two-way stop controlled (TWSC) intersections into J-turns. This study evaluated the effectiveness of the J-turn intersection design in Missouri utilizing field studies, a public survey, crash analysis, and traffic conflict analysis. The field studies collected detailed video data at a J-turn site and a control site. The crash analysis included a statistically rigorous empirical Bayes before-after safety evaluation of five J-turn sites in Missouri. The J-turn design resulted in a 34.8% reduction in crash frequency for all crashes and a 53.7% reduction in crash frequency for all injury and fatal crashes. Both reductions were significant at the 95% confidence level. Annual disabling injury crashes and minor injury crashes decreased by 86% and 50%, respectively. None of the five sites exhibited a fatal crash following J-turn implementation. This five-site analysis showed that annual right angle crashes decreased from 6.3 to 1.3, a 80% reduction. One of the most severe crash types, the left turn, right angle crash, was completely eliminated by the J-turn. One conflict measure, average time to collision, was found to be four times higher at the J-turn site compared to the control TWSC site among minor road turning vehicles, indicating greater safety at the J-turn site. The average wait time at the J-turn site was half the wait time at the control site, while the average travel time at the J-turn site was approximately one minute greater than at the TWSC site. When the public was surveyed regarding trip time perceptions resulting from the J-turn, the majority said there was no adverse effect. A high percentage of minor road left turning and through movements at the J-turn site merged into the travel lanes within the first 400 feet of the acceleration lane. Public opinion regarding the J-turn at US 63 and Deer Park Rd was mixed. Frequent concerns raised by respondents included difficulty merging following the U-turn, improper use of acceleration and deceleration lanes, insufficient U-turn radius to accommodate large vehicles, and driver confusion.			
17. Key Words J-turns, RCUT, Superstreet, Alternative intersection designs		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 89	22. Price

Table of Contents

Table of Contents	iii
List of Figures	iv
List of Tables	v
Acknowledgments	vi
Disclaimer	vii
Chapter 1 Introduction	1
Chapter 2 Literature Review	5
2.1. Operational Measures	5
2.2. Safety Measures	6
2.3. Design Guidance	8
2.4. Public Opinion Survey	9
Chapter 3 Methodology	11
3.1 Introduction	11
3.1.1 Field Studies	12
3.1.1.1 Operational Measures	23
3.1.1.2 Safety Measures	27
3.1.1.3 Public opinion survey of the J-turn on US 63	43
Chapter 4 Results	50
4.1 Introduction	50
4.1.1 Operational Measures	50
4.1.1.1 Travel Times	50
4.1.1.2 Wait times for minor road left turn vehicles	53
4.1.1.3 Acceleration Lane Use	55
4.1.1.4 Operational Measures Summary	59
4.1.2 Safety Measures	60
4.1.2.1 Time to collision	60
4.1.2.2 Gap acceptance	62
4.1.2.3 Crash Analysis	64
4.1.3 Survey Analysis	69
Chapter 5 Summary and Conclusions	75
References	78

List of Figures

Figure 1.1 Schematic of TWSC intersection	2
Figure 1.2 Schematic of J-turn intersection	3
Figure 3.1 Map showing locations of treatment and control sites. (Google 2013).....	13
Figure 3.2 Control site location, US 63 and E. Calvert Hill Rd/E. Hinton Rd.	14
Figure 3.3 US 63 and Deer Park Rd./Rte. AB before J-turn implementation.....	15
Figure 3.4 Entire J-turn segment at US 63 and Deer Park Rd./Rte. AB (Google 2013)	16
Figure 3.5 U-turn north of Deer Park Rd. (Google 2013)	17
Figure 3.6 US 63 and Deer Park Rd. J-turn intersection (Google 2013).....	17
Figure 3.7 U-turn south of Deer Park Rd. (Google 2013)	18
Figure 3.8 Location of cameras, radars, and delineators at the J-turn site.....	20
Figure 3.9 Location of cameras, radars, and delineators at the control site.....	22
Figure 3.10 Time stamp at which vehicle arrives on the minor road (tt_1)	24
Figure 3.11 Time stamp at which vehicle completes its movement (tt_2).....	25
Figure 3.12 Merging vehicle from the acceleration lane (camera 1).....	28
Figure 3.13 Trailing vehicle on major road approaching the intersection (camera 2).....	29
Figure 3.14 Time of minor road vehicle's 1 st merge	31
Figure 3.15 Time of major road vehicle's arrival at minor road vehicle's 1 st merge point	31
Figure 3.16 Time of minor road vehicle's 2 nd merge.....	32
Figure 3.17 Time of major road vehicle's arrival at minor road vehicle's 2 nd merge point	33
Figure 4.1 Cumulative distribution of travel times of major road left turns	51
Figure 4.2 Cumulative distribution of travel times of minor road left turns.....	53
Figure 4.3 Cumulative distribution of wait times for minor road left turns	54
Figure 4.4 Right turn acceleration lane usage.....	56
Figure 4.5 U-turn acceleration lane usage	57
Figure 4.6 Measurements of lengths of acceleration and deceleration lanes at the J-turn site on US 63 and Deer Park Rd.	58
Figure 4.7 Time to collision for J-turn and TWSC sites on US 63.....	61
Figure 4.8 Cumulative distribution of accepted time gaps for minor road left turns.....	63
Figure 4.9 Annual crash frequency by severity before and after J-turn (sum of all 9 sites).....	65
Figure 4.10 Annual crash frequency by type before and after J-turn (sum of all 9 sites).....	66

List of Tables

Table 2.1 Summary of sample questions and responses from Hummer et al. (2010)	10
Table 3.1 Data collection information	19
Table 3.2 Characteristics of the J-turn sites included in the safety evaluation	35
Table 3.3 SPF Coefficients for Three- and Four-Leg Intersections with Minor-Road Stop Control for Total and Fatal-and-Injury Crashes (HSM, 2010).....	40
Table 4.1 Travel time statistics for major road left turns	51
Table 4.2 Travel time statistics for minor road left turns	53
Table 4.3 Descriptive statistics of TTC measure	62
Table 4.4 Empirical Bayes-based before-after comparison of crashes	67
Table 4.5 Empirical Bayes-based before-after comparison of injury crashes	68
Table 4.6 Demographic information of survey respondents.....	70
Table 4.7 Responses to survey questions with Yes/No choices	71
Table 4.8 Responses to survey questions with five choices	72
Table 4.9 Common issues raised by survey respondents.....	73

Acknowledgments

The authors are thankful for the assistance provided by MoDOT staff John Miller, Mike Curtit, Jon Nelson, Nicole Hood, Trent Brooks, and Sally Oxenhandler for coordinating field data collection sites, providing design plans, and survey outreach. Additional thanks to Joseph Rickman and Leo Cologna for providing information on J-turns in the southwest district. The authors wish to acknowledge the contributions of Henry Brown, Kyoungmin Nam, Kevin Koines, Zhongyuan Zhu, Igor Claus, and Andrew Robertson, who helped with data collection, as well as Kevin Koines, Tim Cope, Boris Claros, and Zach Osman, who assisted with the data processing and analysis.

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. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Abstract

Research shows that a high percentage of crashes that take place on high-speed rural expressways occur at intersections with minor roads. One low-cost alternative design for improving the safety of at-grade intersections on such expressways is the J-turn. In the last few years, the Missouri Department of Transportation has converted some two-way stop controlled (TWSC) intersections into J-turns. This study evaluated the effectiveness of the J-turn intersection design in Missouri utilizing field studies, a public survey, crash analysis, and traffic conflict analysis. The field studies collected detailed video data at a J-turn site and a control site. The crash analysis included a statistically rigorous empirical Bayes before-after safety evaluation of five J-turn sites in Missouri. The J-turn design resulted in a 34.8% reduction in crash frequency for all crashes and a 53.7% reduction in crash frequency for all injury and fatal crashes. Both reductions were significant at the 95% confidence level. Annual disabling injury crashes and minor injury crashes decreased by 86% and 50%, respectively. None of the five sites exhibited a fatal crash following J-turn implementation. This five-site analysis showed that annual right angle crashes decreased from 6.3 to 1.3, a 80% reduction. One of the most severe crash types, the left turn, right angle crash, was completely eliminated by the J-turn. One conflict measure, average time to collision, was found to be four times higher at the J-turn site compared to the control TWSC site among minor road turning vehicles, indicating greater safety at the J-turn site. The average wait time at the J-turn site was half the wait time at the control site, while the average travel time at the J-turn site was approximately one minute greater than at the TWSC site. When the public was surveyed regarding trip time perceptions resulting from the J-turn, the majority said there was no adverse effect. A high percentage of minor road left turning and through movements at the J-turn site merged into the travel lanes within the first 400 feet of the acceleration lane. Public opinion regarding the J-turn at US 63 and Deer Park Rd was mixed.

Frequent concerns raised by respondents included difficulty merging following the U-turn, improper use of acceleration and deceleration lanes, insufficient U-turn radius to accommodate large vehicles, and driver confusion.

Chapter 1 Introduction

A large number of crashes occurring on high-speed rural expressways occur at their intersections with minor roads (Maze et al. 2010). The majority of crashes occurring at intersections are right-angle crashes resulting from turning movements. For example, Maze et al. (2010) reported the proportion of right-angle crashes at rural high-speed expressways in Minnesota (57%), Utah (69%), and Iowa (52%). Clearly, the issue of right-angle crashes is of concern to Midwestern states, since this crash type exhibits an elevated percentage of fatal and serious injuries, while rural expressways are a major component of the roadway network in these states. As a result, state departments of transportation (DOTs) are looking for ways to improve safety at at-grade intersections on rural expressway corridors. The NCHRP 650 report (Maze et al. 2010) presents three treatment strategies for DOTs to consider toward eliminating or reducing right-angle crashes on rural expressways. These strategies include: 1) the use of alternative designs, such as J-turns and offset T-intersections, that have fewer conflict points and less severe conflicts as a replacement for conventional two-way stop control (TWSC) intersections, 2) improving intersection sight distance and advice on gap selection for minor road traffic, and 3) cautioning the traffic on both minor and major roads of the upcoming intersection.

At a TWSC intersection on a four-lane divided highway, vehicles accessing the major highway from the minor road can make a left turn or through movement at the intersection by crossing the major road movements. Highways with high volumes or high speeds may make these movements unsafe to execute, and cause long delays. On the other hand, in a J-turn design, vehicles accessing the major highway from the minor road make a right turning movement and then use a U-turn at a downstream location. The major road vehicles accessing the minor road via a left turning movement may or may not have to use the U-turn for their movements. One

variation of the J-turn design allows for major road turning movements to occur at the intersection, but still requires the minor road movements to use the U-turn. An example of a TWSC and a J-turn intersection are shown in figures 1.1 and 1.2, respectively. Figure 1.1 represents the left-turning movement from the minor road at the TWSC intersection. Figure 1.2 represents the left-turning movement from the minor road at the J-turn intersection.

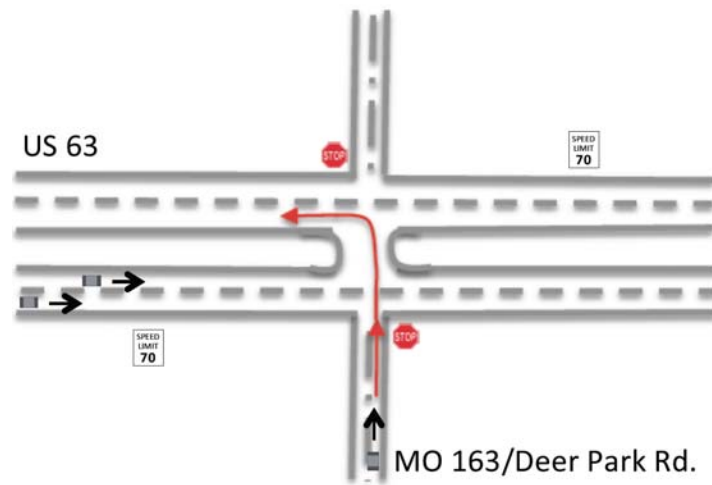


Figure 1.1 Schematic of TWSC intersection

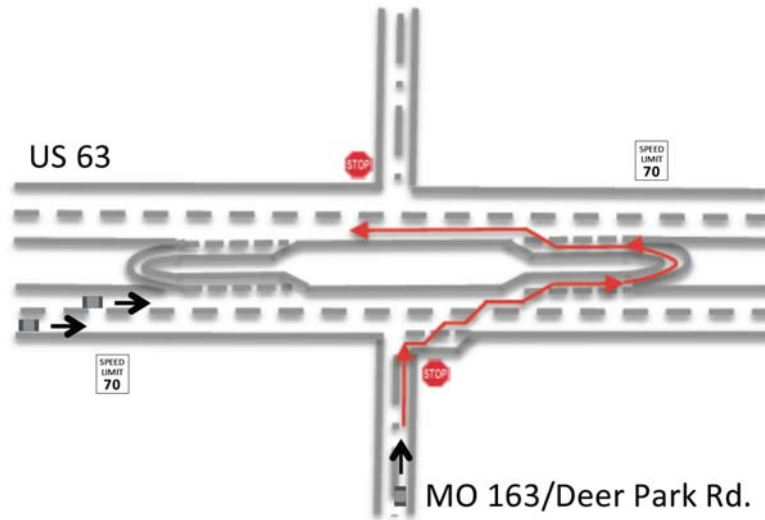


Figure 1.2 Schematic of J-turn intersection

The safety of the J-turn design stems from the elimination of severe high-risk conflict points. A conflict point occurs whenever there is the possibility for two vehicles to occupy the same position. According to NCHRP 650 (Maze et al. 2010), a TWSC intersection has 42 conflict points, while a J-turn intersection has 24 conflict points. Not only does the J-turn have fewer total conflict points, but it eliminates the most severe forms of conflict, i.e., crossing conflicts that result in right-angle crashes.

In the last few years, the Missouri Department of Transportation (MoDOT) has converted some TWSC intersections on high-speed, four-lane divided highways into J-turns. Despite their increased use in Missouri, the safety and mobility effects of J-turns have not been investigated and documented. This research project attempted to address the effectiveness of the J-turn design in Missouri. Specifically, the following objectives were accomplished in this project:

1) *Field studies were conducted to collect video data of traffic movements at a J-turn site, and safety and mobility performance measures were analyzed.* The analysis focused on several safety and operational performance measures, including conflicts, time to collision, travel times,

and wait times. The J-turn study site was located on a four-lane divided highway on US 63 at Deer Park Road, nine miles south of Columbia, Missouri. The annual average daily traffic at this location was 27,321 vehicles. The J-turn was opened to traffic in October, 2012. Prior to that time, the intersection operated as a TWSC intersection.

2) *A traveler survey obtained the perceptions of travelers traversing the J-turn on US 63 and Deer Park Road.* The survey focused on obtaining qualitative information on both mobility and safety.

3) *Crash analysis was conducted using all J-turn sites in Missouri for which sufficient after-installation period crash data was available.* Four additional J-turn sites were included in the crash analysis. Two crash analysis methods were utilized. First, a simple before-and-after comparison of crash data based on severity was conducted. The second approach used the empirical Bayes method to account for regression to the mean. The empirical Bayes approach is favored by the Highway Safety Manual (AASHTO 2010). A crash modification factor value was also computed for a J-turn intersection on a four-lane divided high-speed rural highway.

This report presents the results of the performance measurement of J-turns using video data, a traveler survey, and crash analysis. The report is organized as follows:

A review of relevant literature is presented in chapter 2. The study methodology, including field studies, survey creation, and crash analysis, are discussed in chapter 3. The results are presented and discussed in chapter 4, and conclusions are drawn in chapter 5.

Chapter 2 Literature Review

Existing literature pertaining to the design and evaluation of J-turn intersections was reviewed. The review focused on four areas: 1) operational performance measures, 2) safety performance measures, 3) design guidance, and 4) a public opinion survey.

2.1 Operational Measures

Inman and Haas (2012) conducted an evaluation of a restricted crossing U-turn (RCUT) design in Maryland; the RCUT and Superstreet designs are alternative names for the J-turn design. The authors conducted field observations of an RCUT intersection on a rural, four-lane divided highway. Both mobility and safety performance measures were extracted from the field data. Mobility measures included travel times and acceleration lane usage. Safety measures included conflict analysis and weaving behavior. Since field data were not available for the pre-RCUT period, a control site along the same corridor was used for comparison. A control site was also utilized in the present study. Evaluated operational measures consisted of travel times and acceleration lane usage. Average travel times for the conventional intersection were 19 seconds and 28 seconds for through and left-turn movements from the minor road, respectively. The average travel times for the RCUT intersection were 83 seconds and 80 seconds for through and left-turning movements, respectively. Thus, the additional travel time at the RCUT intersection was approximately one minute higher than at the control intersection. This increase in travel time was due to the additional 4,000 ft. traversed to complete the movement. The travel times included wait times for gaps in the through traffic. There was also little to no wait time for a gap in traffic, creating a reduction in wait time in comparison to the TWSC without an acceleration lane (Inman and Haas 2012).

The extent of the utilization of the acceleration lanes by the right turning vehicles from minor road and the U-turn vehicles were also extracted from field data. The intent of studying acceleration lane usage was to justify its necessity for future designs. If traffic volumes on the major road are low, minor road vehicles can merge directly into the travel lanes, thus, not necessitating an acceleration lane. To determine acceleration lane usage, the acceleration lane was divided into five merging zones for vehicles making a right turn from the minor road, and three merging zones for vehicles accessing the major road from the U-turn acceleration lane (Inman and Haas 2012). The analysis found that acceleration lanes were being used by a majority of vehicles; thus, both the U-turn and right turn acceleration lanes were required for future RCUT designs in Maryland.

A study by Hummer et al. (2010) evaluated benefits of the Superstreet design in North Carolina. The operational analysis was conducted for signalized Superstreet designs only, while the statistical analysis of crashes was performed for unsignalized Superstreet designs. The analysis focused on measuring travel times using GPS units installed in probe vehicles. The probe vehicles were driven several times during a 90-minute period. This procedure differed from the Inman and Haas (2012) study, which derived travel times by processing the trajectories of vehicles recorded on video. The sample size of travel time measurements obtained via video processing was higher than that obtained by the probe vehicle measurement technique. However, probe vehicles were intended only to provide average travel times, while the processing of trajectories from video data is time consuming.

2.2 Safety Measures

Two types of safety performance measures were utilized in previous evaluations of the J-turn design. One set of measures involved conflict analysis, while the other set involved the

empirical analysis of crashes before and after J-turn installation. Inman and Haas (2012) reported using lag as a conflict measure in lieu of the time to collision measure. Lag is the time difference between the arrival of a merging vehicle and the arrival of the following vehicle on the mainline at the same crossing point. If the following vehicle does not change speed, i.e., neither accelerates nor decelerates, lag is the same as the time to collision. Time to collision (TTC) is another conflict measure used to study intersection safety (MacCarley 2011). TTC is defined as the time it takes for a collision between two vehicles to occur if the vehicles do not take an evasive action. The equation for computing TTC was presented in MacCarley (2011). Higher TTC values indicate safer conditions.

Crash analysis was reported in Hummer et al. (2010) and Inman and Haas (2012). Both studies conducted two levels of crash analysis—a simple before-and-after comparison of crash frequency for different severities and a more thorough empirical Bayes (EB) method recommended by the Highway Safety Manual (HSM 2010). The EB method for assessing the safety effectiveness of a treatment is documented in chapter nine of the HSM. Chapter 11 of the HSM discusses the predictive method for rural multilane highways. The crash modification factors applied to the predicted crash frequency are discussed in chapter 14 of the HSM. The EB method, prediction models, and associated crash modification factors and calibration factors are discussed in section 3 of the current report.

Crash analysis using the EB method revealed a 44% reduction in total crash frequency for J-turns in Maryland (Inman and Haas 2012) and a 27.2% reduction in North Carolina. In terms of reduction in crash severity, Maryland J-turns witnessed 70% and 42% reductions in fatalities and injury crashes, respectively. In North Carolina, J-turns resulted in a 51% reduction in fatal and injury crashes.

2.3 Design Guidance

Existing guidance on the J-turn design was reviewed. The AASHTO Green Book (AASHTO 2011) does not contain guidance specific to the J-turn intersection, but provides general design guidance that may apply to the J-turn. Chapter 9 of the Green Book presents design guidance for intersections. Auxiliary lane guidelines for intersections can be used as a starting point to develop design standards for acceleration and deceleration lanes in a J-turn intersection design. The recommended minimum lane width for auxiliary lanes is 10 ft., but it is desirable to have the same width as the adjacent through lanes. A shoulder next to the auxiliary lane must have a minimum width of 6 ft., and it is desirable to keep it the same width as the shoulder next to the through lanes. Other design factors for auxiliary lanes are subject to change based on varying traffic conditions pertaining to speed, volumes, truck percentage, capacity, highway classification, right-of-way availability, maintenance, and frequency of intersections (AASHTO 2011).

The use of deceleration lanes could be considered when designing J-turn intersections. The design requirements for deceleration lanes at intersections are also provided in chapter 9 of the Green Book. These requirements may be considered as the minimum requirements for deceleration lanes at a J-turn. The recommended design requirements for the deceleration lane are shown in Table 9-22 on page 9-126 of the Green Book (AASHTO 2011). For example, a deceleration lane length of 820 ft. is recommended for a design speed of 70 mph (AASHTO 2011).

The Green Book provides additional considerations for determining deceleration lane lengths based on expected maximum queues and storage, number of turning vehicles, and opposing traffic volume. Guidance on different taper designs and lengths is also provided in the

Green Book, as is guidance on the location and design of U-turn median openings, in section 9.9.4; additionally, Table 9-30 on page 9-166 discusses recommended median widths based on the design vehicle. The suggested distance for the U-turn is 660 ft. from the main intersection, and does not vary with the speed limit (AASHTO 2011).

The Alternative Intersections and Interchanges Informational Report (FHWA 2009) provides additional information on the crossover spacing for J-turns. It reports that the minimum spacing between the main intersection and crossover in Michigan is 660 ± 100 ft., similar to the AASHTO guidance for median U-turns. In North Carolina the crossover spacing value is 800 ft.

Guidance on acceleration lanes is available in chapter 10, “Interchanges,” of the Green Book. Although J-turns are typically built on multilane highways, not freeways, the only guidance available for acceleration lanes in the Green Book is for those provided at interchanges. Table 10-3 on page 10-110 of the Green Book shows acceleration lane lengths for various design speeds. For example, for vehicles to accelerate from stop condition to a design speed of 75 mph, the necessary length of the acceleration lane is 1,620 ft. (AASHTO 2011).

2.4 Public Opinion Survey

The opinions of travelers who navigate a J-turn are essential toward understanding how the design is being used, and to reveal any perceived safety or operational concerns. Despite the importance of J-turns, only a few studies have conducted surveys to obtain the opinions of travelers. Hummer et al. (2010) was one of the few studies that conducted a survey of residents living near a J-turn site who drove the J-turn on a regular basis. A household mail survey focused on navigation, travel time, and safety measures. A summary of the main findings for unsignalized superstreet intersections is presented in table 2.1. Similar questions and concepts were applied to the survey used for the Missouri J-turn on US 63. As shown in table 2.1, drivers

in Hummer et al. were divided in terms of the question regarding navigation, but drivers felt safer with the J-turn by a margin of over two-to-one. Over half of the respondents did not sense a change in travel time, but a third did believe the travel time was longer.

Table 2.1 Summary of sample questions and responses from Hummer et al. (2010)

Question	Response	Percentage
How does navigation through the superstreet compare to a typical intersection?	Easier/less confusing	38%
	Same	21%
	More difficult/more confusing	32%
How do you, personally, feel the superstreet has affected your ability to safely navigate the roadway compared to the previous roadway design?	Positively	56%
	Same	17%
	Negatively	23%
What differences, if any, have you, personally, experienced in travel time since the opening of superstreet?	Less travel time	10%
	No change	52%
	More travel time	33%
What differences, if any, have you, personally, noticed in the number of stopped vehicles waiting to make a safe maneuver since the opening of the superstreet?	Fewer stopped vehicles	38%
	No change	26%
	More stopped vehicles	28%

Chapter 3 Methodology

3.1 Introduction

This section discusses the field study procedures and computation of performance measures for the current study. Three main procedures utilized in this project included: 1) original data collection through field studies to measure performance, 2) before-after analysis of crash data at multiple J-turn sites in Missouri, and 3) a survey of motorists. Field studies were conducted at a J-turn site on US 63 and Deer Park Rd, and at a control site with a two-way stop control, also on US 63 at Calvert Hill Rd. These two locations were recommended by the Missouri DOT technical review panel for the project, since both locations shared similar operational and geometric characteristics. Several safety and operational performance measures were computed from the field data. The set of measures included: time to collision (TTC), time to intersection (TTI), gap acceptance (GA), travel times (TT), wait times (WT), and acceleration lane usage. The conflict measures, TTC, TTI, and GA, are a unique contribution of this study, as they have not been used in the evaluation of J-turns in previous research. These measures expanded upon the use of the lag conflict measure in Inman and Haas (2012). The field studies were carefully designed to ensure that data required for each measure were collected. For example, the number of video cameras, speed guns, their positioning, and orientations were all carefully determined. The details of the field studies are presented in section 3.1.1.

The safety effects of J-turns were also assessed using crash data. Five J-turn sites in Missouri were included in the analysis. The before-after analysis of crashes using the empirical Bayes method is discussed in section 3.1.1.2.4.

A public opinion survey was conducted to obtain the perceptions of motorists who have driven the J-turn site on US 63 and Deer Park Rd. The survey was carefully designed to obtain

information on driving behavior, driver confusion, and driver perceptions of operational and safety effects of the J-turn. The survey design, deployment, and analysis of responses are presented in section 3.1.1.3.

3.1.1 Field Studies

The project timeline did not allow for the collection of data from the period preceding the installation of the J-turn at the US 63 and Deer Park Rd. intersection. Thus, a control site on the same US 63 highway corridor was selected for comparison. This control site approach is similar to that of previous studies, including Inman and Haas (2012). The control site was the intersection of Calvert Hill Rd/Hinton Rd and US 63, which operated as a traditional two-way stop control (TWSC) intersection. This site, recommended by MoDOT, was chosen due to its similarity to the treatment site in terms of geometry, access to services, and driving population. Both sites occurred on a four lane divided highway with a speed limit of 70 mph. The treatment site, US 63 at Deer Park Rd, also operated as a two-way stop control prior to the J-turn treatment. The AADT for the J-turn site was 27,321, and 17,217 for the control site. A map of the treatment and control intersections is shown in figure 3.1. In the figure, location A is the J-turn site, and location B is the TWSC control site. Between these intersections lies the urban city of Columbia, Missouri. Figure 3.2 displays the TWSC intersection that was used as the control site. The green arrows show the left turn paths of the minor road to the major highway. Figure 3.3 displays the TWSC intersection at the treatment site before J-turn implementation. The figure also shows the construction of the new southbound US 63 lanes in the middle, which were unopened to traffic.

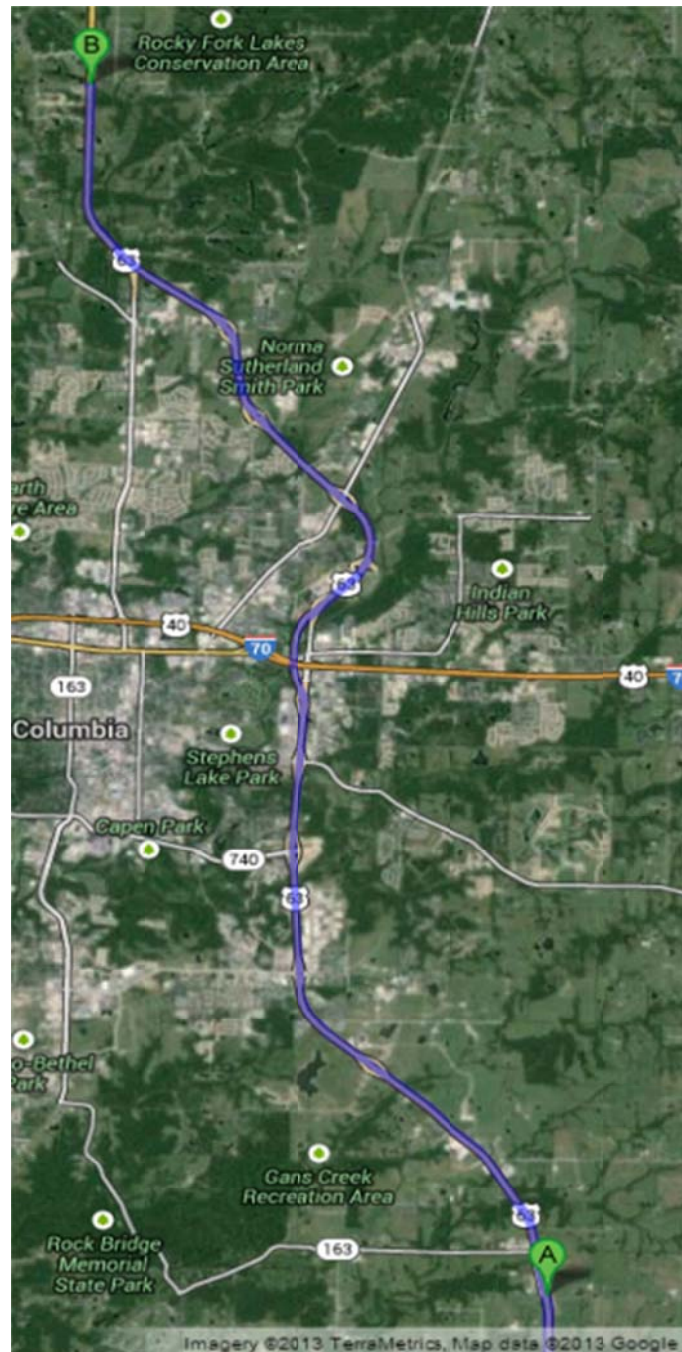


Figure 3.1 Map showing locations of treatment and control sites (Google 2013)

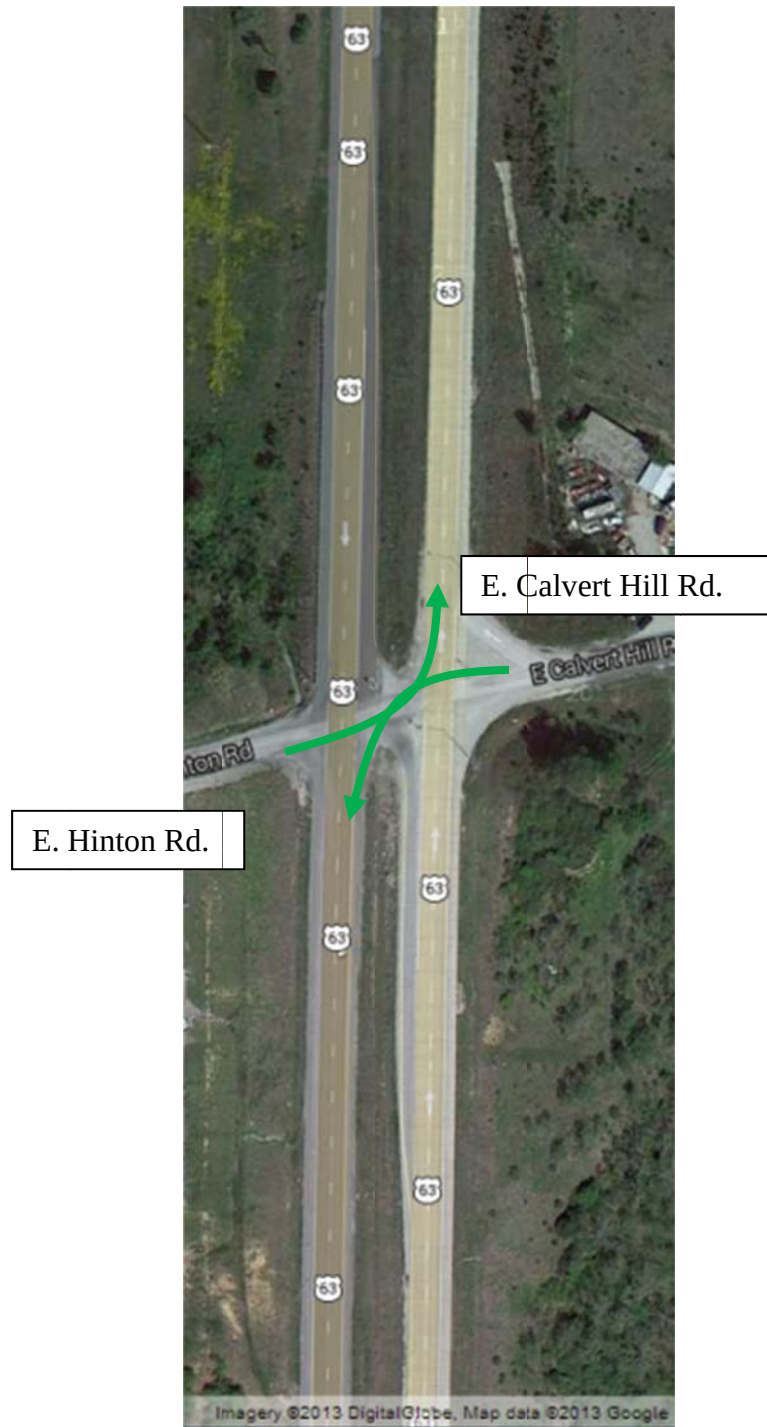


Figure 3.2 Control site location, US 63 and E. Calvert Hill Rd/E. Hinton Rd
(Google 2013)

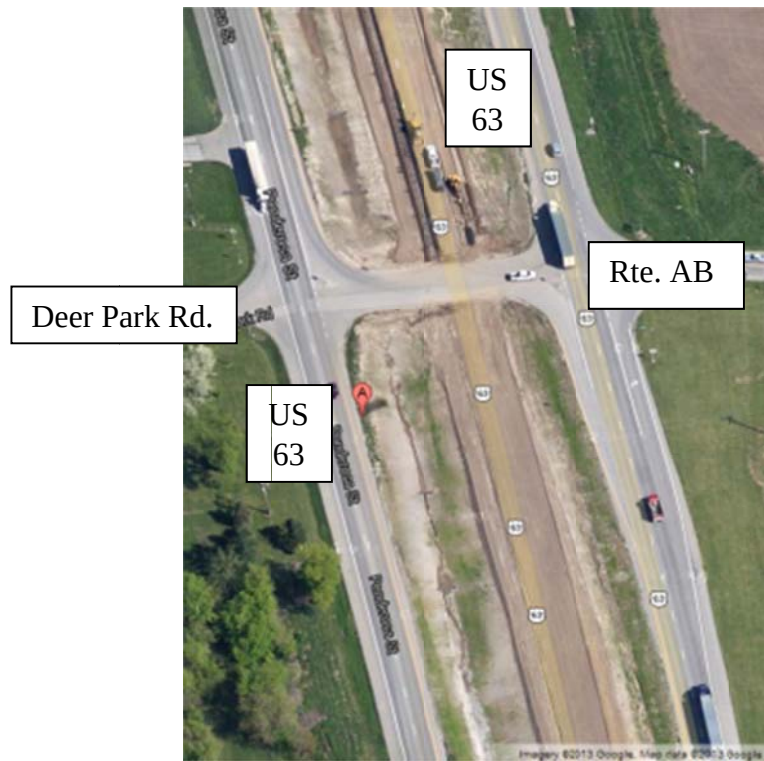


Figure 3.3 US 63 and Deer Park Rd./Rte. AB before J-turn implementation
(Google 2013)

Figure 3.4 shows the overall segment of the J-turn, and figures 3.5-3.7 show the individual components. Figure 3.4 shows the footprint of the entire J-turn intersection covering both U-turns and the main intersection; in the figure, point A is the location of the U-turn south of Deer Park Rd, and point B is the location of the U-turn north of Deer Park Rd. The green arrows show the left turn paths from the minor road to the major highway via a U-turn in both directions. Figure 3.5 is a close up view of the U-turn at point B; the figure shows a deceleration lane before the U-turn and an acceleration lane after the U-turn. Figure 3.6 is the main intersection at Deer Park Rd after J-turn implementation; the figure shows that no median crossovers are permitted. Figure 3.7 is a close up of the U-turn at point A; the figure is similar to figure 3.5, and shows both deceleration and acceleration lanes.



Figure 3.4 Entire J-turn segment at US 63 and Deer Park Rd/Rte. AB (Google 2013)



Figure 3.5 U-turn north of Deer Park Rd (Google 2013)



Figure 3.6 US 63 and Deer Park Rd J-turn intersection (Google 2013)



Figure 3.7 U-turn south of Deer Park Rd. (Google 2013)

The J-turn intersection was opened to traffic in October of 2012. Video data was collected at the treatment and control sites in November, 2012 and May, 2013. The duration of video data used for each performance measure is shown in table 3.1; as illustrated in the table, the critical peak hour time periods were collected.

Table 3.1 Data collection information

Measure	Location	Time Collected	Date Collected
Travel time	J-turn and Control	AM peak (7 am-9 am), PM peak (4 pm-6 pm)	November 2012
Wait time	J-turn and Control	AM peak (7 am-9 am)	November 2012
Acceleration lane usage	J-turn	AM peak (7 am-9 am), PM peak (4 pm-6 pm)	November 2012, May 2013
TTC	J-turn and Control	AM peak (7 am-9 am)	May 2013
Gap Acceptance	J-turn and Control	AM peak (7 am-9 am), PM peak (5 pm-7 pm)	November 2012, May 2013

The locations of cameras, speed radars, and delineators at the J-turn site are shown in figure 3.8. The green rectangles in the figure represent the cameras that collected data relevant to TTC and acceleration lane use. The green triangles next to the green rectangles represent the radar guns used to collect speeds for TTC for Deer Park Rd. The yellow rectangles represent cameras that were used to collect travel times from Deer Park Rd. The blue rectangles represent cameras that were used to collect TTC for Rte. AB. The blue triangles represent the radar guns used to collect speeds for the TTC measures from Rte. AB. The orange diamonds represent the delineators used to mark the acceleration lanes.

For the J-turn site, the following equipment was utilized. To collect TTC data, three cameras and two radars were used for both directions. To collect travel time data, two cameras were used to capture the origin and destination of each turning maneuver. To collect acceleration lane data, one camera was used for each direction.

For the control site, the following equipment was used. To collect travel times, one camera was used. To collect TTC data, one camera and one radar gun were used in each direction. Wait time data for both sites were extrapolated from the travel time video data.

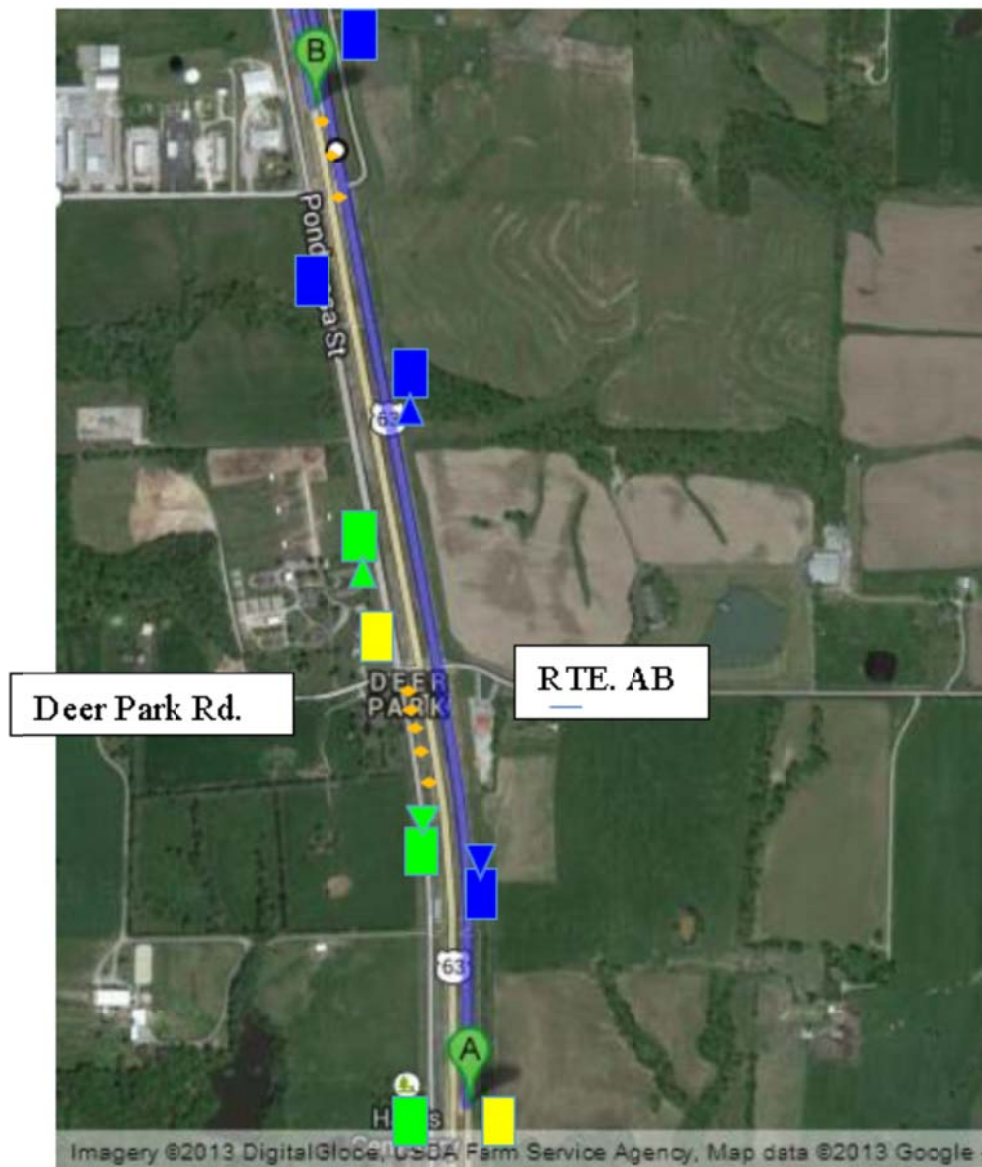


Figure 3.8 Location of cameras, radars, and delineators at the J-turn site

Figure 3.9 (next page) shows the locations of cameras and radars at the control site. The red rectangle represents the camera that was used to capture travel times and wait times. The yellow rectangles and triangles represent the cameras and radars that were used to capture data needed for the TTC measure.



Figure 3.9 Location of cameras, radars, and delineators at the control site

3.1.1.1 Operational Measures

Data was collected for three operational measures: travel times, wait times, and acceleration lane use. The computations of these measures from video data are discussed next.

3.1.1.1.1 Travel Times (TT)

The travel times of vehicles turning left from the major road to the minor road were measured for the J-turn and TWSC. For TWSC, travel time included the wait time at the intersection and the time taken to cross two lanes on the mainline. For the J-turn, travel time included the time taken to traverse the distance between the intersection and the U-turn, and the time taken to traverse the distance between the U-turn and the minor road. Due to the additional distance traversed in the J-turn, travel times were expected to be greater than at the TWSC.

Travel times were also measured for vehicles turning left from the minor road to the major road at both the J-turn and TWSC sites. The green arrows shown in figure 3.2 and 3.4 clearly contrast the left turn paths taken by the minor to major road left turn vehicles in the J-turn versus the TWSC.

A video camera was set up at the control site intersection, as shown in figure 3.9. The camera is represented by a red rectangle. The view captured all movements in and out of the intersection, and captured the variables needed to calculate TT. The following equation was used to calculate the TT measure:

$$TT = tt_2 - tt_1 \quad (3.1)$$

where,

tt_1 - time at which the vehicle arrives at the intersection;

tt_2 – time at which the vehicle completes its turning movement.

This equation was used to collect travel times for left turn movements from the minor road to the major road and from the major road to the minor road. In figure 3.10, the white van shown sitting at the stop sign is attempting to make a left turning maneuver from the minor road to the major road. When the vehicle arrived at the stop sign, the time stamp, shown as 8:04:04, was recorded as the value of tt_1 . Figure 3.11 displays the screenshot at the point at which the white van has completed its left turning maneuver. The time stamp shown as 8:04:18 was recorded as the value of tt_2 . Using equation 3.1, the value for travel time can be computed: $tt_2 - tt_1 = (8:04:18) - (8:04:04) = 14$ seconds.



Figure 3.10 Time stamp at which vehicle arrives on the minor road (tt_1)



Figure 3.11 Time stamp at which vehicle completes its movement (tt_2)

Collecting video data at the J-turn location required a larger viewing area and multiple camera locations to obtain the necessary timestamps tt_1 and tt_2 . Travel times were collected for the left turn movements from the major and minor roads. The travel time values collected for both maneuvers differed from the control due to the geometry of the alternative J-turn design. For the left turning maneuver from the minor road to the major road, vehicles must turn right then access a U-turn downstream to complete the movement. Similarly, the left turning movement from the major road must continue past the intersection and utilize the downstream U-turn, travel in the opposite direction, then turn right into the minor road.

3.1.1.1.2 Wait Times (WT)

Wait times (WT) represent the amount of time a vehicle must wait before initiating a turning movement. The J-turn site had an acceleration lane for minor road turning movements, thus reducing vehicle wait time. Wait times were obtained for the left turning movements from

the minor road. Unlike the analysis for the travel time measure, the wait time measure required only one camera recording the minor road movements. The equation used to calculate wait time was as follows:

$$WT = t_1 - tt_1 \quad (3.2)$$

where,

t_1 = time at which vehicle departs the stop bar on the minor road to complete the turning maneuver;

tt_1 = time at which vehicle arrives at the intersection.

3.1.1.1.3 Acceleration Lane Use

Not all J-turn designs implemented in Missouri had acceleration lanes for minor road turning vehicles or vehicles merging from the U-turn onto the major road. The J-turn design on US 63 and Deer Park Rd had acceleration lanes for both movements—turning right onto the minor road and completing the U-turn. Thus, this site provided a unique opportunity to analyze the use of acceleration lanes. The proportion of vehicles merging at different lengths of the acceleration lane was extracted using strategically placed video cameras and delineators. The video data were used to extract two variables: a vehicle's final destination and the point at which the vehicle merged into the right lane on the major road from the acceleration lane.

The acceleration lane that extended from the minor road (Deer Park Rd) intersection on southbound US 63 was 1,000 ft. long from the intersection to the taper. To determine where a vehicle was merging, the acceleration lane was divided into five merging zones, 200 ft. long each, using delineators. The acceleration lane that extended from the U-turn on northbound US

63 was approximately 750 ft. long from the U-turn to the beginning of the taper. The limited shoulder width next to the acceleration lane did not allow for the safe deployment of delineators for this acceleration lane. Thus, existing traffic signs, pavement markings, and reflectors were used to define three merging zones. The first zone included the first 120 ft. from the U-turn; the second zone included the distance between 120 ft. and 480 ft.; and the third zone included the area between 480 ft. to the beginning of taper.

3.1.1.2 Safety Measures

Video monitoring was also used to obtain safety measures. The methods used to extract three safety measures—time to collision at the J-turn, time to intersection at the TWSC, and accepted gaps—are presented next.

3.1.1.2.1 Time to Collision (TTC)

Time to collision, or, TTC, is a surrogate safety measure that was developed and used originally by Hayward (Hayward 1971; Minderhoud and Bovy 2001) to evaluate the interactions between vehicles. The equation developed by Hayward was developed to relate the difference in speed between nearby vehicles with collision risk (MacCarley 2011):

$$TTC = (x_{i-1} - x_i - l_{i-1}) / (v_i - v_{i-1}), v_i > v_{i-1} \quad (3.3)$$

where,

x_{i-1} = the position of the lead or merging vehicle;

x_i = the position of the trailing or mainline vehicle;

l_{i-1} = length of the trailing vehicle (20 ft. was used as the average vehicle length);

v_{i-1} = velocity of the lead or merging vehicle;

v_i = velocity of the trailing or mainline vehicle.

One camera was used to record the speed displayed on the radar gun and the corresponding time stamp for the leading vehicle merging from the acceleration lane into the right lane of the major road. Figure 3.12 shows an example of a merging vehicle whose speed (v_i), position (x_i), and time stamp could all be obtained from the view. A second camera was deployed upstream of the intersection to detect the speed and position of mainline vehicles approaching the intersection. A view from this camera is shown in figure 3.13. Vehicle speed (v_{i-1}), position (x_{i-1}), and time stamp can be obtained for the trailing vehicle from this camera footage.



Figure 3.12 Merging vehicle from the acceleration lane (camera 1)



Figure 3.13 Trailing vehicle on major road approaching the intersection (camera 2)

A third camera was deployed to record the type of movement made from the minor road. This camera footage was used to separate minor road vehicles into right turns, left turns, and through movements. If a minor road vehicle continued to travel on the major road past the U-turn, the movement was counted as a right turn. It was important to identify the minor road movements to allow for a fair comparison with the control TWSC site. This is because a minor road right-turning vehicle has no intention of merging quickly to make the U-turn.

3.1.1.2.3 Gap Acceptance

Gap acceptance is a conflict measure defined as the gap accepted by a merging vehicle. For through and left turn movements originating from the minor road, the J-turn replaced the crossing conflicts across the major road by merging conflicts. The crossing gap at the control site involved a vehicle crossing both lanes of the major roadway in the same direction at one time, while the merging conflict occurred sequentially as a vehicle traveled from the minor road to the major right lane, from the major right lane to the left lane, and finally to the U-turn. Even though merging and crossing gaps are different types of gaps, they both reflect the willingness of a driver to make a maneuver in light of a potential conflict.

The accepted gaps were measured by processing video data for all vehicles merging from the acceleration lane into the right through lane and from the right through lane to the left through lane. A higher accepted gap enhances the safety of a merging maneuver safer. The accepted gaps were analyzed for both the AM and PM peak periods (see table 3.1).

The U-turn movements from Deer Park Rd to southbound US 63 and from Rte. AB to northbound US 63 were investigated. The steps involved in determining the accepted gap for a vehicle moving from Deer Park Rd to US 63 are shown in figures 3.14-3.17. The through and left-turning vehicles from the minor road that made two lane changes (from the acceleration lane to the right lane and from the right lane to the left lane) and accessed the deceleration lane to utilize the U-turn were of interest. Figure 3.14 shows a minor road vehicle merging from the acceleration lane into the right through lane. The time at which the next major road vehicle arrived at the merge point in the right through lane is shown in figure 3.15. The gap acceptance for the first merge was calculated as:

$$\text{Gap Acceptance}_1 = t_2 - t_1, (\text{sec}) \quad (3.5)$$

where,

t_1 = time at which the minor road vehicle merged from acceleration lane to the right through lane;

t_2 = time at which the next mainline vehicle in the right through arrived at the merge point.

For example, the gap acceptance of the merging vehicle shown in figures 3.14 and 3.15 was measured using equation 3.5 as $\text{Gap Acceptance}_1 = t_2 - t_1 = (7:21:56) - (7:21:53) = 3$ seconds.



Figure 3.14 Time of minor road vehicle's 1st merge



Figure 3.15 Time of major road vehicle's arrival at minor road vehicle's 1st merge point

The gap acceptance for the second merge, from the right through lane to the left through lane, was measured in a similar way as:

$$\text{Gap Acceptance}_2 = t_4 - t_3, (\text{sec}) \quad (3.6)$$

where,

t_3 = time at which the minor road vehicle merged from the right through lane to the left through lane;

t_4 = time at which the next mainline vehicle in the left through lane arrived at the merge point.

For example, the second merge for the vehicle previously described in figure 3.14 is shown in figure 3.16. The gap acceptance is calculated using the time stamps recorded in figures 3.16 and 3.17 using equation 3.6 as $Gap\ Acceptance_2 = t_2 - t_1 = (7:21:59) - (7:21:55) = 4$ seconds.



Figure 3.16 Time of minor road vehicle's 2nd merge



Figure 3.17 Time of major road vehicle's arrival at minor road vehicle's 2nd merge point

The minor road through and left turn movements at the control TWSC intersection cut across the major road through movements. The gaps accepted for crossing the major road traffic were also calculated using the time stamps recorded in the video data. However, the gap acceptance values obtained for the J-turn site could not be compared with those obtained for the control TWSC site since the type of conflicts were entirely different. The conflicts assessed for the J-turn were merging conflicts, whereas the conflicts assessed for the TWSC intersection were crossing conflicts.

3.1.1.2.4 Crash Analysis

A safety evaluation was performed by analyzing the crashes occurring before and after the implementation of the J-turn design. The safety evaluation was performed using two methods. The first method compared the crash frequency for different severity levels and types for the before and after period. The second method was more statistically rigorous, and utilized the empirical Bayes method (Persaud et al. 2001).

A total of five J-turn sites in Missouri were included in the safety evaluation. Four other J-turn sites that were constructed on a new rural expressway, on US 65, were not included in the

crash analysis since there was no before-treatment data. Table 3.2 shows information on each J-turn, including the location, intersection geometry, AADT, speed limit, duration of before and after periods, and total number of crashes in the before and after periods. All five sites were located in rural areas with major road speed limits of 65 mph or higher. The major road AADT ranged between 10,326 and 25,862 vehicles per day. Four of the five sites were four-leg intersections, and one was a three-leg intersection.

Table 3.2 Characteristics of the J-turn sites included in the safety evaluation

J-Turn Location	Year Open	Average AADT Before		Average AADT After		Type	Speed Limit	Before Period	After Period	Before period Crashes		After period Crashes	
		Maj	Min	Maj	Min					All	Injury	All	Injury
US 63 & Deer Park Rd.	2012	25807	1059	26470	987	4-leg	70	3	1	40	7	6	0
US 54 & Honey Creek Rd.	2011	18848	508	18922	505	4-leg	65	3	2	8	6	5	1
US 54 & RT E	2011	15541	1389	15591	1340	4-leg	65	3	2	18	5	2	1
MO 13 & Old MO 13	2009	10630	447	10630	447	4-leg	65	3	3	9	4	9	3
Rte. M & Old Lemay Ferry Rd.	2007	10326	434	10326	434	3-leg	65	3	3	11	5	5	3

The crash frequency per year was computed for each site by dividing the total number of crashes by the duration. Crash frequencies were computed for four severity levels:

- 1) Property Damage Only (PDO)
- 2) Minor Injury (MI)
- 3) Disabling Injury (DI)
- 4) Fatality (F)

The effects of the J-turn on specific crash types were also analyzed. Specifically, the following intersection-related crash types were analyzed:

- 1) Right Angle (RA)
- 2) Right Turn (RT)
- 3) Right Turn Right Angle (RTRA)
- 4) Left Turn (LT)
- 5) Left Turn Right Angle (LTRA)
- 6) Rear End (RE)
- 7) Side Swipe (SS)
- 8) Passing (P)

The angle crash types were included since they are common occurrences at at-grade intersections and are typically of high severity. The J-turn design introduces new weaving maneuvers between the minor road and the U-turn. Thus, rear end, sideswipe, and passing types of crashes were also analyzed.

The second method, empirical Bayes (EB), has been used in previous studies to evaluate the safety effectiveness of alternative intersection designs (Persaud et al. 2001; Hummer et al. 2010; Inman and Haas 2012). The EB method is also recommended by the Highway Safety

Manual (HSM 2010) for conducting safety evaluations. Chapter 9 of the HSM discusses safety effectiveness evaluation methods. These safety effectiveness evaluation methods use several types of performance measures, such as percent reduction of crashes, shift in crash type and severity, and crash modification factors (CMF) (HSM 2010). For observational before-after studies, it is important to understand the underlying causes for implementing a certain treatment. Sites chosen for implementing a J-turn are typically sites with either high crash frequency or severity. Thus, a selection bias is introduced into the sample. To account for this bias and the resulting regression to the mean, the HSM recommends using the EB method.

The EB method utilizes safety performance functions (SPF) to estimate the average crash frequency for treated intersections during the after period as though the treatment had not been applied (HSM 2010). The estimated average crash frequency is then compared with the actual crash frequency during the after period. The HSM recommends using 10 to 20 sites that have been treated with approximately 3-5 years of crash data. This study included five treatment sites for which post J-turn implementation crash data were available. As crash data from additional J-turns in Missouri becomes available in the future, additional sites can be added to the EB analysis. Predictive models, CMFs, and SPFs from the HSM are discussed below.

The crash prediction model for intersections on rural multilane highways from the HSM (2010) is as follows:

$$N_{\text{predicted}} = N_{\text{spf}_x} \times C_i \times (CMF_{1x} \times CMF_{2x} \times \dots \times CMF_{4x}) \quad (3.7)$$

where,

$N_{\text{predicted}}$ = predicted average crash frequency for a specific year on site type x ;

N_{spf_x} = predicted average crash frequency determined for base conditions of the SPF developed for site type x ;

CMF_{yx} = crash modification factors specific to site type x and specific geometric design and traffic control features y ;

C_i = calibration factor to adjust SPF for local conditions for site type x .

The base conditions for three-leg and four-leg stop-controlled intersections on a rural multilane highway from the HSM (2010) are:

- 1) Intersection skew angle 0°
- 2) Intersection left-turn lanes 0, except on stop-controlled approaches
- 3) Intersection right-turn lanes 0, except on stop-controlled approaches
- 4) Lighting None

A CMF is used when the corresponding base condition is not met. Chapter 14 of the HSM provides CMF values for the geometric and lighting features described above. For example, the J-turn intersection on US 63 and Deer Park Rd had two left turn lanes on the major road, one in each direction, and one right-turn lane. The CMF values from the HSM for these features are 0.52 for left turn lanes and 0.86 for right turn lanes for all severities, and 0.42 and

0.77 for injury crashes. The calibration factors for all severities for three-leg and four-leg intersections were calculated for Missouri as 0.28 and 0.39, respectively (Sun et al. 2013). The calibration for injury-related crashes was not available; thus, a value of 1.00 was used.

The expected average crash frequency was computed using the SPF provided in the HSM (2010) as follows:

$$N_{spf_int} = \exp[a + b \times \ln(AADT_{maj}) + c \times \ln(AADT_{min})] \quad (3.8)$$

where,

N_{spf_int} = SPF estimate of intersection-related expected average crash frequency for base conditions;

$AADT_{maj}$ = AADT (vehicles per day) for major-road approaches;

$AADT_{min}$ = AADT (vehicles per day) for minor-road approaches;

a, b, c, d = regression coefficients.

The regression coefficients vary depending on the type of intersection (three-leg versus four-leg), and the type of severity (all severities versus fatal and injury only). Table 3.3 shows the coefficients for the different types as provided in the HSM (2010).

Table 3.3 SPF Coefficients for three- and four-leg intersections with minor-road stop control for total and fatal-and-injury crashes (HSM 2010)

Intersection Type/Severity Level	a	b	c	Overdispersion Parameter (Fixed k)
4ST Total	-10.008	0.848	0.448	0.494
4ST Fatal and Injury	-11.554	0.888	0.525	0.742
3ST Total	-12.526	1.204	0.236	0.460
3ST Fatal and Injury	-12.664	1.107	0.272	0.569

4ST denotes a four-leg intersection and 3ST denotes a three-leg intersection

The prediction model was used to predict the total number of crashes for the before and after periods. Persaud et al. (2001) presented the equations used for computing the measures in the EB method from the HSM. These equations are reproduced here to aid in understanding of the EB application. A ratio of the predicted values of before and after period crashes is calculated as follows (Persaud et al. 2001):

$$R = P_A/P_B \quad (3.9)$$

where,

R = the ratio of the after period to the before period regression predictions;

P_A = regression prediction from the after period;

P_B = regression prediction from the before period.

The expected annual number of crashes during the before period, m_b , and after period, m_a , are calculated as follows (Persaud et al. 2001):

$$m_b = [(k + x_b) / ((k/P_B) + y_b)] \quad (3.10)$$

where,

m_b = the expected annual number of crashes during the before period;

k =overdispersion parameter associated with the roadway segment;

x_b = count of crashes during the before period of length y_b ;

y_b = years of before period.

$$m_a = R \times m_b \quad (3.11)$$

where,

m_a = the expected annual number of crashes during the after period

In the next step, the EB estimate (B), the expected number of crashes that would have occurred if the treatment was not implemented, and the variance of B ($Var(B)$), are determined as follows (Persaud et al. 2001):

$$B = m_a \times y_a \quad (3.12)$$

where,

y_a = years of after period.

$$Var(B) = \frac{(m_b) \times (R \times y_a)^2}{\left[\frac{k}{P_B} + y_b \right]} \quad (3.13)$$

The reduction in the number of crashes (δ) is calculated as (Persaud et al. 2001),

$$\delta = \pi - \lambda \quad (3.14)$$

where,

π = the summation of the EB Estimate (B) for all sites;

λ = the summation of the observed number of crashes for all sites.

The variance of the reduction in the number of crashes ($Var(\delta)$) is calculated as (Persaud et al. 2001),

$$Var(\delta) = \sum Var(B) + \sum Var(A) \quad (3.15)$$

In addition to the δ value, an index of safety effectiveness, θ , is calculated as (Persaud et al. 2001),

$$\theta = \frac{\frac{\lambda}{\pi}}{\left\{1 + \left[\frac{Var(\pi)}{\pi^2}\right]\right\}} \quad (3.16)$$

The variance of θ , $Var(\theta)$, is calculated as (Persaud et al. 2001),

$$Var(\theta) = \frac{\theta^2 \times \left\{ \left[\frac{Var \lambda}{\lambda^2} \right] + \left[\frac{Var \pi}{\pi^2} \right] \right\}}{\left[1 + \frac{Var \pi}{\pi^2} \right]^2} \quad (3.17)$$

The index of safety effectiveness is the same as the crash modification factor for the J-turn countermeasure. The percent change in crashes due to the J-turn was computed as $100 \times (1 -$

θ). After determining the variance of θ , the next step was to determine whether the observed change in crash frequency was statistically significant. Three steps were performed to determine the statistical significance. These steps consisted of calculating the standard error of the variance of θ , calculating the standard error of the safety effectiveness, and assessing the statistical significance of the estimated safety effectiveness (HSM 2010). Equation 3.18 shows the calculation of the standard error of the variance of θ .

The standard error of the variance of θ was calculated as (HSM 2010),

$$SE(var(\theta)) = \sqrt{var(\theta)} \quad (3.18)$$

After calculating the standard error of the variance of θ , the standard error of the safety effectiveness could be calculated by multiplying the result from equation 3.18 by 100. The statistical significance of the estimated safety effectiveness was calculated as (HSM 2010),

$$test\ statistic = \left| \frac{\theta}{SE(\theta)} \right| \quad (3.19)$$

The test statistic value calculated using equation 3.19 was used to determine the significance at a given confidence level.

3.1.1.3 Public opinion survey of the J-turn on US 63

A survey was designed to obtain feedback from motorists who had driven the J-turn on US 63 and Deer Park Rd. This survey was jointly designed by the University of Missouri and MoDOT Central District staff. The survey was deployed using a web service. The survey link was disseminated through social media, news, and other media outlets with the assistance of

MoDOT's customer relations personnel. The web survey was open for three weeks, from July 22nd to August 12th, 2013.

After providing a brief introduction to the J-turn and TWSC designs, motorists were asked the following questions:

- 1) Are you familiar with the J-turn intersection on US 63 near MO-163?
- 2) Have you driven through this J-turn intersection?
- 3) Did you use the acceleration lane after the J-turn?
- 4) Was the J-turn easy to navigate?
- 5) Are you familiar with the safety benefits of a J-turn as compared to a two-way stop controlled intersection on a high-speed highway?
- 6) Do you feel safer making the left turning movement from MO-163 onto US 63 via a J-turn instead of directly turning left by crossing US 63?
- 7) Do you feel safer making the left turning movement from US 63 to MO-163 via a J-turn instead of directly turning left by crossing US 63?
- 8) Was it easy to merge onto US 63 from the acceleration lane?
- 9) How much time did the J-turn add to your trip time?
- 10) Do you feel the additional time (if any) did not affect your trip?
- 11) Did any issues arise during the use of J-turn? If yes, please explain.
- 12) What additional education and outreach can be made available to help the public better understand the operation and safety benefits of J-turns?

The survey concluded by collecting demographic information regarding the respondents. The requested information included age range, gender, residency, trip purpose, and vehicle type. A five-point Likert scale ranging from "strongly agree" to "strongly disagree" was used as the

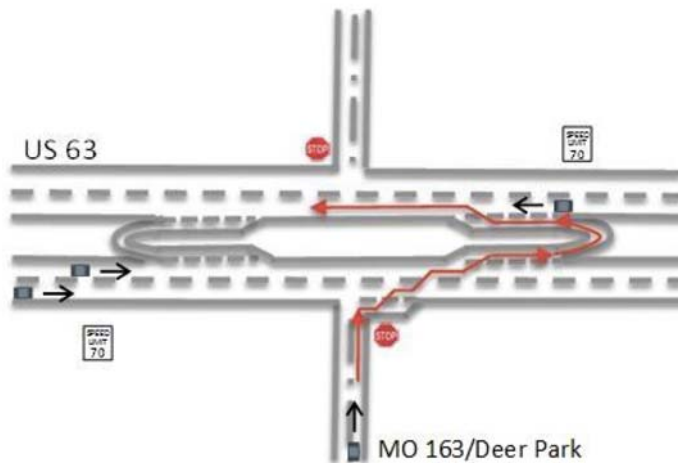
response set for most questions. Likert scales and demographic-based questions are commonly used in many transportation surveys (Mounce et al. 2007; Edwards and Young 2009). The entire survey as it appeared on the website is included in the following pages.

J-turn Public Survey

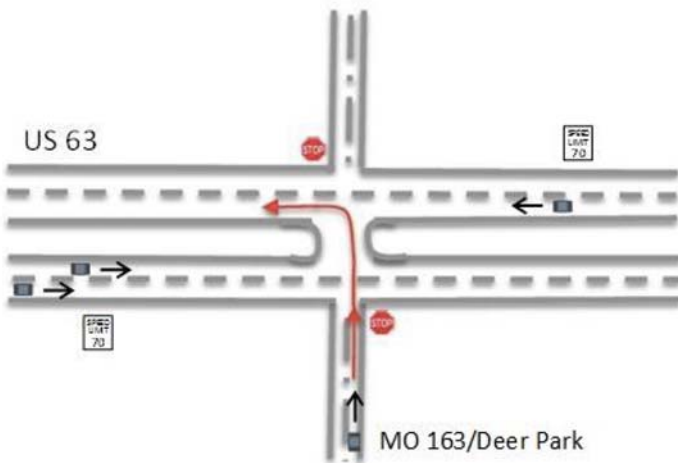
The intent of this survey is to gather public feedback on J-turns on US 63 near MO 163, south of Columbia. The survey was developed by the Civil Engineering Department at the University of Missouri. The survey results assist with the development of cost-effective solutions to improve safety at severe crash locations. The survey consists of 17 multiple choice and comment based questions. The survey should take you no longer than 5 minutes to complete.

The J-turn intersection design improves safety over two-way stop controlled intersections on high-speed rural highways. The J-turn eliminates severe left-turn crossing crashes by replacing left turns with a more gradual maneuver (see figure below, not to scale).

J-turn Intersection



Conventional Intersection



J-turn Public Survey

Please answer the following questions to the best of your ability.

1. I am familiar with the J-turn Intersection on U.S. 63 near MO-163.

- ☐ Yes
☐ No

2. I have driven through this J-turn intersection.

- ☐ Yes
☐ No

3. I used the acceleration lane after the J-turn.

- ☐ Yes
☐ No

4. The J-turn was easy to navigate.

- ☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

5. I am familiar with the safety benefits of a J-turn as compared to a two-way stop controlled intersection on a high-speed highway.

- ☐ Yes
☐ No

6. I feel safer making left turning movements from MO-163 onto U.S. 63 via a J-turn instead of directly turning left by crossing U.S. 63.

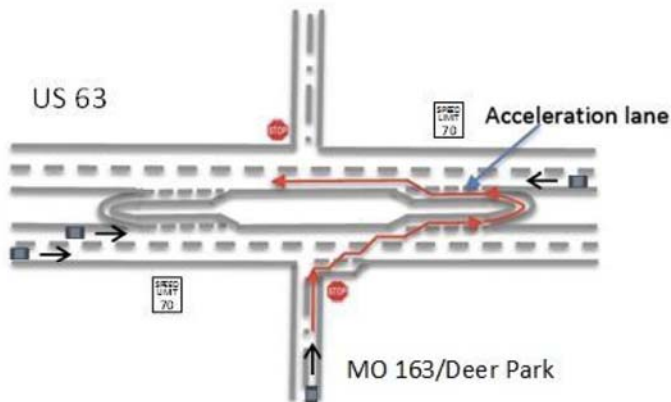
- ☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

7. I feel safer making left turning movements from U.S. 63 to MO-163 via a J-turn instead of directly turning left by crossing U.S. 63.

- ☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

J-turn Public Survey

Acceleration Lane



8. It was easy to merge onto U.S. 63 from the acceleration lane (see above figure)

- ☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

9. Driving the J-turn intersection added the following amount of time to my trip.

- ☐ None ☐ 0-1min. ☐ 1-3min. ☐ 3-5min. ☐ 5-7min.

10. I feel that the additional time (if any) did not affect my trip.

- ☐ Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree

11. Did any issues arise during the use of the J-turn?

- ☐ Yes
☐ No

12. If you answered yes on question 11, please explain the issue(s) that you experienced:

13. What additional education and outreach can be made available to help the public better understand the operation and safety benefits of J-turns?

J-turn Public Survey

Please answer the following demographic questions below.

14. Age range

- ☐ 16-25 ☐ 26-40 ☐ 41-55 ☐ 56-70 ☐ 71-95

15. Gender

- ☐ Male
☐ Female

16. My Residency

- ☐ Local Mid-Missouri
☐ Visitor

17. My Trip Purpose

- ☐ Work Related
☐ Recreation

18. My Vehicle Type

- ☐ Passenger Car
☐ Vehicle Pulling Trailer
☐ Delivery/Moving Truck
☐ Tractor Trailer Truck
☐ Bus

If you have any additional comments, concerns, or need more information on the J-turns, please contact Ms. Nicole Hood, P.E., Missouri Department of Transportation, at (573)-526-6997 or (888)-275-6636.

Thank you for completing the survey! We greatly appreciate your time.

Chapter 4 Results

4.1 Introduction

This section presents the results for the performance measures discussed in the previous section. The measures extracted from the field data were compared for the J-turn and TWSC control intersections. Operational measures, safety measures, and a public opinion survey were analyzed. The operational measures consisted of travel times, wait times from the minor road to the major road, and acceleration lane use before and after accessing the U-turn. The safety measures consisted of time to collision and gap acceptance. The comprehensive safety evaluation was conducted using crash data for five J-turn locations in Missouri. The EB-based safety evaluation derived crash modification factors for all crash severities and for injury and fatal crashes.

4.1.1 Operational Measures

Operational performance measures were analyzed using the field data collected at the US 63 and Deer Park Rd J-turn site and the US 63 and Calvert Hill Rd TWSC site. A comparison of travel times and wait times was performed between the J-turn and TWSC intersections. Acceleration lane use at the J-turn site was also analyzed.

4.1.1.1 Travel Times

In comparison to the TWSC design, all minor road movements and major road turning movements require travel of some additional distance in a J-turn design to complete their movements. The increases in travel times for these movements were measured in the field. A survey question also investigated motorists' perceptions of the increase in travel times.

The cumulative percentage of vehicle travel times for the TWSC and J-turn designs is shown in figure 4.1. For example, the 80th percentile travel time at the TWSC site was 19

seconds, compared to 67 seconds at the J-turn site. Travel time statistics are shown in table 4.1. The mean travel time at the J-turn site was 58 seconds greater than at the TWSC site. Thus, on average, the J-turn design increased the travel time of major road left turn vehicles by about one minute.

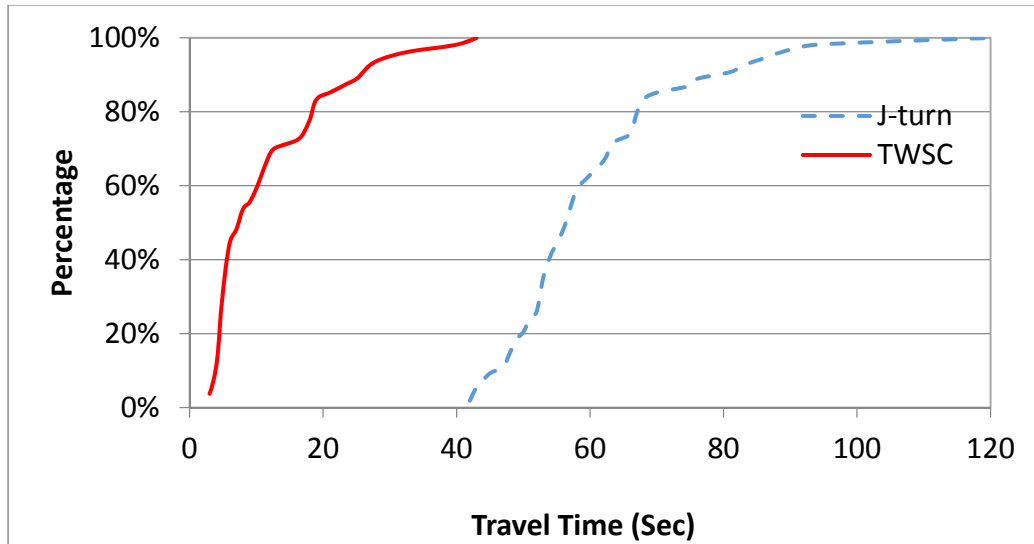


Figure 4.1 Cumulative distribution of travel times of major road left turns

Table 4.1 Travel time statistics for major road left turns

	J-turn	TWSC
Mean (seconds)	70	12
Median (seconds)	58	8
Mode (seconds)	62	5
Std. Dev. (seconds)	36	10
Sample Size (vehicles)	59	54

The travel times of vehicles turning left from the minor road to the major road were also measured for the J-turn and TWSC. For the TWSC, travel time included wait times at the intersection and the time it took to cross two lanes of traffic to the median then access the major road on the opposite side. For the J-turn, travel time included wait time, the time it took for the vehicle to drive from the minor road to the U-turn, and the time taken to travel the distance from the U-turn to the intersection to complete the turning movement. Since the J-turn site on US 63 had acceleration lanes for the minor road turning movements, the wait time, if any, was minimal. Once again, due to the additional distance traveled at the J-turn, the travel times were expected to be greater than at the TWSC. The cumulative percentage of vehicle travel times for both designs is shown in figure 4.2. For example, 80th percentile travel time at the TWSC site was 33 seconds, compared to 84 seconds at the J-turn site. The travel time statistics are shown in table 4.2. The mean value of travel time computed for the J-turn site was 56 seconds greater than at the TWSC site. On average, the J-turn design increased the travel time of minor road left turn vehicles by approximately one minute.

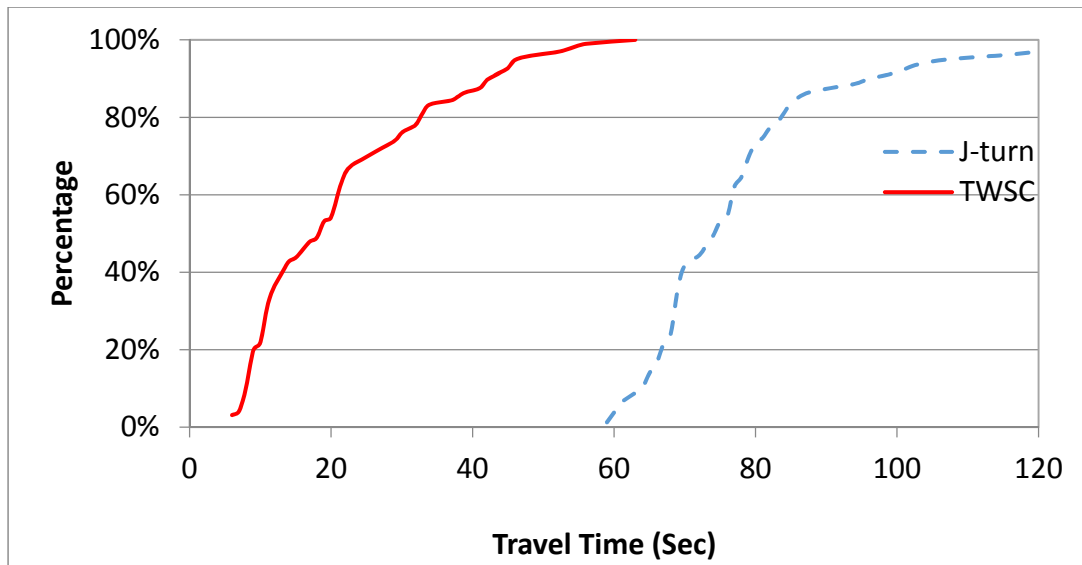


Figure 4.2 Cumulative distribution of travel times of minor road left turns

Table 4.2 Travel time statistics for minor road left turns

	J-turn	TWSC
Mean (seconds)	78	22
Median (seconds)	75	19
Mode (seconds)	69	11
Std. Dev. (seconds)	17	14
Sample Size	79	96

4.1.1.2 Wait times for minor road left turn vehicles

The wait times of vehicles wanting to turn left from the minor road onto the major road were measured at the TWSC and J-turn sites. The travel times measured at the TWSC, described previously, included this wait time. Drivers at the J-turn site turned right into the acceleration lane and then merged onto the through lanes. Unlike the TWSC intersection, the J-turn with an acceleration lane eliminated the need to wait for an acceptable gap in the major road. Thus, the wait times for left turns from the minor road at the J-turn site were expected to be lower than

those at the TWSC site. A cumulative percentage of the wait times for the two designs is shown in figure 4.3. For example, 85th percentile wait time at the J-turn site was 10 seconds, compared to 21 seconds at the TWSC site. The mean wait times were 5 seconds for the J-turn and 11 seconds for the TWSC site. This difference in wait times was significant, especially since the major road AADT at the J-turn site was higher (27,321) than at the control site (17,217). As major road AADT increases, the wait times at the TWSC were expected to increase. The presence of an acceleration lane for turning vehicles at the J-turn site signified that the major road AADT did not significantly affect wait times.

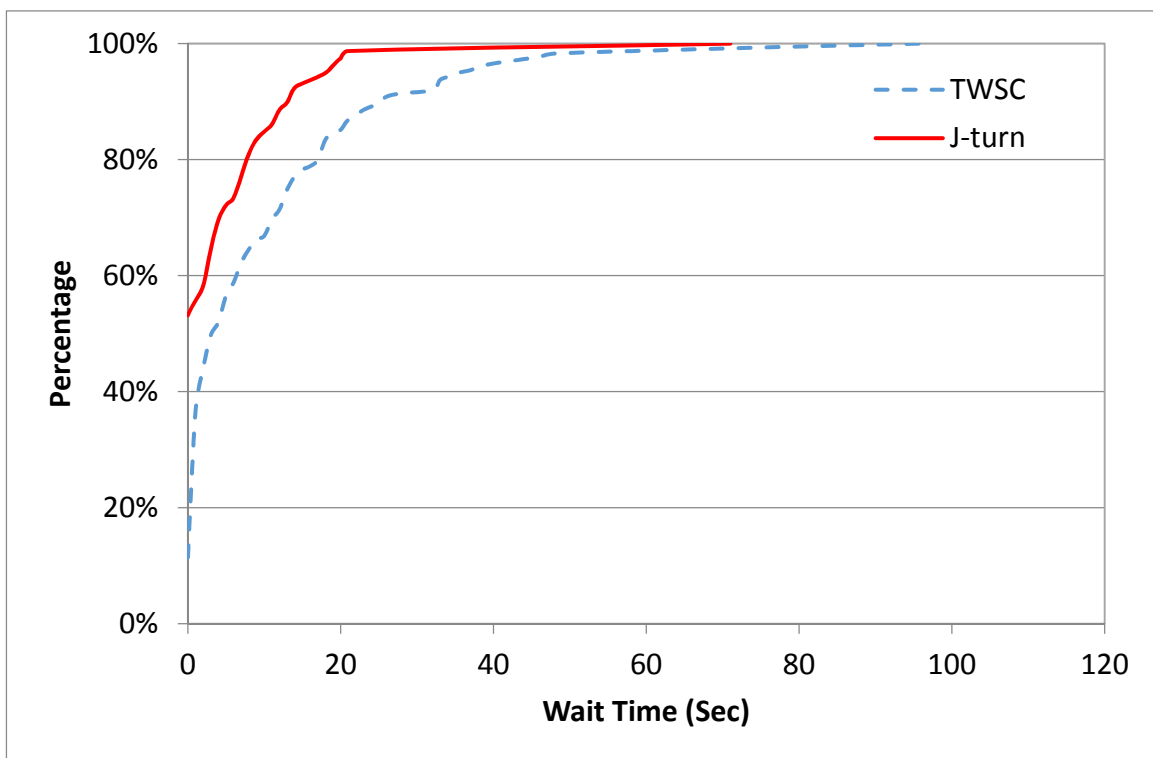


Figure 4.3 Cumulative distribution of wait times for minor road left turns

4.1.1.3 Acceleration Lane Use

There were two acceleration lanes at the US 63 and Deer Park Rd J-turn: one acceleration lane was located at the beginning of the minor road, to be used by minor road vehicles for turning right and getting up to speed to merge into the major road; the second acceleration lane was located after the U-turn to help turning vehicles accelerate and merge into the passing lane on the major road. The portions of the acceleration lane used by vehicles before merging into the through lanes on the major road were extracted from video data. The usage of the right turn acceleration lane and the U-turn acceleration lane are shown in figures 4.4 and 4.5, respectively. In figure 4.4, the acceleration lane is divided into 200 ft. segments, and the percentages of vehicles merging in each segment are shown. The orange bars show the percentages for the left turn vehicles that accessed the U-turn downstream. The green bars show the results for the non-U-turn vehicles, i.e., those vehicles that continued on the major road without accessing the U-turn. Figure 4.4 shows that most of the U-turn vehicles, 78%, left the acceleration lane within the first 400 ft of the acceleration lane. These vehicles did not reach the mainline speed limit of 70 mph prior to merging into the right through lane. The turning vehicles not using the U-turn used a larger portion of the acceleration lane before merging into the major road. One reason most vehicles accessing the U-turn were merging within the first 400 ft. is that they were attempting to position themselves to be able to make lane changes in time to access the U-turn. Figure 4.6 shows the lengths of the acceleration and deceleration lanes estimated from the design plans for the J-turn site. From the figure, the entrance to the deceleration lane into the U-turn was located at 2,025 ft. for the northbound direction and 1,620 ft. for the southbound direction.

The use of the U-turn acceleration lane is shown in figure 4.5 for U-turn vehicles (shown in orange), and only those vehicles that accessed the minor road through a right turn downstream

(shown in green). The acceleration lane was divided into three segments: the first 120 ft.; 120 ft. to 480 ft.; and greater than 480 ft. The distribution of all U-turn vehicles was more or less uniform across the three segments. Of those vehicles accessing the minor road, 48% used only 120 ft. of the acceleration lane, and 78% used only 480 ft. of the acceleration lane to merge onto the major road. As shown in figure 4.6, the entrance to the deceleration lane into the right turn lane was located at 1,270 ft. in the northbound direction and 2,370 ft. in the southbound direction.

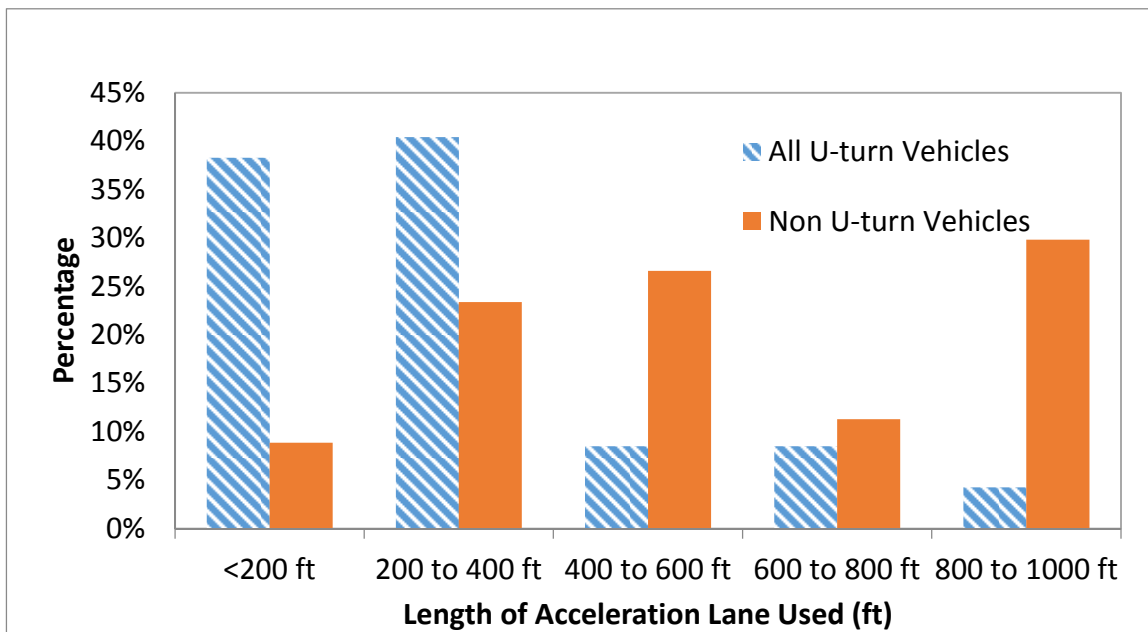


Figure 4.4 Right turn acceleration lane usage

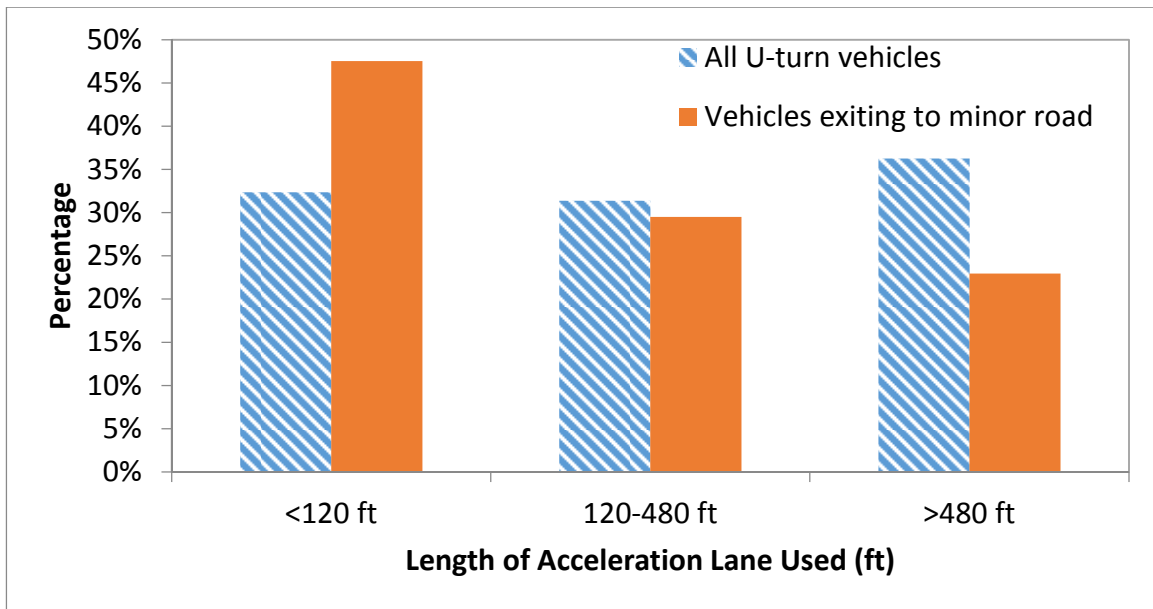


Figure 4.5 U-turn acceleration lane usage

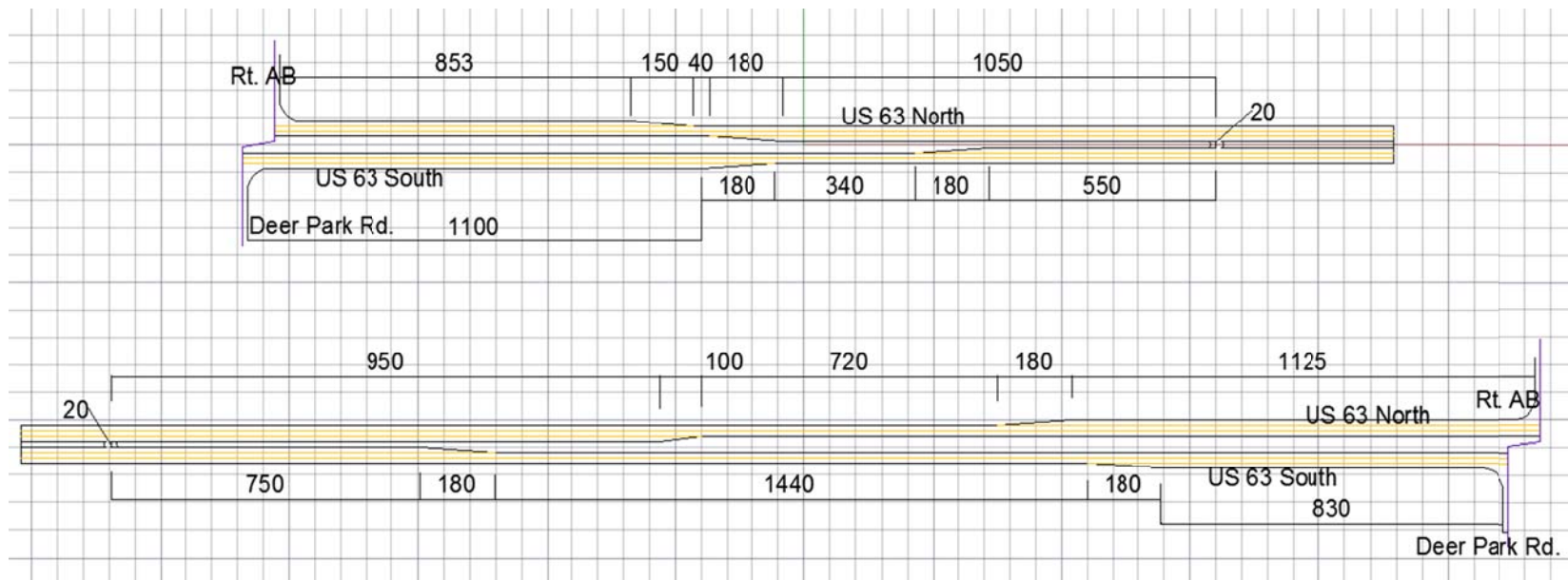


Figure 4.6 Measurements of lengths of acceleration and deceleration lanes at the J-turn site on US 63 and Deer Park Rd.

4.1.1.4 Operational Measures Summary

In summary, the travel times at the J-turn site were approximately one minute higher than at the TWSC site for both minor and major road turning movements. This increase is similar to the finding of Inman and Haas (2012) at the RCUT site in Maryland.

The wait times at the J-turn site were significantly lower than those at the TWSC site despite the higher AADT on the major road at the J-turn site. The lower wait times at the J-turn site were primarily due to the presence of acceleration lanes for turning movements. Inman and Haas (2012) reported almost zero wait times at the RCUT site. As drivers become used to the J-turn site on US 63 and Deer Park Rd, it is anticipated that wait times will decrease even further. Minor road left-turning and through movements at the J-turn site merged into the travel lanes within the first 400 ft. of the acceleration lane 78% of the time. The RCUT evaluation in Maryland (Inman and Haas 2012) found that 83% of the minor road turning vehicles using the U-turn merged directly into the left travel lane from the minor road. In the current study, the use of the acceleration lane after making the U-turn was also similar, with 48% of vehicles merging within the first 120 ft., and 78% merging within the first 480 ft. In terms of safety, it is desirable to have sufficient spacing between the minor road and the U-turn. Such spacing should allow vehicles to accelerate to the major road operating speed using the acceleration lanes, and to access the deceleration lanes without any sudden braking or any adverse impact upon the major road vehicles. However, there are a few practical challenges to consider in accomplishing sufficient spacing. First, the designer is faced with the task of balancing mobility and safety effects of the spacing. Higher spacing may be safer, but mobility could suffer. Second, the roadway geometry characteristics, such as terrain, presence of an interchange nearby, available median width, and vertical alignment affect the location of the U-turn, and thus the spacing.

Third, the need for consistency in the speed limit with adjacent sections of the major road could also affect spacing.

For the US 63 J-turn site, the following practical challenges existed. First, there was a bridge over Turkey Creek, located 0.1 miles south of the current northbound U-turn location. To accommodate any additional spacing between the main intersection and the U-turn, the bridge would have to be widened, or the U-turn would have to be located further south of the bridge, thus adversely affecting travel times. For the southbound U-turn, located north of the main intersection, additional spacing was not practical because of the horizontal curvature and superelevation of the US 63 segment north of the main intersection. Due to the realignment of southbound US 63, the median width was reduced, which affected the U-turn radius.

4.1.2 Safety Measures

4.1.2.1 Time to Collision

Time to collision (TTC) is a conflict measure defined as the time after which a vehicle will collide with another vehicle if both vehicles were to maintain their current speed and path. The smaller the TTC value, the higher the likelihood of a collision occurring if no evasive action were to be taken. In this study, the TTC value was computed using a through moving vehicle on the major road and a left turning vehicle from the minor road. The TTC value is a function of the traffic flow on the major road, so higher flows will lead to smaller TTC values.

The location of the left turn from the minor road to the major road differs between the traditional TWSC and J-turn design. In the TWSC design, minor road vehicles turning left onto the major road cross through traffic then merge into the opposing lanes; whereas in a J-turn, minor road vehicles make a right turn into an acceleration lane and then use the downstream U-turn to complete the turn. Thus, the potential conflict in a J-turn design occurs downstream of the

intersection, unlike the TWSC, where it occurs at the intersection. The additional distance to the conflict in a J-turn is expected to result in higher TTC values for the J-turn, compared to the TWSC, design. The differences in TTC values at the J-turn site (US 63 and Deer Park Rd) and the TWSC site (US 63 and Calvert Hill Rd.) are shown in figure 4.7. The figure shows that the majority of TTC values (74%) for the J-turn design were greater than 20 seconds. On the other hand, the TWSC design saw lower TTC values, with 62% of those values less than 10 seconds. The mean TTC value for the J-turn design was 41 seconds, compared to 10 seconds for the TWSC design—a 300% difference. Higher TTC values indicate safer traffic conditions. Other descriptive statistics, such as median and standard deviation, are shown in table 4.3.

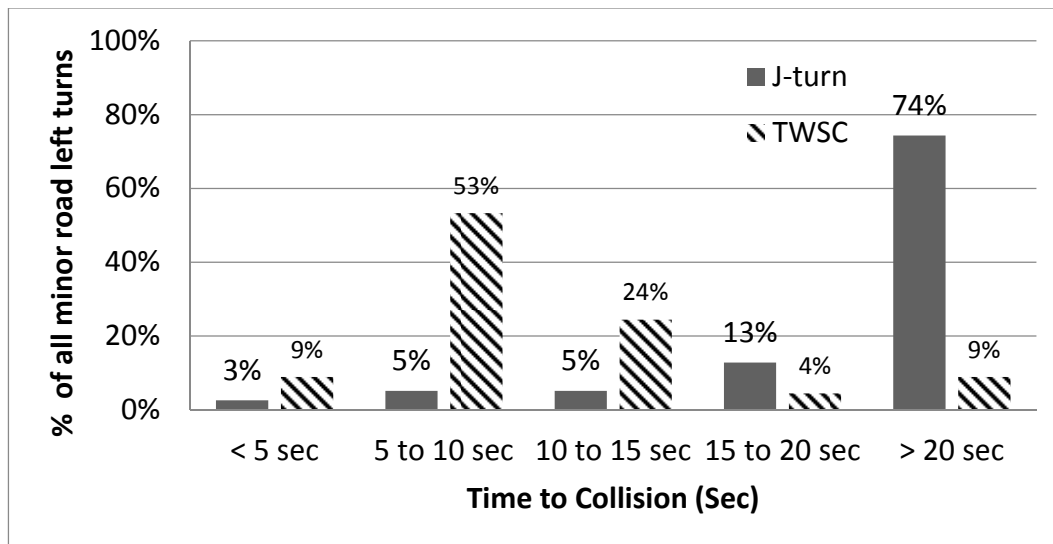


Figure 4.7 Time to collision for J-turn and TWSC sites on US 63

Table 4.3 Descriptive statistics of TTC measure

J-turn		TWSC	
Measure	Time (sec)	Measure	Time (sec)
Mean	41.28	Mean	10.40
Median	34.59	Median	9.10
Standard deviation	30.34	Standard deviation	6.80
Minimum	3.14	Minimum	3.80
Maximum	114.48	Maximum	36.90
Count	39	Count	45

4.1.2.2 Gap Acceptance

At the J-turn site, a vehicle intending to turn left from the minor road onto the major road must turn right into the acceleration lane, then change two lanes—driving (right lane) and passing (left lane)—followed by another lane change into the deceleration lane. The vehicle then uses the acceleration lane after making the U-turn and merges into the passing lane of the major road. The time gaps accepted by turning movements from the minor road at the J-turn site were computed from video data. Time gaps were computed for two lane changes: 1) from the right turn acceleration lane to the right lane, and 2) from the right lane to the left lane. Figure 4.8 shows the cumulative distribution of the two gaps. Vehicles accepted shorter gaps for the first lane change, from the acceleration lane to the right lane, than for the second lane change, from the right lane to left lane. This could mean that drivers were more cautious when changing to the passing lane, possibly due to higher operating speeds in the passing lane and due to the impending deceleration into the U-turn lane. The mean accepted time gap for entering the right lane was 8.3 seconds, compared to 11.6 seconds for entering the passing lane.

Unlike the J-turn design, left turn vehicles in the TWSC design face a crossing conflict with the major road through movement. This is an important difference between the two designs;

the J-turn design eliminates the crossing conflict and replaces it with lane change or merging conflicts. In terms of safety, a crossing conflict is more dangerous since it could result in a severe angle crash. On the other hand, the potential rear-end or sideswipe crashes that could result from a lane change are less severe than those observed in an angle crash. Thus, in the J-turn design, a severe crash type is traded for a less severe crash type. Also shown in figure 4.8 is the cumulative distribution of the accepted time gaps at the control TWSC site. The plot shows that the accepted gaps were longer than those at the J-turn site. The mean accepted time gap for the minor road vehicle to enter the median was 21 seconds. This time gap value for a TWSC may not be directly compared to the values obtained at the J-turn site, since the two designs consist of different conflict types, i.e., crossing versus diverging.

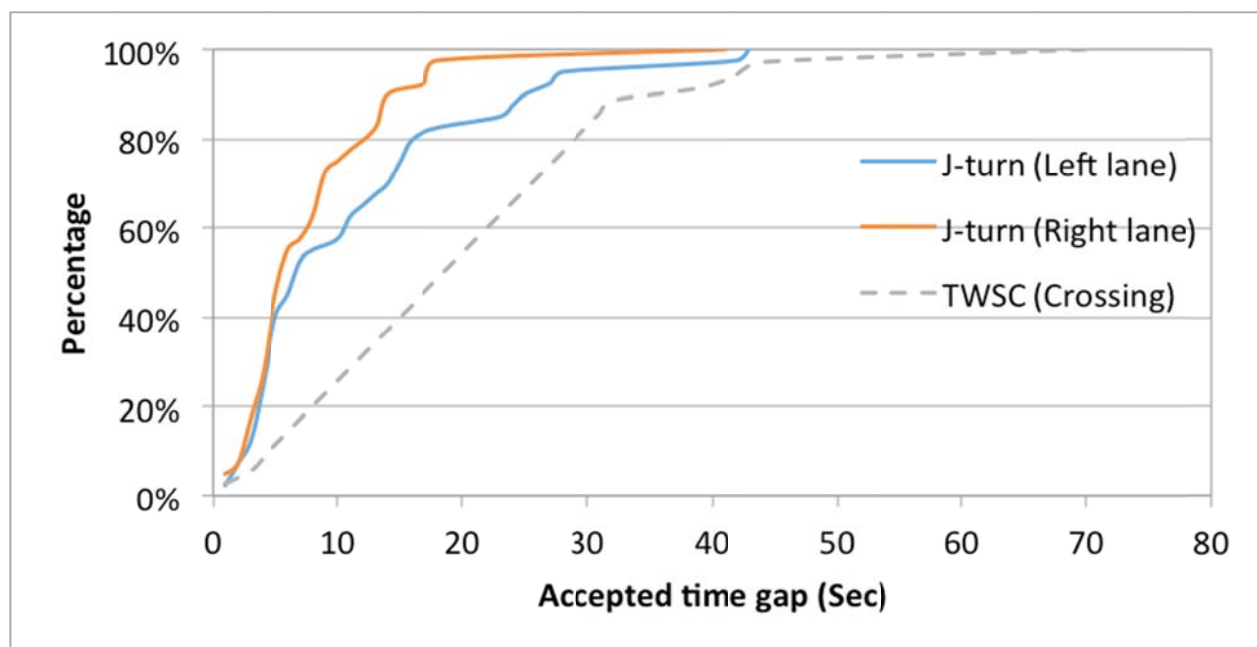


Figure 4.8 Cumulative distribution of accepted time gaps for minor road left turns

4.1.2.3 Crash Analysis

Crash data for five J-turn sites in Missouri were analyzed. The location of sites and the duration of the before-and-after period chosen for the crash analysis were previously illustrated in table 3.2. Two methods were used to compare before and after crash frequency and severity. The first method was a simple graphical comparison by severity (fig. 4.9) and by crash type (fig. 4.10) across five J-turn sites. The second, the empirical Bayes method, improves upon the simple method by addressing selection bias and regression to the mean.

For method one, the total number of crashes per year combined across all sites and all severities decreased from 28.7 to 14.2 (51% reduction) due to the J-turn treatment. There were no fatal crashes at any of the sites in the after period. Disabling injury crashes per year decreased from 2.3 to 0.3 (86% reduction). The elimination of fatal crashes and a significant reduction in disabling injury crashes are substantial safety improvements offered by the J-turn treatment. Minor injury crashes per year also decreased from 5.3 to 2.6 (50% reduction). Property damage only crashes per year decreased from 20.0 to 11.1 (43% reduction).

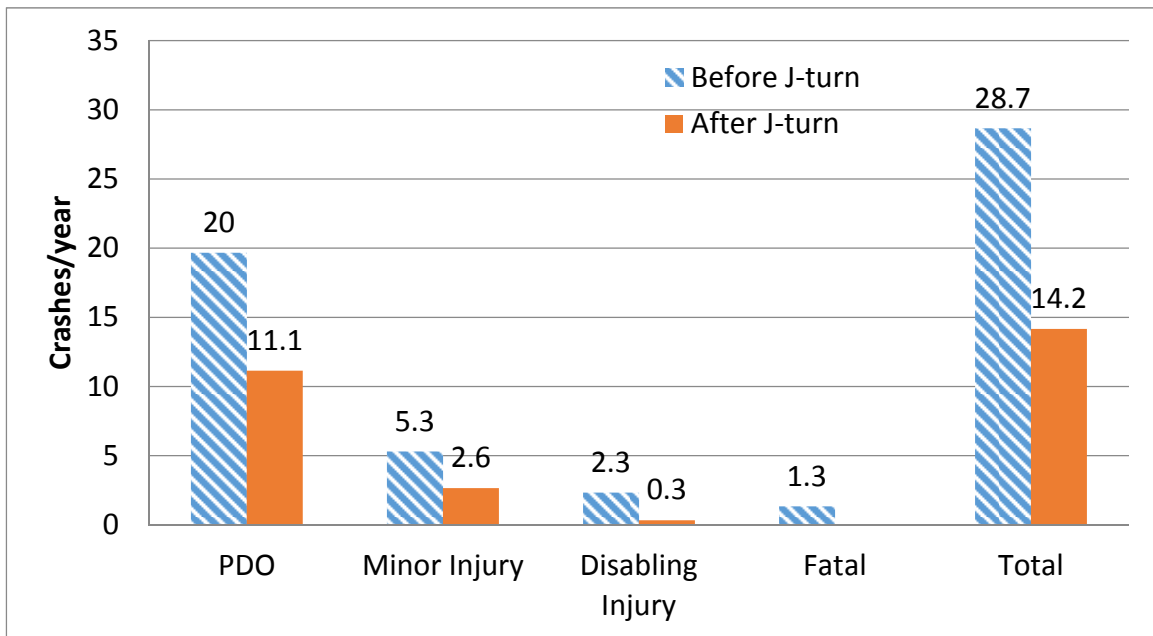


Figure 4.9 Annual crash frequency by severity before and after J-turn (sum of all five sites)

The J-turn is designed to decrease angle crashes. Figure 4.10 shows that this goal was accomplished: right angle crashes per year decreased from 6.7 to 1.3. One of the most severe crash types, left turn right angle crashes, were totally eliminated by the J-turn. Rear-end and passing crashes also decreased post J-turn implementation.

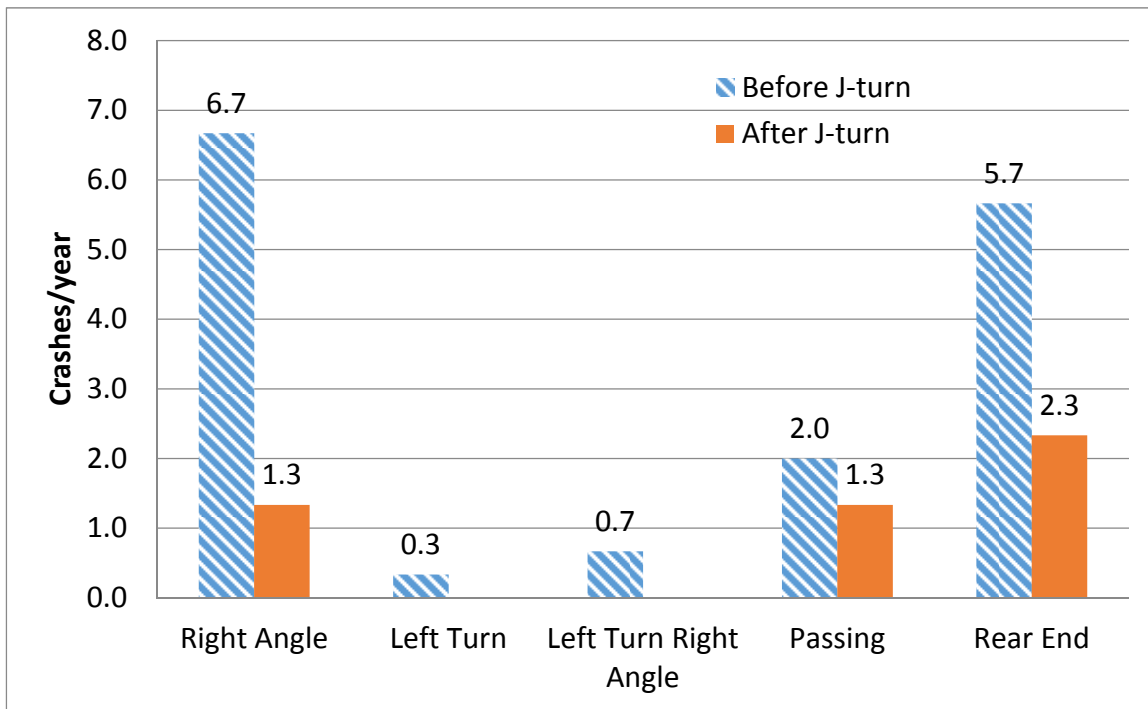


Figure 4.10 Annual crash frequency by type before and after J-turn (sum of all five sites)

The second method utilized to compare before and after crash frequency was the EB method, as previously utilized by Persaud et al. (2001). The EB method compared the predicted crash frequency without the J-turn to the actual crash frequency with the J-turn. The calibration factors used for all crashes in Missouri were 0.27 and 0.39 for three-legged and four-legged intersections, respectively. These calibration factors were established in another study that established calibration values for different facility types in Missouri (Sun et al. 2013); however, calibration factors were established for “all crashes” only, not “injury only” crashes. Thus, for “injury only” crashes, a calibration factor value of 1.0 was utilized.

Table 4.4 shows the crash frequency per year for five intersections. The second column of table 4.4 shows the actual crash frequency, and the third column shows the predicted crash frequency for the after period. Variance in the predicted crash frequency is shown in the fourth column. The last row of table 4.4 is a summation of values from all five rows. Using equation

3.16, it was demonstrated that the J-turn countermeasure reduced total crash frequency by 34.8%. Using equation 3.19, the ratio of crash reduction and the standard error was found to be 34.8/14.5, or 2.4, which was greater than the p-value of 1.96 for a 95% confidence level. Thus, the reduction in total crash frequency due to the J-turn was statistically significant at the 95% confidence level.

Table 4.4 Empirical Bayes-based before-after comparison of crashes

Intersection	After Period Count (A)	EB Estimate (B)	Var (B)
1	6	10.86	3.07
2	5	5.01	2.95
3	9	7.69	6.23
4	5	7.47	4.87
5	2	9.84	5.53
Total	Sum (λ)=27	Sum (π)=40.87	Var (B)=22.65

Table 4.5 shows the injury-related crash frequency per year for all five intersections. This included minor injuries, disabling injuries, and fatal crashes. The J-turn countermeasure reduced total crash frequency by 53.7%. The ratio of crash reduction and the standard error of the safety effectiveness was 53.7/17.9, or, 2.98, which was greater than the p-value of 1.96 for a 95% confidence level. Thus, the reduction in injury crash frequency due to the J-turn was statistically significant at the 95% confidence level.

Table 4.5 Empirical Bayes-based before-after comparison of injury crashes

Intersection	After Period Count (A)	EB Estimate (B)	Var (B)
1	0	2.04	0.53
2	1	3.91	2.26
3	3	3.71	2.90
4	3	3.94	2.79
5	1	3.08	1.65
Total	Sum (λ)=8	Sum (π)=16.68	Var (B)=10.13

4.1.2.4 Safety Measures Summary

In summary, three different safety measures were analyzed to assess the safety effectiveness of the J-turn design. The higher TTC values for the J-turn imply that the intersection allowed for safer interactions between minor road and major road vehicles in comparison to the TWSC intersection. The availability of acceleration lanes at the J-turn site contributed to the higher TTC values.

The average gap acceptance value for minor road vehicles merging from the acceleration lane into the right lane was 8.3 seconds, and 11.6 seconds for merging from the right lane to the left lane. The higher accepted value for the merge into the left passing lane was presumably due to higher traffic speeds in the passing lane. One study by Inman and Haas (2012) reported a lag measure for a J-turn site in Maryland. The lag measure was similar to the gap acceptance measure used in the current study. Lag values ranging between 4.4 seconds and 5.3 seconds were reported for vehicles merging from the acceleration lane into the right lane. These values were smaller than the 8.3 seconds observed at the J-turn site in Missouri.

A simple before-after comparison of crash frequency data showed a 51% reduction in all crashes, an 86% reduction in disabling injury crashes, a 50% reduction in minor injury crashes, and 43% reduction in PDO crashes. None of the J-turn sites witnessed any fatal crashes in the

period since the J-turns became operational. One main goal of implementing a J-turn design is to reduce angle crashes. Right angle crashes at all five J-turn sites decreased by 80%, and left-turn right angle crashes were completely eliminated. Rear end and passing type crashes also decreased by 58.8% and 33.3%, respectively, after J-turns were implemented.

The statistically rigorous EB method revealed a 34.8% reduction in all crashes, and a 53.7% reduction in all injury crashes. The Maryland study (Inman and Haas 2012) reported a 44% reduction in all crashes, a 42% reduction in injury crashes, and a 70% reduction in fatal crashes. The North Carolina study (Hummer et al. 2010) reported a 27.2% reduction for all crashes and a 51% reduction in injury and fatal crashes. The current study is consistent with previous studies that showed significant reductions in total crash frequency and injury and fatal crash frequency.

4.1.3 Survey Analysis

The results of the public opinion survey responses are presented in this section. The survey was completed by 423 respondents. The demographic information of the respondents is shown in table 4.6.

Table 4.6 Demographic information of survey respondents

Demographic variable	Group	Percentage
Age range	16-25	7.3%
	26-40	27.4%
	41-55	36.8%
	56-70	25.6%
	71-95	2.9%
Gender	Female	55.4%
	Male	44.6%
Residency	Local	98.4%
	Visitor	1.6%
Trip Purpose	Work Related	61.3%
	Recreation	38.7%
Vehicle Type	Passenger Car	86.3%
	Vehicle Pulling Trailer	10.3%
	Delivery/Moving Truck	3.2%
	Tractor Trailer Truck	0.3%
	Bus	0.0%

Table 4.7 provides the results for questions with two choices, “Yes” or “No.” The number of responses for each choice, and the respective percentages, are shown in the second and third columns of table 4.7.

Table 4.7 Responses to survey questions with Yes/No choices

Survey Question	Yes	No
I am familiar with the J-turn Intersection on US 63 near MO-163.	411 (98%)	9 (2%)
I have driven through this J-turn intersection.	383 (92%)	35 (8%)
I used the acceleration lane after the J-turn.	361 (87%)	52 (13%)
I am familiar with the safety benefits of a J-turn as compared to a two-way stop control intersection on a high-speed highway	321 (80%)	83 (20%)
Did any issues arise during the use of the J-turn?	270 (71%)	112 (29%)

The responses presented in table 4.7 show that almost all survey respondents (98%) were familiar with the subject J-turn intersection on US 63. Similarly, a high percentage of respondents (92%) had driven the J-turn intersection. These two responses show that the survey reached the target driving population. About 80% of respondents said they were familiar with the safety benefits of the J-turn in comparison to TWSC intersections. The majority of respondents, 87%, indicated using the acceleration lane to accelerate before merging into the travel lane.

The respondents were asked questions pertaining to ease of navigation, perception of safety in making turning movements, merging into the major road, and the effect of additional travel time on their trip. These questions allowed for the following five responses: strongly agree, agree, neutral, disagree, and strongly disagree. The responses are summarized in table 4.8. When asked if the J-turn was easy to navigate, 26% of the respondents agreed or strongly agreed, 12% neither agreed nor disagreed, and 62% either disagreed or strongly disagreed. Although 80% of respondents said they were familiar with the safety benefits of a J-turn compared to a TWSC intersection (table 4.7), when asked if they felt safer making left turning movements from the minor road, 29% agreed or strongly agreed, 13% neither agreed nor disagreed, and 58% either disagreed or strongly disagreed. The perception of safety for making left turning movements from the major road was similar: 28% of the respondents either agreed or strongly

agreed, 12% neither agreed nor disagreed, and 60% disagreed or strongly disagreed. The final row of table 4.8 shows the results regarding the manner in which users perceived the additional travel time caused by the J-turn, if any, affected their trip. Only 33% of respondents stated that the additional travel time adversely affected their trip.

Table 4. 8 Responses to survey questions with five choices

Survey Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The J-turn was easy to navigate.	41 (10%)	66 (16%)	49 (12%)	115 (28%)	141 (34%)
I feel safer making left turning movements from MO-163 onto US 63 via a J-turn instead of directly turning left by crossing US 63.	55 (14%)	59 (15%)	53 (13%)	88 (22%)	146 (36%)
I feel safer making left turning movements from US 63 to MO-163 via a J-turn instead of directly turning left by crossing US 63.	53 (13%)	58 (15%)	49 (12%)	91 (23%)	150 (37%)
It was easy to merge onto US 63 from the acceleration lane.	38 (9%)	91 (23%)	69 (17%)	85 (21%)	121 (30%)
I feel that the additional time (if any) did not affect my trip.	51 (13%)	108 (28%)	100 (26%)	76 (20%)	49 (13%)

Looking back at table 4.7, 71% of respondents said that issues arose while using the J-turn. Table 4.9 lists some of the most frequent issues raised by the survey respondents. The percentage of respondents that raised a specific issue is shown in the third column of table 4.9. Some of the issues raised helped explain responses to the questions regarding safety perceptions and ease of merging as reported in table 4.8.

Table 4.9 Most frequent issues raised by survey respondents

Issue	Description	Percentage of responses
No issue reported	The user said they did not have any issues or concerns.	26%
Merge after the U-turn	The user said he/she did not feel safe while merging from the median U-turn into the passing lane of US 63.	24%
Acceleration/Deceleration lane usage	The user felt that the acceleration or deceleration lanes were not of adequate length, or noticed improper use of these lanes by other merging vehicles ahead.	18%
U-turn radius	The user said their vehicle was too large for the U-turn turning radius that was provided.	17%
Merge from the minor road	The user stated having a problem merging from the minor road into the major road.	11%
Driver confusion	The user said he/she was not able to navigate the J-turn correctly, or felt confused.	8%
Signage	The user suggested that the existing signage was inadequate and that the addition of more signs, striping, or lighting would help.	2%
Speed limit	The user felt that the current speed limit was high, and a reduced speed limit would enhance safety.	1%

As with any new intersection design, there is a learning period during which drivers become acclimated to navigating the new design. Additional improvements could alleviate some of the concerns raised by drivers. Additional signs alerting the major road traffic of merging traffic ahead of the U-turns could help avoid unexpected braking or aggressive merging maneuvers. The survey respondents indicated some drivers stopping in the acceleration lane following the U-turn. Since J-turns were a new concept to some drivers, adding a sign informing drivers to use the acceleration lane could improve overall safety and mobility. As mentioned in

table 4.9, some drivers suggested lowering the speed limit on US 63 at the J-turn location. A lower speed limit, e.g., 65 mph, may make the operators of U-turn vehicles feel safer while merging into the left lane. However, since the speed limits of adjacent sections of US 63 are 70 mph, any reduction in speed limit could increase the speed variance between vehicles on the major road, which could be a safety concern. Thus, lowering the speed limit at the J-turn site may not be a satisfactory option. Some survey respondents stated instances where major road vehicles used the U-turn acceleration lane as a passing lane. Additional lane markings, such as the use of a solid white line, as well as additional signage, could help to prevent such driving behavior.

The percentage of tractor-trailer trucks at the US 63 J-turn site was 5% of the AADT (MoDOT 2011). As shown in table 4.6, tractor-trailer traffic comprised 0.3% of the survey responses. Due to a narrow median width of 20 ft., the U-turn was not designed to accommodate tractor-trailer trucks. However, there are interchanges on both sides of the J-turn intersection that can accommodate larger vehicles such as tractor-trailer trucks. The nearest interchange to the north, at Gans Creek Rd, is located 2.4 miles past the southbound U-turn; the nearest interchange to the south, at Rte. H, is located 1.4 miles past the northbound U-turn.

Chapter 5 Summary and Conclusions

This research project addressed the effectiveness of the J-turn intersection design in Missouri. Using field studies, a public opinion survey, and crash analysis, the performance of the J-turn design was evaluated. Field studies were conducted at a J-turn site on US 63 and Deer Park Rd, and at a TWSC intersection control site also on the same US 63 corridor. A public opinion survey was also conducted for the same J-turn. The crash analysis consisted of a five-site before-after comparison of crash frequency and a statistically rigorous empirical Bayes before-after safety evaluation. The main findings of the study are as follows:

1) For five sites in Missouri, the EB analysis showed that the J-turn design resulted in a 34.8% reduction in crash frequency for all crashes, and a 53.7% reduction in crash frequency for injury and fatal crashes. All reductions were significant at the 95% confidence level. Annual disabling injury crashes decreased by 86% and minor injury crashes decreased by 50%. None of the five sites exhibited a fatal crash following J-turn implementation. The elimination of fatal crashes and a significant reduction in disabling injury crashes are substantial safety improvements offered by the J-turn design.

2) The main goal of the J-turn design is to decrease the frequency of angle crashes. This five-site analysis showed that annual right angle crashes decreased from 6.3 to 1.3, a 80% reduction. One of the most severe crash types, the left turn, right angle crash, was completely eliminated by the J-turn. Rear-end and passing crashes also decreased post J-turn implementation.

3) The average time to collision for minor road turning vehicles at the J-turn site was four times higher than the value observed at a control TWSC intersection. This higher time to

collision value implies that the J-turn intersection allowed for safer interactions between the minor road vehicles and the major road vehicles, as compared to the TWSC intersection.

4) Wait times at the J-turn site were lower than those at the TWSC site, despite the higher AADT on the major road at the J-turn site. The average wait time at the J-turn site was five seconds, compared to 11 seconds at the control TWSC site. Another study reported almost no wait times at a J-turn site (Hummer et al., 2010). As drivers become used to the J-turn intersection, and especially with the use of acceleration lanes, it is anticipated that wait times will decrease even further.

5) Average travel times at the J-turn site were about one minute longer than at the TWSC site for minor road and major road turning movements. When the public was surveyed regarding their perceptions on how the additional travel time affected their trip, 41% said it did not adversely affect their trip, 26% were neutral, and 33% said it did adversely affect their trip.

6) A high percentage (78%) of minor road left turning and through movements at the J-turn site merged into the travel lanes within the first 400 ft. of the acceleration lane. This finding indicates that these vehicles were not reaching the mainline speed limit of 70 mph prior to merging into the major road. The use of the acceleration lane after making the U-turn was similar, with 48% of vehicles merging within the first 120 ft. and 78% merging within the first 480 ft. Minor road turning vehicles not using the U-turn, i.e., right turns, used a larger portion of the acceleration lane before merging into the major road.

7) Public opinion regarding the J-turn at US 63 and Deer Park Rd was mixed. Some of the common concerns raised by survey respondents included difficulty in merging after the U-turn, improper use of acceleration and deceleration lanes, insufficient U-turn radius to

accommodate large vehicles, and driver confusion. Some respondents felt that additional signage and striping would improve the J-turn.

8) The J-turn on US 63 and Deer Park Rd was designed per the available standards within the geometric constraints of the site, and was properly signed per the MUTCD (2009). This J-turn design was a retrofit, similar to most other J-turn sites in Missouri, being fitted to an existing roadway, thus requiring designers to work within space and geometric constraints while determining the spacing of U-turns and acceleration and deceleration lane lengths.

References

- American Association of State Highway and Transportation Officials (AASHTO). 2011. *A Policy on Geometric Design of Highways and Streets*, 6th ed., Washington, D.C.
- American Association of State Highway and Transportation Officials AASHTO. 2010. *Highway Safety Manual*, 1st ed., Washington, D.C.
- Edwards, M. and R. Young. 2009. *Developing System for Consistent Messaging on Interstate 80's Dynamic Message Signs Phase I*. United States Department of Transportation, Wyoming.
- Hayward, J. Ch. 1972. *Near miss determination through use of a scale of danger*. Report No. TTSC 7115, The Pennsylvania State University, PA, USA.
- Hughes, W., R. Jagannathan, D. Sengupta, and J. E. Hummer. 2010. *Alternative Intersections/Interchanges: Informational Report (AIIR)*, Final Report, FHWA-HRT-09-060.
- Hummer, J. E., R. L. Haley, S. E. Ott, R. S. Foyle, and C. M. Cunningham. 2010. *Superstreet Benefits and Capacities*, Final Report, NCDOT, Project: 2009-06.
- Inman V.W., and R. P. Haas. 2012. *Field Evaluation of a Restricted Crossing U-turn Intersection*, Final Report, FHWA-HRT-11-067.
- MacCarley, A. C. 2011. "A Comparison of Real-time and Short-term Aggregated Metrics of Potential Accident Risk and Severity." *Transportation Research Record*, TRB, Washington, D.C., 1-17.
- Manual of Uniform Traffic Control Devices, 2009 Edition. FHWA, U.S. Department of Transportation.
- Maze, T., Hochstein, J., Souleyrette, R., Preston, H., Storm, R. *Median Intersection Design for Rural High-Speed Divided Highways*. NCHRP Report 650. TRB, Washington, D.C., 2010.
- Minderhoud, M. M. and P. H. Bovy. 2001. "Extended time-to-collision measures for road traffic safety assessment," *Accident Analysis and Prevention*, 33(1), 89-97.
- Missouri DOT, Central District Traffic Volume and Commercial Vehicle Count Map, 2011. <http://www.modot.org/safety/trafficvolumemaps.htm>
- Mounce, J. M., G. Ullman, G. Pesti, and V. Pezoldt. 2007. *Guidelines for the Evaluation of Dynamic Message Sign Performance*, Texas Department of Transportation, Texas.

Persaud, B. N., R. A. Retting, P. E. Garder, and D. Lord. 2001. "Safety Effect of Roundabout Conversions in the United States: Empirical Bayes Observational Before-After Study." *Transportation Research Record* 1751, Transportation Research Board, Washington, D.C., 1-8.