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Restricted Crossings on Rural Highways

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16. Abstract

This study examines the potential for replacing the standard intersection design at two-way stop control (TWSC) and all-way stop control (AWSC) intersections along rural highways with a roundabout or a restricted crossing u-turn (RCUT) facility. The geometry of the RCUT design prohibits left and through movements from the side road, and provides a u-turn location downstream from the main crossing. This type of facility has been implemented for rural highways extensively in both Maryland and North Carolina, as well as in limited cases in many other states such as Minnesota and Missouri, with the potential to serve as a cost-effective solution to improve roadway safety within Nebraska. The primary takeaway from the research is that both a roundabout and an RCUT design can be relied upon to lead to significant safety improvements for unsignalized intersections on rural highways, and that the decision of which one to use should factor in the potential increase in delays to the minor approach at the RCUT design if a high demand volume is anticipated (such as Dakota City), or the consideration of whether it is permissible to interrupt the flow of the major arterial through movement with a roundabout versus leaving it free-flowing with the RCUT.

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Executive Summary

This study examines the potential for replacing the standard intersection design at two-way stop control (TWSC) and all-way stop control (AWSC) intersections along rural highways with a roundabout or a restricted crossing u-turn (RCUT) facility. The geometry of the RCUT design prohibits left and through movements from the side road, and provides a u-turn location downstream from the main crossing. This type of facility has been implemented for rural highways extensively in both Maryland and North Carolina, as well as in limited cases in many other states such as Minnesota and Missouri, with the potential to serve as a cost-effective solution to improve roadway safety within Nebraska.

The three case study site locations selected are chosen from a list of candidate sites provided by the Nebraska Department of Transportation. Each of these locations meets the criteria of being an unsignalized TWSC or AWSC junction between a four-lane rural highway and a minor road arterial, as well as having a higher than average observed crash frequency and severity over the previous five years.

Comparative analysis is conducted for three site locations (Humphrey, Madison, and Dakota City, Nebraska) with either TWSC or AWSC existing geometry, analyzing the anticipated impacts of mitigation with a roundabout or an RCUT design. Initial geometric analysis suggests that most potential RCUT locations in the state will require some realignment of the roadway to achieve the necessary separation to make the u-turn movement, with significant full-depth roadway reconstruction increasing the cost of the project. The existing 40-foot medians are approximately 24-feet too narrow to accommodate a u-turn movement by a WB-40 design vehicle.

Assessing TWSC, AWSC, roundabout, and RCUT geometries in both Humphrey and Madison, all four geometries are predicted to have average delays of fewer than 15 seconds per

vehicle during the peak hour, well below acceptable thresholds. The intersection of US-75 and Nebraska-35 in Dakota City experiences significantly more demand volume than the other two sites, and while it is appropriate to keep this site unsignalized, the TWSC and RCUT designs exhibit much higher average delays, closer to 25 seconds per vehicle, with some movements in failure for both designs. The take-away from the operational analysis is that while the roundabout and RCUT designs do no harm for low demand volume conditions, at higher volumes the traffic experiences significant delay, and the TWSC and roundabout options operate better as volumes climb toward the need for signalization.

The costs and benefit analysis from implementing the various intersection geometries includes monetized delay costs, monetized crash costs, and anticipated construction costs. Comparing the TWSC and AWSC intersections against the roundabout, the anticipated delay is sometimes less and sometimes more for the roundabout, but the relative costs for delay over the course of the year are minimal, in the range of $100 to $200 thousand per year. The experienced travel time at the RCUT intersection is anticipated to be around twice that of the existing TWSC and AWSC intersections, but again in a relatively low range of $200 to $600 thousand per year. In contrast, the monetized crash costs for the existing geometries ranged from the low of $1.6 million for the relatively safe AWSC site in Dakota City, to the higher $2 million for the TWSC site near Madison, all the way up to $7.5 million per year for the location in Humphrey which has experienced a high crash rate in recent years. Mitigating these locations with either a roundabout or an RCUT intersection is anticipated to reduce the monetized safety costs by an order of magnitude, in the range of $200 to $250 thousand at Dakota City, $135 to $145 thousand at Madison, and $350 to $450 thousand per year at Humphrey. Combining the safety and operations data, the combined benefit per year of constructing an RCUT junction compared with the existing condition is around $1.1 million for Dakota City, $1.8 million for Madison, and $4.8 million per year for Humphrey. The roundabout exhibits less delay and has slightly better safety performance than the RCUT, and the anticipated benefits for it are around a 10% improvement over the RCUT. If these monetized delay and safety costs are assumed to be equivalent weight to the construction costs expended to implement the design, both a roundabout and an RCUT design would provide a positive return on investment after less than one year, with an anticipated lifetime of 20 to 30 years before reconstruction may become necessary. In the most extreme case of a roundabout intersection being constructed at Humphrey, the return on investment was calculated at just 0.07 years, or 25 days.

However, despite the potential benefit of reconstructing every unsignalized rural highway intersection to achieve the anticipated safety benefits associated with these designs, there is limited budget for construction in any given year, and an increasing need to spend that limited budget to maintain the aging surface roadway infrastructure, rather than taking on new projects such as roundabout and RCUT reconstruction. State agencies thus need some methodology to triage which intersections to examine for potential mitigation, and the decision matrix provided is intended to assist with this process. The decision matrix seeks to assess specifically whether an RCUT intersection would be appropriate, and the five factors for consideration identified include (1) the safety concerns at the location, (2) the overall levels of traffic demand, (3) the balance between major and minor movement traffic demand, (3) the presence of obstructions along the main roadway that would impact u-turn bay placement, and (5) the available space in the median for the u-turn bay.

The primary takeaway from the research is that both a roundabout and an RCUT design can be relied upon to lead to significant safety improvements for unsignalized intersections on rural highways, and that the decision of which one to use should factor in the potential increase in delays to the minor approach at the RCUT design if a high demand volume is anticipated (such as Dakota City), or the consideration of whether it is permissible to interrupt the flow of the major arterial through movement with a roundabout versus leaving it free-flowing with the RCUT.

Chapter 1 Introduction

1.1 Background and Motivation

Median-divided rural highways have intersections with minor roads that are two-way stop controlled throughout the less populated areas of Nebraska. These high-speed road crossings with a low-volume crossing street pose severe safety concerns, as drivers pulling out sometimes misjudge the time available for their maneuver, leading to the most severe types of crashes.

Three example locations that meet the criteria described above were chosen from around the state of Nebraska for analysis in this report, including the intersection of US Highway 75 (US-75) and Nebraska Highway 35 (NE-35) just to the west of Dakota City, the intersection of US Highway 81 (US-81) with Nebraska Highway 91 (NE-91) to the east of Humphrey, and the intersection on US Highway 81 (US-81) with Nebraska Highway 32 (NE-32) east of Madison.

The intersection of US- 75 and NE-35 near Dakota City, is currently an all-way stop-control (AWSC) intersection and has a high crash-rate history including angle, rear-end, and left-turn leaving crashes. Many solutions have been proposed for this site by the state, including the installation of a roundabout. The intersection of US-81 with NE-91 to the east of Humphrey, is currently a two-way stop-controlled (TWSC) intersection experiencing high crash rates, with a frequency that is nearly four times that of the state average. This intersection has just recently been pushed forward to receive immediate design changes with the intent to be converted to a restricted crossing u-turn. Finally, the intersection of US-81 and NE-32 east of Madison is currently TWSC, has had a history of crash occurrences and has been identified as a concern by NDOT for remediation. This site is unique in that it has geometry restrictions with its narrow median width.

In all of the cases above, demand volumes are too low to meet volume criteria for signalization. The state is actively pursuing methods to improve safety, such as providing displaced right-turn lanes, or signalizing these locations in hopes that signal control may help with the crash patterns observed. In some cases, grade separation is being proposed, a solution that will correct the existing crash patterns, but will cost roughly 12 million dollars per treatment. This report sets out to document safe and cost-effective at-grade crossing alternatives, such as the restricted crossing u-turn design, to improve safety on our road network while limiting expenditures.

1.2 Research Questions and Contribution

This study examines the potential for replacing the standard intersection design at TWSC and AWSC intersections along rural highways with a roundabout or a restricted crossing u-turn (RCUT) facility. The geometry of the RCUT design prohibits left- and through-movements from the side road, and provides a u-turn location downstream from the main crossing. This type of facility has been implemented for rural highways extensively in both Maryland and North Carolina, as well as in limited cases in many other states such as Minnesota and Missouri, and has the potential to serve as a cost effective solution to resolve safety issues within Nebraska.

This research will aid the Nebraska Department of Transportation (NDOT) in providing guidance on a safe, efficient, and field-tested solution to cost-effectively mitigate current safety concerns and future conditions at two- and four-way stop controlled intersections of rural highways and minor roads. As an alternative to providing grade-separation as a safety treatment, the RCUT design is expected to save up to ten million dollars per treatment location. However, these designs require a sizable median to implement, and this research is necessary to determine both the best practices for which geometry to implement in a variety of conditions, but also what the potential cost impacts could be depending on the existing configuration of the roadway.

Recognizing that the RCUT design is not the only potential at-grade alternative, comparative analysis is performed between TWSC, AWSC, roundabout, and RCUT designs. Cost effectiveness will include the incorporation of monetized delay experienced by drivers, monetized safety costs associated with predicted crash frequency and severity, and direct costs associated with construction of this type of facility.

1.3 Methodology

This research study analyzes predicted safety and economic impacts from the conversion of traditional two-way stop controlled (TWSC) and all-way stop controlled (AWSC) intersections on rural highways to safer intersection alternatives such as roundabouts and restricted crossing u-turn (RCUT) designs. The primary inputs for the study are the existing geometric conditions, the crash history, and the observed peak-hour traffic at each of the sites selected for study. The output of the study is the economic analysis of the intersections with both existing and proposed conditions, using multiple service measures such as average delay per vehicle, and reduction of crash severity and frequency. Of primary concern is an examination of construction cost, including a return-on-investment analysis of the implementation of intersection improvements such as roundabouts or restricted crossing U-turns (RCUT), as this economic analysis will have the greatest impact on the formation of a decision matrix for future use by the Nebraska Department of Transportation (NDOT).

Site selection is conducted in conjunction with NDOT, with geometric data collected from a combination of photogrammetry and site observations, and traffic data collected using

MioVision Scout cameras on site. Operational analysis is conducted using the Highway Capacity Manual methodology, with validation of results provided by microsimulation.

1.4 Document Layout

This thesis is divided into eight chapters. Chapter 1 is the introduction, providing an overview of the purpose for this research, as well as the methods by which it is investigated. Chapter 2 reviews the available literature related to the topic, exploring the current state of the practice as well as identifying key areas for further investigation relating to this research. Chapter 3, the methodology, provides details about site selection, data collection, operational analysis, safety assessment, and economic analysis. Chapter 4 reviews the case study sites selected for analysis as well as the process by which those locations were chosen. Chapter 5 explains the operation analysis portion of the project, assessing vehicle delay and travel time for four at-grade, unsignalized intersection designs at each case study location. Chapter 6 discusses cost analysis and return on investment of each of the design alternatives, and presents a decision matrix providing guidance on when to select the RCUT design versus other design alternatives. Chapter 7 discusses the limitations of the work performed during the course of the research. Finally, Chapter 8 provides a summary of the findings from the research, identifying both conclusions and recommendations for further research with this area.

Chapter 2 Literature Review

Restricted Crossing U-turn (RCUT) intersections, also known as J-turns and Superstreets, are an alternative intersection design solution recently being adopted by many state departments of transportation to improve safety while maintaining throughput on rural highways. The concept for the RCUT design was first proposed in the mid-1980s by Richard Kramer. [1] Maryland and North Carolina were among the first to widely adopt the RCUT intersection design, and it has been implemented in ten different states at the time of this report's publication.

This report provides a literature review of the state of research concerning RCUT design. The main focus of the literature review is on the operational and safety benefits of the design, as well as geometric design alternatives, and site constraint considerations for implementation. Traffic characteristics, bicycle/pedestrian considerations, and user perception are also investigated as secondary considerations.

2.1 Restricted Crossing U-turn Intersection (RCUT)

The Restricted Crossing U-turn concept was first published in the 1980s. Some advantages of the RCUT design over conventional intersections include a reduction in delay for major street traffic, and a reduction in conflict points, leading to increased safety. RCUT intersections can be divided into three different types: signalized, stop-controlled, and merge/yield-controlled [1], though the majority of implementations and research to date has been with unsignalized RCUT intersections. RCUT intersections throughout this report are assumed to be unsignalized, unless otherwise stated.

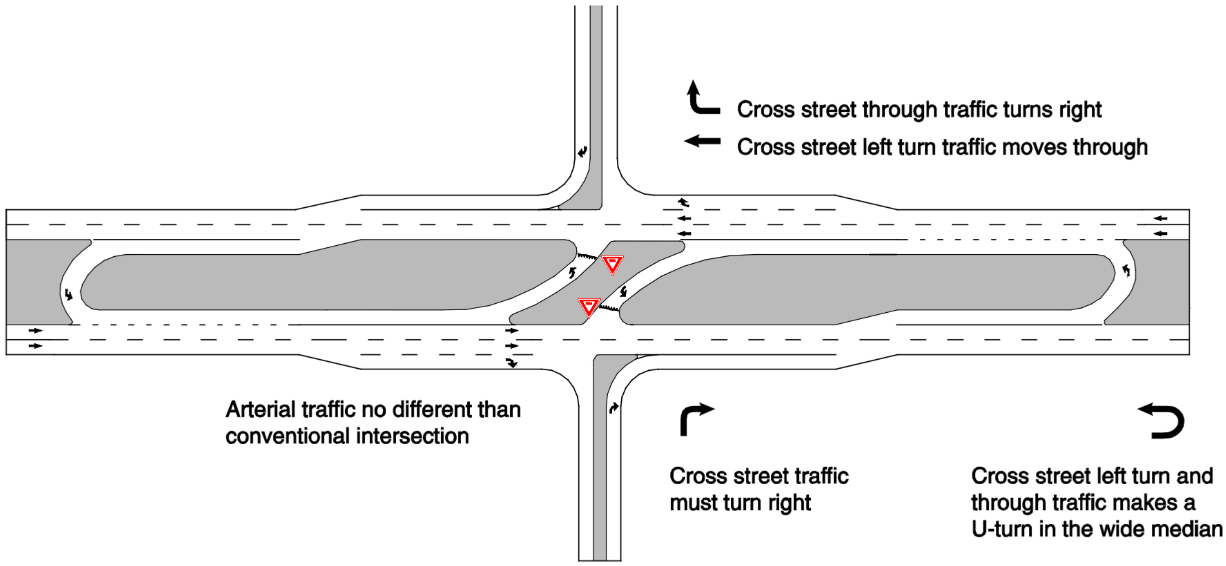


Figure 2.1 Typical yield-controlled RCUT intersection with merges [1]

2.1.1 History of RCUT Implementation

Richard Kramer provided the theory and approach of what was to become the RCUT intersection design in 1987 [2]. Variations of the design were first implemented in Michigan, Maryland, and North Carolina in the 1980s [3]. It slowly spread to other states over the last few decades, with a recent increase in the rate of implementation. Advancing research in the area of alternative intersection designs has contributed to this, as well as the release of a number of publications by the Federal Highway Administration (FHWA), most notably which a Tech Brief on the RCUT design, providing guidance for DOTs interested in implementing the alternative design [1].

2.1.2 Variation in Geometric Design of RCUTs

Three major geometric design features need to be considered when implementing RCUT designs: u-turn spacing, acceleration-deceleration zones, and the median u-turn area. Design parameters for each of these are made on a case by case basis, but RCUT designs usually align themselves into two categories, urban or rural. Although this report exclusively investigates rural intersections, urban RCUT designs are also discussed due to their prevalence.

Unlike rural RCUT intersections, which are almost exclusively unsignalized, urban RCUTs are often signalized, requiring the design of signal-timing patterns and the movement of pedestrians through the intersection. Due to increased site constraints, urban RCUT designs are often more compact, with shorter turn bays, and smaller offsets between the main intersection and the u-turn location. The u-turn offset is often only a few hundred feet in urban areas, as opposed to a typical range of 1,000 to 2,000 feet in a rural setting. In addition, the lack of medians in cities often cause urban RCUT junctions to use pavement bump-outs called "loons," (because the shape of the paved area is similar to the head of the bird), beyond the limits of the opposing travel way, to accommodate the turning radius of larger vehicles.

Although FHWA has provided general guidance on best practices for implementing these designs, specific geometric layout of these intersections has been left largely to the state DOTs to design [1].

2.1.2.1 U-turn Spacing

Determination of the optimal distance between the main intersection and the downstream u-turn at an RCUT intersection is an ongoing topic of discussion and debate within the literature. Claros et al. used a crash analysis based approach to determine optimal spacing, finding that crash frequency decreased as the u-turn spacing increased [4]. Twelve RCUT facilities were studied and separated into three categories for u-turn spacing: under 1,000 feet, 1,000 to 1,500 feet, and over 1,500 feet. Claros et al. found a significant decrease in frequency of crashes for each step of increased distance, specifically for sideswipe and rear-end collisions, as shown in figure 2.2.

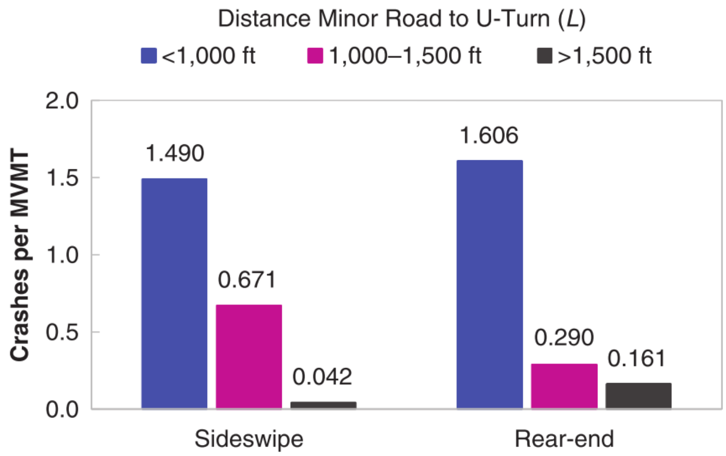


Figure 2.2 Major Road Sideswipe and Rear-end Crash Rates [4]

The main drawback of Claros et al.'s research is the small sample size of RCUT intersections examined. Xu et al. investigated the same issue, varying the offset lengths in three categories: 700, 1,100, and 1,500 feet. Their results indicated that safety performance is not improved increasing from 1,000 to 1,500 feet, but again with a very limited sample size of data [5].

Sun et al. approached the problem of determining optimal offset distance through the use of a driving simulator. Conducting various experiments with around 30 participants, they analyzed offset distances of 1,000 and 2,000 feet [6]. They compared these two distances against various lane configurations, and found that 2,000 feet was preferred when acceleration lanes were present, but that 1,000 feet was adequate for a deceleration only configuration [6].

Zhang et al. provided verification for the results stated above through the analysis of 35 rural RCUT intersections and their respective crash data. They found that when the u-turn offset is less than 1,500 feet, crash rates increased in the presence of acceleration lanes. They also determined that this trend reversed when the offset was greater than 2,000 feet.

Urban RCUTs have seen much less research on u-turn spacing compared with rural locations. This is due in part to the geometric restrictions that exist in an urban setting. Within a rural setting the u-turn can be placed thousands of feet down the road without complicating other traffic movements. Urban environments are much more compact, and the u-turn is often just a few hundred feet downstream. The close location of the urban RCUT u-turn bay is largely due to the signalized control of the movements, as the minor approach weaving movement is not occurring at the same time as a high-speed major approach through movement, as it does in a rural setting where the major movements are unimpeded.

2.1.2.2 Acceleration-Deceleration Lanes

Along with the examination of optimal u-turn spacing, Claros et al. determined if the presence of acceleration lanes made a significant difference in safety. Based analysis of crash histories, they found that without the presence of acceleration lanes after the minor road there was a 33% increase in crashes, and a 393% increase if an acceleration lane was not present after the u-turn [4]. They also used the FHWA's surrogate safety assessment model (SSAM) to analyze their simulation models and confirmed that the presence of acceleration lanes leads to a net decrease in conflicts, regardless of the u-turn offset length.[4].

Sun et al. analyzed the presence of deceleration and acceleration lanes with a driving simulator. They found that having both acceleration and deceleration lanes decreased critical safety events by 66.3%, compared with a deceleration-only lane configuration [6]. However, this research also had a low number of scenarios tested, and a more thorough evaluation was recommended for the future.

2.1.2.3 Median U-turn Considerations

Based on A Policy on Geometric Design of Highways and Streets by AASHTO, typically referred to as "the Green Book," [7], Hochstein et al. developed a table using the Green Book's median u-turn design criteria that shows the minimum median width for different design vehicles. They found that the school bus is often the design vehicle used for design of rural highways, requiring a minimum median width of 63 feet [8]. In contrast, the typical median for rural highways in Nebraska is 40 feet, so a loon would be necessary to accommodate this design criteria.

2.2 Operational Impacts

In addition to site geometry, operational impacts of the intersection need to be considered, encompassing travel time, delay, travel time reliability, movement prioritization, and multi-modal considerations. The operational impacts of an RCUT design are dependent on the existing travel demand flowrates, and lane configurations of the intersection should be tailored to turn-movement demands at each site for proper analysis.

2.2.1 Overview of Operational Impacts for RCUT designs

The u-turn offset is the geometric feature that has the largest effect on the overall delay experienced by motorists as they travel through the intersection. The u-turn offset is dictated by site restrictions and safety needs [5]. Engineers create the offset as short as possible without compromising safety in order to keep travel time to a minimum. It should be noted that additional travel time due to rerouting when traveling through an RCUT only applies to minor-street through and left-turning movements.

Haley et al. found in their simulation study that RCUTs had a lower travel time standard deviation compared with an equivalent conventional intersection, meaning that although travel times may have increased, they were more consistent [9]. Their study also revealed that RCUTs led to an overall reduction in travel time, for some volume scenarios, relative to specific other intersection designs such as the all-way stop controlled intersection (AWSC). The nature of the RCUT intersection prioritizes the major approach movements over the left and through movements at the minor approach. The major road's traffic will flow unimpeded for the most part compared with a conventional AWSC intersection. From a safety perspective there is an adjustment of traffic conflict zones. Instead of one concentrated area at the main intersection, the points of conflict are spread out, allowing motorists to focus on fewer movements at a time to maintain safety. In addition to the spreading of conflict points, there is an overall reduction in number of them, which provides the theory behind the safety results that have been observed at these intersections when implemented [10].

The RCUT design is now established enough that researchers have begun to examine multi-modal considerations. Holzem et al. conducted an in-depth study of pedestrian and bicyclist accommodations at RCUT intersections, examining multiple crossing patterns for pedestrians and bikes to optimize the average travel time and number of stops [11]. Although this is a primary concern for urban RCUT implementations, pedestrian and bicycle concerns are largely not applicable for rural highway locations.

2.2.2 Travel Time Impacts of RCUTs

Holzem et al. found that the travel time at the RCUT intersection was reduced compared with the AWSC intersection [11]. In respect to individual turn movements, the minor approach's left and through movements have an increased delay, but the major street's through and left movements experience a decrease in delay, with unimpeded through movements resulting in the aggregate increase in performance in terms of average delay per vehicle.

Kim et al. also found a travel time savings, with a delay reduction of 28% to 31% for an RCUT design compared with a conventional AWSC intersection, as well as 12% to 23% higher throughput, or maximum capacity [12].

2.2.2.1 Travel Time

Travel time at an RCUT intersection is of concern since the minor road has redirected through and left-turn movements, while the major road through movements are unimpeded. It has been shown that travel time decreased overall for RCUT intersections compared with their corresponding conventional signalized intersection, depending on the volume scenarios examined [13].

Using an empirical evaluation, Edara et al. found that for some traffic demand conditions that the average wait time at unsignalized RCUTs was half, at 5 seconds, compared to a two-way stop controlled intersection, at 11 seconds [14]. This wait time reduction comes from the minor road approach at a location that provided acceleration lanes. In situations without acceleration lanes the wait time to make a right turn movement would most likely increase because of the need to find a gap in traffic.

Edara et al. did consider average gap acceptance values of vehicles downstream from the intersection merging from the acceleration lane into the right lane of traffic, and from the right lane into the left lane. It was found that these merging maneuvers took 8.3 s and 11.6 s, respectively [14]. This difference is most likely due to the higher speeds of vehicles in the through lanes. Even though wait times were reduced, the average travel time for vehicles was 1 minute higher for RCUTs compared with two-way stop controlled intersections [14], due to vehicles having to travel downstream to the u-turn before being able to turn around to access their desired direction of travel.

An FHWA report conducted by Bared et al. used traffic simulation software to compare the operational performance of RCUTs to conventional signalized intersections. They used five RCUT designs and modeled them against three different traffic scenarios. In the cases when the minor street traffic was less than 20% of the total flow, RCUTs had an increased throughput (maximum capacity) of up to 30% and a reduction network travel time by up to 40% [15].

2.2.2.2 Level of Service

The state of North Carolina has a Level of Service (LOS) program that can be used to determine the range of AADT volumes for various intersections, including RCUTs [13]. However, this program only takes into consideration the major road LOS and excludes the minor road traffic, introducing a bias into their design selection process that other state DOTs may object to.

Xu et al. used their linear regression method to find a volume threshold at which the effectiveness of an unsignalized RCUT starts to fail based on the probability of changing lanes from the minor road to the u-turn queue bay downstream, as shown below in figure 2.3. This model was based on a u-turn offset of 1,500 feet. The threshold seems to be located somewhere between 2,500 and 3,000 vph.

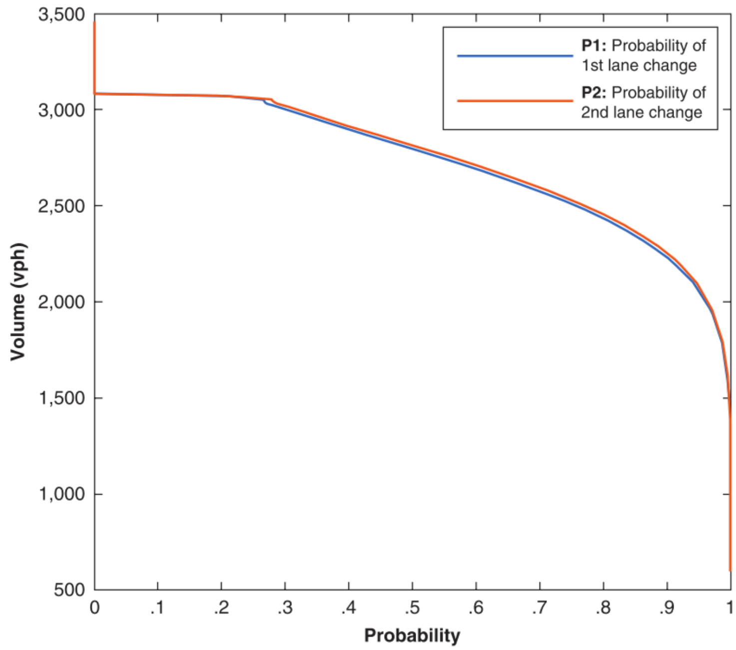


Figure 2.3 Relationship between traffic demand and probability of two lane-changes

2.2.3 Secondary Considerations for Operations at RCUTs

Increased idle time and delay have been shown to have a direct positive relationship with greenhouse gas emissions [16]. The RCUT design has been shown to improve operations at an intersection when compared with signalization, not just in travel time but number of stops and time spent idling [17]. When vehicle stops are introduced to free-flowing vehicles, fuel consumption and vehicle emission rates increase considerably [18].

For some demand volume scenarios, RCUTs have been found to increase the capacity of the intersection. In cases where the minor approach experiences queuing as vehicles wait for a gap to make a left or through movement, some RCUT implementations provide acceleration lanes to allow a continuous stream of traffic from the minor approach to merge with major roadway traffic at speed [19].

2.3 Safety Impacts

By reducing and separating the number of conflict points at the intersection, the RCUT design leads to significant safety benefits, as is well documented in the literature.

2.3.1 Safety Analysis of Conflict Type

Through a safety analysis using the Surrogate Safety Assessment Model (SSAM) developed by FHWA, the total number of conflicts at an RCUT intersection is predicted to be 80% lower than a comparable conventional intersection, when examining one-lane designs, as shown below in table 2.1 [12]. The results are not as positive for two lanes at the u-turn, due to a higher number of lane changes and potential for rear-end collisions.

Table 2.1 SSAM Results of 1 u-turn lane and 2 u-turn lanes [12]

1 u-turn lane case	**Crossing Conflicts**		**Rear End Conflicts**		**Lane Change Conflicts**		**Total Conflicts**	
	Conv.	Super.	Conv.	Super.	Conv.	Super.	Conv.	Super.
Mean	0.40	0.00	100.70	0.00	24.60	27.00	125.70	27.00
Variance	0.93	0.00	360.01	0.00	28.49	35.11	501.57	35.11
t-test value (95%)	1.312 (1.812)		16.783 (1.812)		-0.952 (1.812)		13.473 (1.812)	
Improvement	100.00%		100.00%		-9.76%		78.52%	
Result	Not significant		**Significant**		Not significant		**Significant**	
2 u-turn lanes case	**Crossing Conflicts**		**Rear End Conflicts**		**Lane Change Conflicts**		**Total Conflicts**	
	Conv.	Super.	Conv.	Super.	Conv.	Super.	Conv.	Super.
Mean	0.00	0.00	15.00	27.20	18.70	32.70	33.70	59.90
Variance	0.00	0.00	12.22	21.07	14.90	34.68	41.12	71.88
t-test value(95%)	0.000 (1.812)		-6.687 (1.812)		-6.288 (1.812)		-7.794 (1.812)	
Improvement	0.00%		-81.33%		-74.87%		-77.74%	
Result	Not significant		**Significant**		**Significant**		**Significant**	

Conv. – Conventional Intersection, Super. – Superstreet Intersection
Unit: conflicts per hour

Hochstein et al. found RCUT safety benefits based on an empirical study of RCUT intersection conversions in Maryland and North Carolina, as shown below in table 2.2. Tracking multiple years of crash data both before and after the implementation, they found a large reduction in frequency of almost every crash type [8].

Table 2.2 RCUT intersection conversion safety effectiveness [8]

	LOCATION			
ANNUAL CRASH FREQUENCY	MARYLAND US-301 & MD-313 % CHANGE	N. CAROLINA US-23/74 & SR-1527/1449 % CHANGE	N.CAROLINA US-64 & Mark's Creek Rd. % CHANGE	N. CAROLINA US-321 & SR-1796 % CHANGE
Total Crashes	-91.92 *	-53.33 *	-47.62	-69.23 *
Right-Angle Crashes	-100 *	-100 *	-91.67 *	-100 *
Far-Side Right-Angle Crashes	-100 *	-100 *	-100 *	-100 *
Near-Side Right-Angle Crashes	-100 *	-100 *	-66.67	-100
Left-Turn/Opposing Through Crashes	N/A	+ 66.67	-40.00	+ 100
Rear-End Crashes	-33.33	-25.00	+ Undefined * (+ 0.67 crash/yr)	+ Undefined (+ 0.33 crash/yr)
Total Crashes at Downstream U-turns	No Data	+ 66.67	-9.09	-63.64
* Statistically significant change at 90% confidence level using one-tailed t-test.				

2.3.2 RCUT Crash Severity

The majority of crashes at unsignalized intersections on high-speed rural freeways occur due to turning or through movements of vehicles from the adjacent roadway [14]. These right-angle crashes are of great concern because of their connected relationship to severe injury and fatalities. Many researchers have found that the RCUT design offers a significant reduction to this problem.

Edara et al. analyzed the crash history of five different intersections throughout Missouri and found that the frequency of crashes across all sites decreased by 54.4% after the RCUT design was implemented [14]. An empirical Bayes method was used to compare predicted crash frequency of intersections without the RCUT design to field data. It was found that the RCUT intersection helped reduce the number of crashes by 28-34.2%. The same research found that disabling injury crashes decreased by 91.6%, minor injury crashes decreased by 67.9%, and right angle crashes decreased by 90.2%. However, a limitation of this research is that the RCUT facilities were compared only against a two-way stop controlled (TWSC) intersection. Further analysis should be done to see if similar results would come from comparison with other traditional intersections such as four-way stop controlled, yield controlled, signalized, and grade-separated intersections.

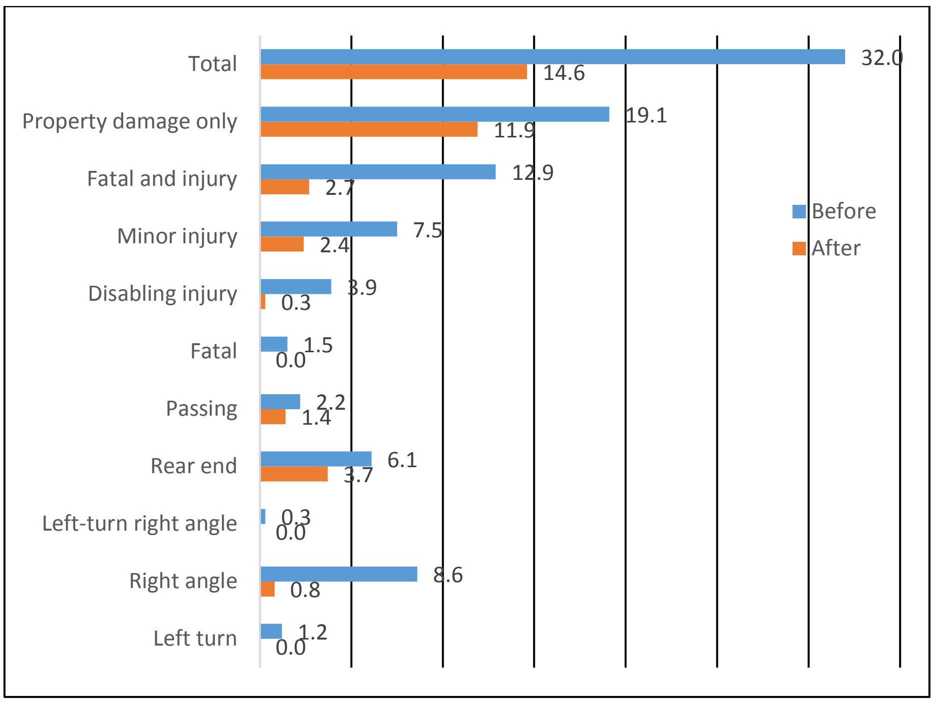


Figure 2.4 Annual crash frequency, before and after RCUT implementation [14]

Research done by Evans et al. for the FHWA confirms many of the findings from Edara et al. Property damage only (PDO), fatal, and all overall injury crashes decreased. Their research shows a 70% drop in fatal crashes, as well as a 42% reduction in injury crashes between the 3-year periods studied, as shown below in table 2.3 [20].

Table 2.3 Observed crashes by severity before and after RCUT treatment [20]

Location	Before Period			After Period		
	PDO	**Fatal**	**Injury**	**PDO**	**Fatal**	**Injury**
U.S. 15 at Hayward Road	32	1	41	36	0	59
U.S. 15 at Willow Road	29	1	22	27	0	22
U.S. 15 at Biggs Ford Road	38	1	46	21	1	10
U.S. 15 at Sundays Lane	13	0	12	17	0	9
U.S. 15 at College Lane	21	0	28	6	0	5
U.S. 15 at Old Frederick Road	23	1	21	23	1	16
U.S. 301 at Main Street	26	2	24	29	0	14
U.S. 301 at Del Rhodes Avenue	20	1	28	7	0	7
U.S. 301 at Galena Road	16	3	30	7	1	3
Total	**218**	**10**	**252**	**173**	**3**	**145**

Ott et al. investigated the safety effects of unsignalized RCUT intersections in North Carolina. They looked at 13 unsignalized intersections and used a traffic flow adjustment, comparison group, and Empirical Bayes analysis [21]. In Ott et al.'s research they used the Highway Safety Manual (HSM) collision prediction model and calculated a calibrated factor that showed the intersections studied had a higher rate of collisions than the HSM's assumed values. Their findings support those of Edara et al.'s, and show a significant reduction in both crash frequency and severity.

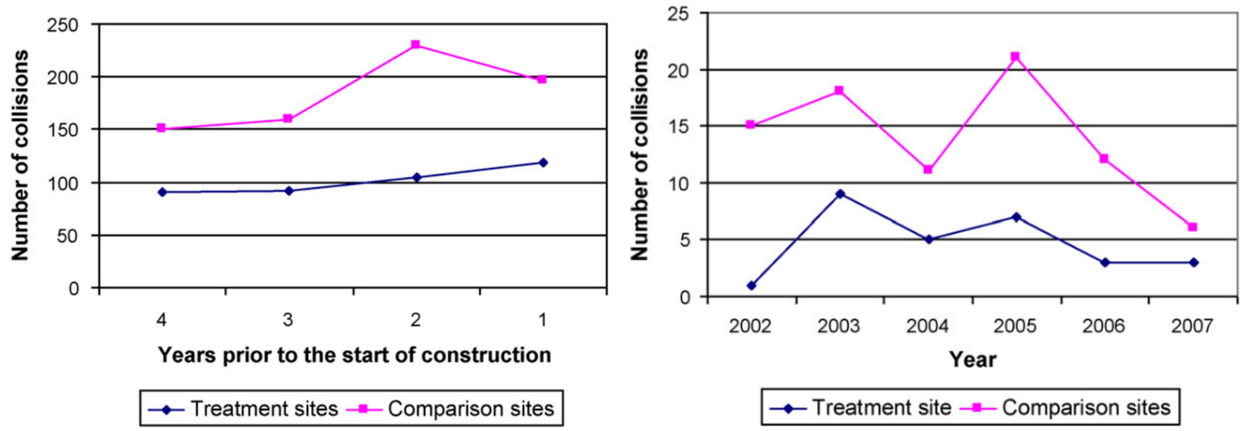


Figure 2.5 Unsignalized RCUT and comparison site collisions before construction [21]

2.4 Secondary Impacts

Other secondary considerations when analyzing RCUT implementation, are likely to include multimodal accommodations, traffic controls, and overall user perception.

2.4.1 Pedestrian and Bicycle Accommodations

The RCUT's design provides unique challenges for accommodating pedestrian and bicycle traffic. The RCUT intersection has a sizable geometric footprint that can make crossings difficult. The federal highway administration only discusses signalized RCUTs when providing accommodations for pedestrian and bicycle traffic [1]. This is due to the lack of demand by multimodal traffic rural locations which are likely to have unsignalized RCUT implementation. Discussion in the literature of pedestrian and bicycle accommodations for RCUTs is assumed to be under signalized conditions.

The "Z" crossing is the most popular crossing configuration, as shown below in figure 2.6. Crossing the major street would be done while the minor movements are taking place. This could be performed in one phase but since the geometric footprint is quite large, two phases could be observed if the minor-road turning phase is short. There would have to be safety accommodations at the median to protect pedestrians walking across the intersection or waiting for the next phase.

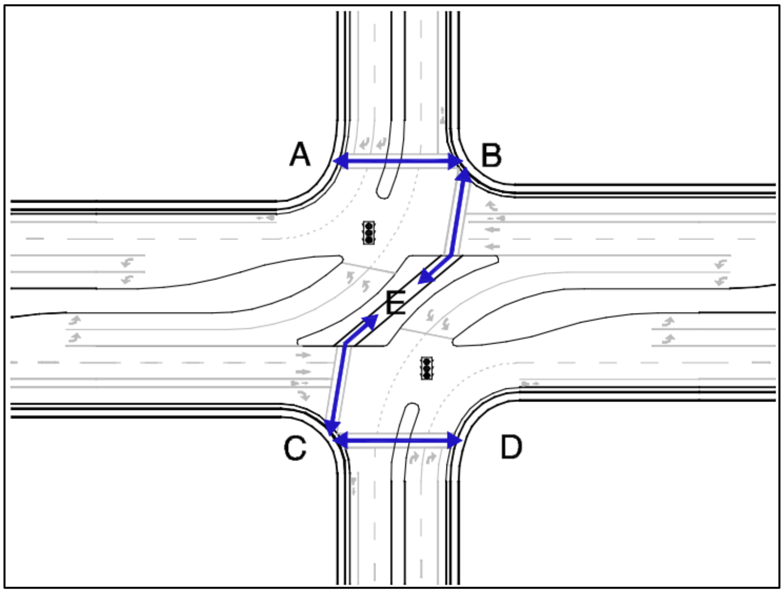


Figure 2.6 Pedestrian Movements in a RCUT intersection [1]

Hummer et al. performed extensive research into this area. They studied signalized RCUTs in North Carolina and found that the two-stage crossing showed the lowest values of average delay, stops, and travel time. This is dependent on high volumes of pedestrian and bicycle traffic, therefore other alternatives may be considered such as the diagonal cross or the midblock cross when lower pedestrian and bicycle volumes are present.

Figure 2.7 Intersection in San Antonio on US 281 [22]

2.4.2 Signing Guidance

The Manual on Uniform Traffic Control Devices (MUTCD) is the standard for guidance on traffic signs, road surface markings, and signals for state agencies [23]. However, the MUTCD does not provide specific guidance for RCUT intersections. Therefore, DOTs that have embraced the RCUT have developed their own guidance and regulations to supplement MUTCD.

There are some minor variances between the guidance thus-far adopted by state agencies. For example, some agencies choose to place signs on the minor approach indicated the need for left-turning and through vehicles to utilize a u-turn bay after making a right turn, while others do not. There are also differences between diagrammatical and directional signage as well [6]. An example of signage guidance used by NCDOT is provided below in figure 2.8. The MUTCD has not been updated since 2009, and the next version of this manual will likely provide national-level guidance on how best to address these issues in implementation.

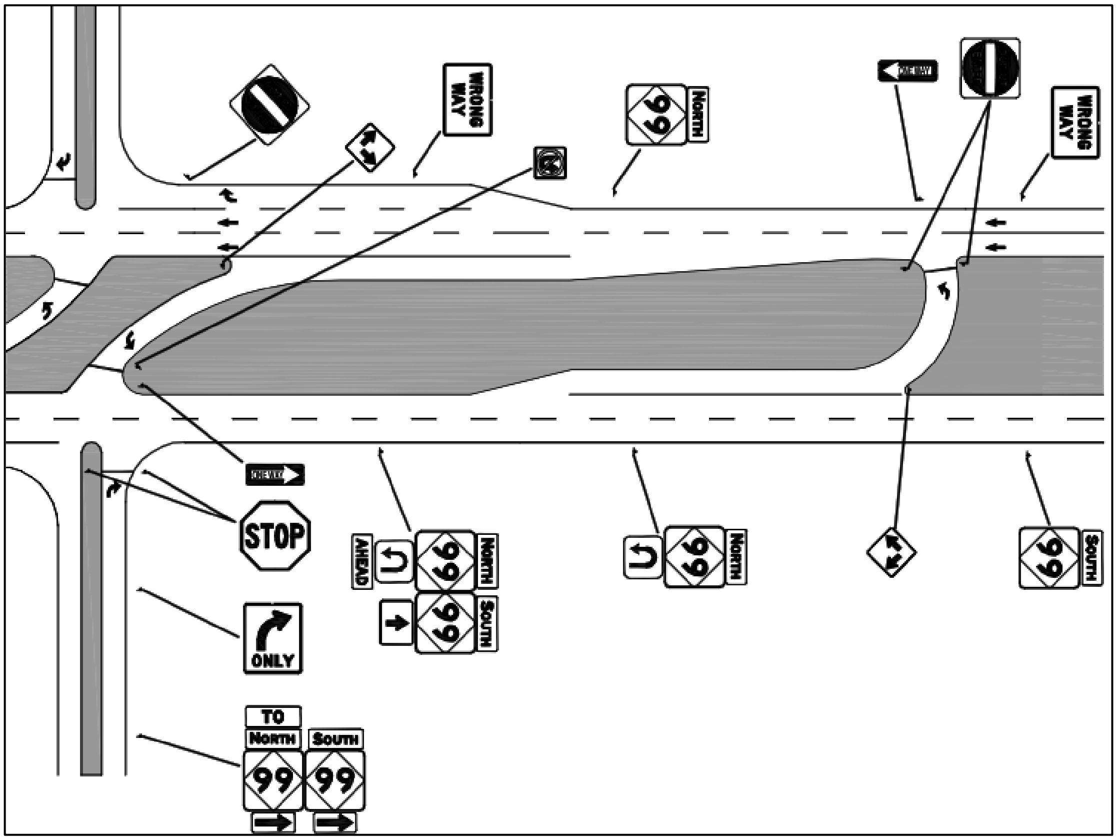


Figure 2.8 Stop-controlled RCUT intersection signing guidance from NCDOT [1]

Some research has been conducted specifically in the area of signage best-practices at RCUT facilities. Sun et al. performed a driving simulator experiment to see whether drivers prefer to drive using diagrammatical- or directional-style signage [6]. They found little difference, with 37% of the drivers surveyed preferring diagrammatic and 47% preferring directional, with the remaining participants indifferent.

2.4.3 User Perception

Ott et al. studied resident, commuter, and business perceptions of RCUT installations, using surveys of the stakeholders in the area. Most residents living near the RCUTs agreed that it increased safety and saw its benefits. Commuters using the intersection perceived the RCUT to be more challenging to navigate, but felt strongly about savings in travel time and queue lengths. Business owners on the other hand felt it created confusion for their customers, and were concerned that it would negatively impact business [24].

A driving simulator study done by Sun et al. investigated user's perception of the intersection as well, but had more experienced participants, with 77% having driven through RCUTs in the past. The majority of participants perceived RCUTs to be easy to navigate, had an appreciation for the safety benefits they provided, and felt safer driving through the RCUT instead of the equivalent two-way stop controlled intersection. The study also surveyed drivers on their opinion of RCUT geometry variances, finding that they preferred having both acceleration and deceleration lanes present as well as longer u-turn offsets, with 83% of respondents preferring the 2,000 foot offset versus only 1,000 [6].

2.5 Economic Analysis

Several economic analyses have been done examining the conversion of TWSC intersections to various other geometries. Bonneson et al. first analyzed the conversion of a TWSC to either a signalized intersection or a grade-separated interchange (GSI) [25]. They found that the GSI had a better return on investment than installing a signal, particularly when the minor road demand is less than half of the major, which is the case for the majority of high-speed rural intersections in Nebraska. Zhao et al. assessed the safety and economic factors of converting a TWSC on rural high-speed locations to roundabouts, and found that the average conversion of these locations with higher-than-normal crash histories resulted in a cost benefit of between $1.0 and $1.6 million annually, based on reduced crash severity and frequency [26].

Morello et al. did a preliminary economic analysis on RCUTs for safety mitigation on rural highways, estimating construction costs based an example RCUT project from the FHWA Information Guide on Restricted Crossing U-turns [1], [27]. They found in most cases that safety and operational benefits of the RCUT provide the best return on investment within a few years, even compared against maintaining the existing TWSC geometry.

Chapter 3 Methodology

This research study analyzes predicted safety and economic impacts from the conversion of traditional two-way stop controlled (TWSC) and all-way stop controlled (AWSC) intersections on rural highways to safer intersection alternatives such as roundabouts and restricted crossing u-turn (RCUT) designs. The primary inputs for the study are the existing geometric conditions, the crash history, and the observed peak-hour traffic at each of the sites selected for study. The output of the study is the economic analysis of the intersections with both existing and proposed conditions, using multiple service measures including average delay per vehicle, reduction of crash severity and frequency, and a number of secondary output measures such as idle time. Of primary concern is an examination of construction cost, including a return-on-investment analysis of the implementation of intersection improvements such as roundabouts or restricted crossing U-turns (RCUT), as this economic analysis will have the greatest impact on the formation of a decision matrix for future use by the Nebraska Department of Transportation (NDOT).

3.1 Proposed Restricted Crossing U-turn Geometric Design

The proposed RCUT analyzed is stop controlled on all movements but the major route through and right-turns. The north and south U-turns are located at 1,300 feet and 1,600 feet respectively from the main intersection. Deceleration lanes are included for both the U-turn approach and the right turning vehicles from the major-roads. All other geometric features are standard RCUT design as laid out in the FHWA RCUT informational manual [1]. Figure 3.1 shows a typical layout implemented as a VISSIM model.

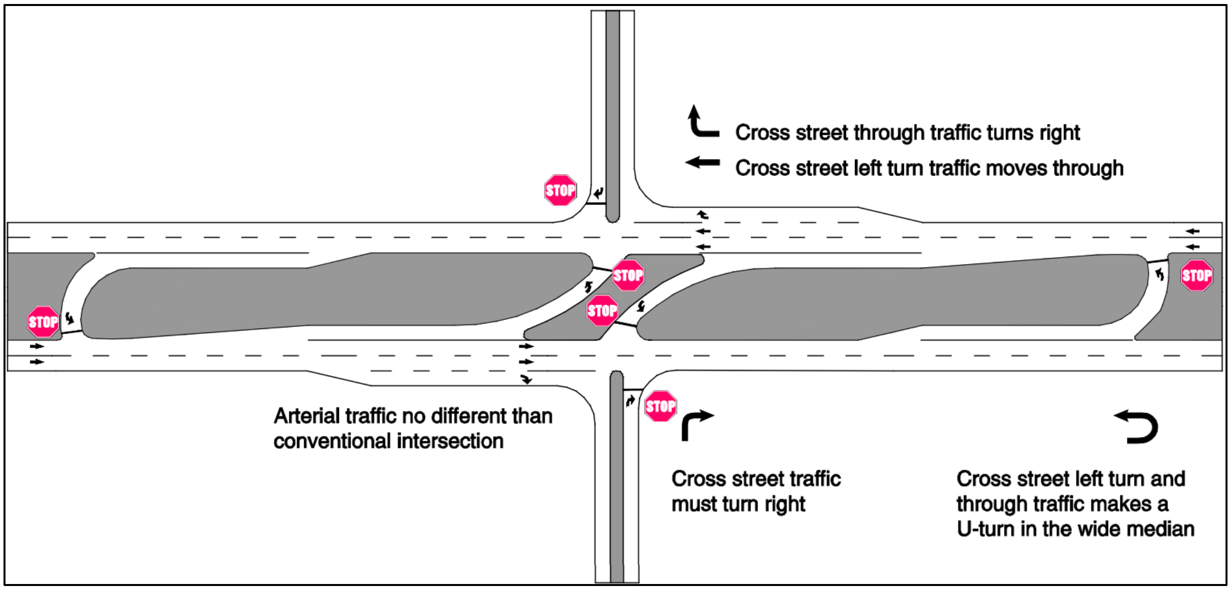


Figure 3.1 Federal Highway Administration diagram of a stop-controlled RCUT [1]

The key feature of the RCUT design is the U-turn aspect. A roadway needs to have adequate median space to accommodate the turn bay and ideally a majority of the U-turn itself. This varies from 8 feet to 76 feet depending on the design vehicle and how much of the turning motion can be fit within the median, as shown below in figure 3.2.

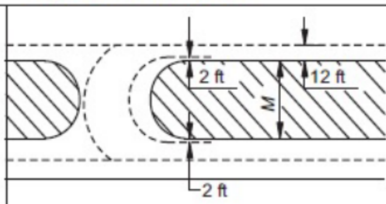
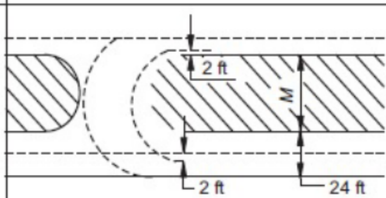
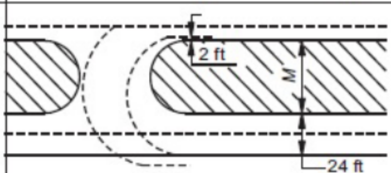
U.S. Customary								
		M—Minimum Width of Median (m) for Design Vehicle						
		P	WB-40	SU-30	BUS	SU-40	WB-62	WB-67
		Length of Design Vehicle (ft)						
Type of Maneuver		19	50	30	40	40	63	68
Inner Lane to Inner Lane		30	61	63	63	76	69	69
Inner Lane to Outer Lane		18	49	51	51	64	57	57
Inner Lane to Shoulder		8	39	41	41	54	47	47

Figure 3.2 AASHTO-recommended minimum median widths for U-turn crossovers [1]

When the U-turn maneuver cannot be completed within the median, extra roadway surface needs to be installed on the shoulder of the major road where the U-turn is being completed. These geometric features are known as loons. They allow for locations restricted by geometry to accommodate a RCUT design. At locations without an existing median, a realignment of the highway, with corresponding additional cost would be incurred.

<u>3.2 Case Study Location Selection Methodology</u>

The case study locations selected were chosen in consultation with the staff at the Nebraska Department of Transportation (NDOT). Key characteristics of potential sites include those that are currently experiencing safety issues, as well as a variety of existing roadway conditions to assess potential cost impacts of exiting median widths.

Both the RCUT and roundabout designs improve safety by restricting movement of left-turning vehicles, reducing and separating vehicle conflict points at an intersection. The best locations for introducing RCUT intersections into Nebraska would therefore be experiencing higher than acceptable crash histories, specifically with a significant number of crashes involving left-turning vehicles. However, a major concern of NDOT is the efficient allocation of limited resources, so cost considerations must also be a major factor in choosing potential locations for these intersection improvements. The sites selected were chosen to exhibit a variety of existing geometric designs, specifically with varying existing median widths, so that the potential cost of roadway realignment could be factored into remediation decisions.

3.3 Traffic Data Collection Methodology

To collect the necessary traffic data for this study, four Miovision Scout cameras were placed at each intersection study location. An example of the equipment setup is shown below in figure 3.3. All data was collected during the month of April for all locations. This was done to ensure that that school-related traffic would be measured. Data collection was conducted between Tuesday and Thursday, under normal weather conditions without precipitation.

Figure 3.3 Setup of Miovision Scout cameras

The collected video data was uploaded for processing to Miovision, which analyzes the video data and provides traffic volume measurements as turn-movement counts for each fifteen-minute period for the duration of the video recording.

3.4 Operational Analysis Methodology

Operational analysis of the case study locations focuses primarily on the standard metrics established by the Highway Capacity Manual, using the average delay of vehicles at the intersection during the peak hour of demand [28]. This measure serves as an indicator for the overall performance of the intersection, communicating its success or failure related to congestion. Secondary analysis includes the investigation of the average delay of specific turn-movements; identifying root causes of intersection underperformance. Specific to the use of alternative intersections as a mitigation strategy, some turn-movement groups become more important than others, due to restrictions and redirection of turn-movements.

The data was analyzed using two separate software applications: Vistro and VISSIM. Vistro is a traffic modeling software based on the Highway Capacity Manual (HCM) [29] methodology, which utilizes macroscopic flow parameters to analyze traffic performance. VISSIM is a micro-simulation traffic modeling software, modeling the flow of each car through a road network [30]. The results from both applications are compared later in this report, showing the strengths and shortfalls of the methodology of each.

3.4.1 HCM Analysis

To establish a baseline for the analysis of case study sites, the existing network performance is analyzed in Vistro. Vistro allows for easy adaptation of the different geometries present at the study locations, so many more alternative designs can be modeled in a short period of time, relative to conducting microsimulation analysis. Vistro is limited, however, in its ability to evaluate alternative intersections, as it only includes HCM analysis included in the 2010 edition of the HCM. Hand calculations were performed to obtain RCUT HCM results, based on the 2016 edition of the manual.

Traffic volumes, heavy vehicle percentatges, and peak-hour factors were all gathered from field data collection and inputted into Vistro. This information is supplmented with geometric characteristics such as median width, lane width, and merge and turn lane pocket lengths. Other key parameters such as free-flow speed are also accounted for. Vistro then incorporates default values for HCM parameters not observed or calibrated in the field.

3.4.1.1 Delay versus level of service

The Highway Capacity Manual's (HCM) primary measure of performance for any intersection is level of service (LOS) [29]. There are six grades defined within LOS, ranging from A to F, which are based on a variety of service measures. The grading scheme is intended to represent travelers' perceptions, and simplify decision making regarding potential future changes to a roadway facility. LOS is directly tied to average vehicle delay at the intersection, though the relationship between the two changes slightly based on the type of intersection being analyzed. Conventional signalized, all-way stop, and two-way stop intersections use control delay to discern a corresponding LOS grade, while alternative intersections incorporate additional travel time due to rerouting, and use experienced travel time (ETT).

The HCM defines control delay as "the delay brought about by the presence of a traffic control device." This includes vehicles slowing before an intersection, wait time at the stop bar, the time within the queue, and the time required to accelerate back to free-flow speed [29]. The control delay excludes delay caused by geometry and delay from vehicles slowing to make a turn or reducing speed for merging vehicles.

Experienced travel time (ETT) is a measure introduced for purposes of assessing alternative intersections, and combines control delay with extra distance travel time (EDTT). EDTT is the time required to travel the additional distance introduced for rerouted turn movements within an alternative intersection. In the case of the RCUT, it is the time it takes minor-street left and through movements to travel from the main intersection to the U-turn and then back again. Vehicles are assumed to be traveling at free flow speed. Figure 3.4 shows the HCM's ETT window for each of the corresponding LOS grades.

ETT (s/veh)	Condition $v/c \leq 1$ and $R_Q \leq 1$ for Every Lane Group	 $v/c > 1$ for Any Lane Group	 $R_Q > 1$ for Any Lane Group
≤10	A	F	F
>10–20	B	F	F
>20–35	C	F	F
>35–55	D	F	F
>55–80	E	F	F
>80	F	F	F

Figure 3.4 LOS Criteria for Each O-D within Alternative Intersections (HCM)

3.4.1.2 Two-way Stop Controlled Intersection LOS

The delay for two-way stop controlled intersections is measured in two different ways in this study. The first uses the Highway Capacity Manual (HCM), the standard in the transportation industry for traffic studies. The HCM uses assumptions from empirical data gathered from previous studies, but is somewhat inflexible to different types of driver behavior across the country. Also, it does not account for through or right turn delay, instead assuming that there is nominal delay if vehicles are not stopped by a traffic control device. Sources of delay experienced in the field but not included in the HCM methodology include impacts of the environment, friction from side street traffic, lane changing behavior, and high vehicle volumes. This being said, the HCM provides an industry standard operations estimation based on well researched and calibrated traffic parameters.

Within the HCM, TWSC intersections and RCUTs are assumed to have different relationships between average vehicle delay and LOS, with the TWSC intersection assumed to have driver expectations for lower delays relative to signalized or alternative intersections. Although there has been discussion in the literature about the potential for a unified delay-LOS relationship, this research will abide by the LOS designations as delimited in the HCM, as shown below in figure 3.5, with signalized interchange denoting intersection designs including RCUTs [31].

Level of Service	**Stop-Controlled Intersection**	**Roundabout**	**Signalized Intersection**	**Roundabout Interchange**	**Signalized Interchange**
A	≤10	x ≤ 10	x ≤ 10	x ≤ 15	x ≤ 15
B	10 < x ≤ 15	10 < x ≤ 15	10 < x ≤ 20	15 < x ≤ 25	15 < x ≤ 30
C	15 < x ≤ 25	15 < x ≤ 25	20 < x ≤ 35	25 < x ≤ 35	30 < x ≤ 55
D	25 < x ≤ 35	25 < x ≤ 35	35 < x ≤ 55	35 < x ≤ 50	55 < x ≤ 85
E	35 < x ≤ 50	35 < x ≤ 50	55 < x ≤ 80	50 < x ≤ 75	85 < x ≤ 120
F	50 < x	50 < x	80 < x	75 < x	120 < x

Figure 3.5 Relationship between average vehicle delay and LOS [31]

3.4.1.3 Restricted Crossing U-Turn LOS

The HCM added methodology to analyze RCUTs in the 6th edition, in 2016. Because there is not yet a significant amount of literature examining the robustness of this new methodology for evaluating RCUT intersections, this report attempts to validate the RCUT analysis results from the HCM using microsimulation results from VISSIM traffic simulation software. Calculating a robust and reliable average delay per vehicle is important for a cost benefit analysis.

The HCM uses the performance measure experienced travel time (ETT) for analyzing alternative intersections with rerouted turn-movements that experience additional travel time due to turn-movement restrictions. The ETT is the control delay at each juncture (d_i), and the extra distance travel time ($EDTT$), as shown below in equation 3-1.

$$ETT = \Sigma d_i + \Sigma EDTT \qquad (3\text{-}1)$$

Within the analysis of an RCUT intersection at the crossing of a minor roadway with the high-speed rural highway, the standard HCM analysis is used for all of the major-road movements as well as the minor-road right turn movements, since these are not impacted by the geometric restrictions. For the minor-road through and left turn movements, an additional geometric delay must be calculated at both downstream U-turn locations. This can be done using the following equation 3-2, as provided in the HCM.

$$c_{p,x} = v_{c,x} \frac{e^{-(v_{c,x} t_{c,x})/3{,}600}}{1 - e^{-(v_{c,x} t_{f,x})/3{,}600}} \qquad (3\text{-}2)$$

Where $c_{p,x}$ is the potential capacity of movement x (veh/h), $v_{c,x}$ is the conflicting flow rate for movement x (veh/h), $t_{c,x}$ is the critical headway for minor movement x (s), and $t_{f,x}$ is the follow-up headway for minor movement x (s). After defining the capacity for the U-turn movement, this quantity can be used to calculate the control delay, d, as shown in equation 3-3.

$$d = \frac{3{,}600}{c_{m,x}} + 900T \left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1 \right)^2 + \frac{\left(\frac{3{,}600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{450T}} \right] + 5 \qquad (3\text{-}3)$$

Where $c_{m,x}$ is the capacity of movement x (veh/h) and is $c_{p,x}$ from the previous equation. T is the analysis time period and has a value of 0.25 h for a 15-min period. v_x is the flowrate for movement x in veh/h.

Referring back to equation 3-1, the last component to define is the $EDTT$. For an RCUT, the $EDTT$ is simply calculated as the distance from the main junction to the U-turn crossover (D_t), and the distance from the U-turn crossover back to the main junction (D_f), divided by the major-street free-flow speed. The delay associated with the deceleration into a turn and the acceleration from the turn (a), is considered to be negligible, and only relevant for RCUTs with merges. The control delay for stop and signalized intersections already accounts for this in this type of implementation. The HCM also includes a conversion factor in its formula, 1.47, to convert mph to ft/s, as seen below in equation 3-4.

$$EDTT = \frac{D_t + D_f}{1.47 \times S_f} + a \qquad (3\text{-}4)$$

Uninterrupted vehicles (those traveling through on the major movement and all right turners) are assumed to operate as interrupted, contributing no delay. One consideration for experienced delay for these movements at RCUT junctions is the friction caused by lane-changing movements that occur in executing the through and left turn movements from the minor approaches. The research used to develop the HCM procedure determined this side-friction to have negligible impact on the average vehicle delay experienced at RCUT junctions.

3.4.2 Microsimulation Operational Analysis

Microsimulation analysis using VISSIM traffic simulation software is conducted by creating two models for each case study site location; one model for the existing condition (TWSC or AWSC) and one model for the RCUT geometry. Measures of effectiveness collected from the microsimulation analysis include average delay per vehicle, maximum queue length per lane, and average experienced travel time per vehicle. Collecting travel time and delay with VISSIM requires the placement of detectors, which are located at the edges of any possible influence. For the major street approaches, data is recorded for vehicles entering the RCUT facility as soon as they pass the upstream U-turn bay, with data no longer recorded as vehicles pass the downstream u-turn location, as shown below in figure 3.6. This extends the area of influence by thousands of feet for the intersection compared to the HCM's definition, but is necessary to incorporate the EDTT measure into the observed travel time data.

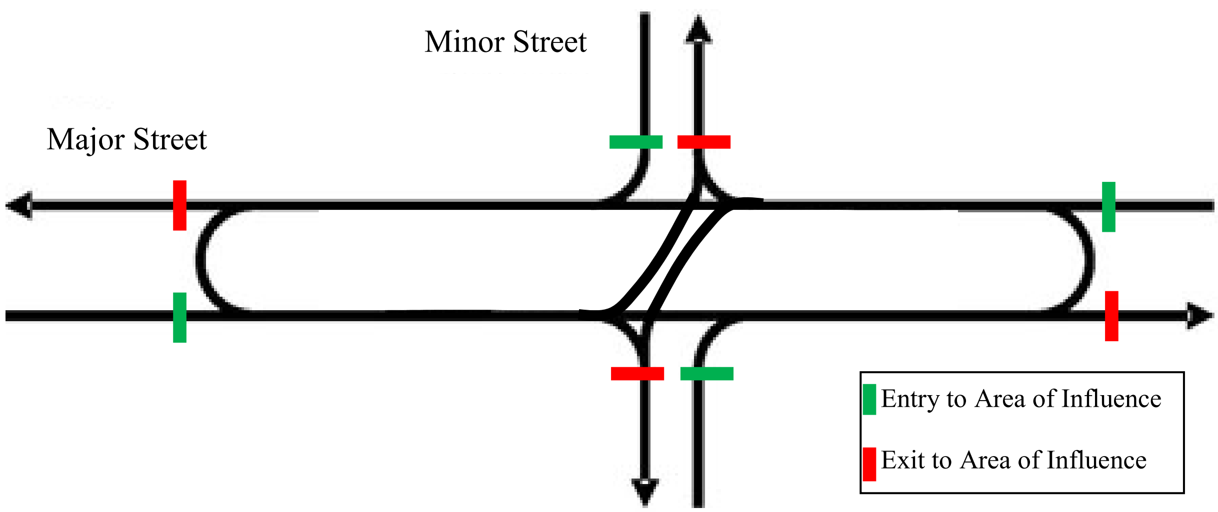


Figure 3.6 VISSUM model's area of influence (not to scale)

Microsimulation models, such as VISSUM, calculate the experienced delay for a vehicle as the cumulative difference between the expected velocity and the experienced velocity as it traverses a network. In the case of alternative intersections, the vehicle may encounter additional travel distance without incurring additional control delay, so long as the desired velocity is met along the stretch. In the case of RCUT intersections, the vehicle may encounter additional travel distance without additional control delay, as long as the desired velocity is met along the stretch.

The HCM only accounts for the travel time it takes to pass through and return to the original intersection. One proposed solution is to tie the travel time metric back to the delay metric by defining a base condition independent of geometry, with each origin-destination point equidistant from the centroid of the intersection, and a base travel time based on the posted speed limit at the site [31].

The models created take an approach in-between these two and ensures that the area of influence was captured but no more. This means that each detector was placed immediately after the U-turns on the major streets. The minor streets were a little different and they were calculated by measuring the max queue and placing the detector just beyond the measured distance. This ensures that no delay is left unmeasured.

Each simulation was run for 25 minutes, with data collected on all vehicles scheduled to enter the network between 5 and 20 minutes. The initial five minutes allows traffic on the network to load from zero vehicles up to steady-state conditions, and the last five minutes allows for vehicles which have just entered the network to complete their travel before metrics are taken on them. Each volume scenario simulation was run with ten different random seeds, for a total of 150 minutes worth of data to generate robust aggregate results.

The VISSUM model was calibrated for the existing conditions scenarios using the HCM's TWSC methodology. The TWSC methodology within the HCM has been extensively validated and is widely considered to be a reliable methodology. The simulation values calibrated for the TWSC scenario are then implemented in the RCUT scenarios to ensure an unbiased comparative analysis between the two.

The primary variable used for calibration was the vehicle headway. Typical vehicle headways within the HCM methodology assume 4.2 seconds; which is implemented at each turning or merging conflict point to ensure that the simulated vehicles waited for the proper gap in traffic. The speed distribution and passing characteristics were adjusted to match observed field conditions.

3.5 Safety Benefits of Alternative Geometries

Crash Modification Factors (CMFs) are the measure the safety effectiveness of an intersection treatment primarily used by the Highway Safety Manual [32], and have become an industry standard for predictive safety analysis. Safety performance of RCUTs have been evaluated extensively. RCUTs have less conflict points than a conventional intersection, which does not necessarily mean that they are safer, but is a good indicator of safety improvements [17]. Ott et al. did a thorough study, including an empirical Bayes statistical analysis, to show that there was a significant reduction in vehicle collisions with implementation of an RCUT intersection [21]. They recommended using a crash modification factor of 46% when converting a typical unsignalized arterial intersection into an RCUT [21]. Edara et al. performed an empirical evaluation of RCUTs on high-speed rural highways, analyzing before and after crash rates of traditional TWSC intersections converted into RCUTs [14]. They found that RCUTs reduced property damage only (PDO) crashes by 38%, minor injuries by 68%, disabling injuries by 92%, and fatal crashes were totally mitigated with the RCUT design.

Roundabouts have commonly been accepted as an alternative to traditional intersections for quite some time [33], but their use on high-speed rural TWSC intersections is a more recent development. Isebrands et al. determined the efficacy of roundabouts implemented to improve the safety of high-speed rural TWSC intersections by analyzing the before and after crash rates of traditional TWSC intersections converted into roundabouts. Their study showed statistically significant reduction in crash rates after the conversion from a conventional intersection design

[34]. There was no difference found for PDO crashes, but non-incapacitating injuries decreased by 83%, incapacitating injuries decreased by 89%, and as with RCUT fatal injuries were decreased by 100%.

The CMF values are also validated by other studies that have found RCUTs and roundabouts to be much safer than TWSC intersections. Claros et al. performed a crash review of 12 RCUT sites across Missouri and found that RCUTs decreased the crash occurrence for the five major crash types studied [4]. Zhang et al. also performed an empirical analysis of crashes before and after RCUTs were implemented [35], finding the average reduction for fatal, injury, and PDO crashes was 74%, 57%, and 9% respectively.

3.6 Economic Analysis

Quantifying the costs and benefits of building an RCUT or roundabout can be broken down into three major categories: reduction in vehicle crash severity and rate, reduction in average delay per vehicle, and the costs associated with completing construction. Each of these factors is important to assess as agencies work to properly estimate potential cost savings and evaluate which solution to pursue. With delay measures being calculated as described in section 3.4 of this report, safety and cost assessment methodologies must yet be defined. Historical crash data was provided for the case study locations by NDOT, with a literature review conducted to assess appropriate crash modification factors (CMF) for analysis with the proposed mitigation geometries. Construction cost data for RCUT facilities was requested from numerous State Department of Transportation organizations, and was ultimately provided by the North Carolina DOT, which has done extensive work in RCUT implementation.

Additional considerations, such as idling time and fuel consumption may play a role in some transportation infrastructure projects, but are expected to have nominal impact on the overall assessment conducted herein. For example, Rakha et al. found that fuel consumption impacts due to vehicle stops is insignificant within the overall vehicle use costs at a rural high-speed junction facility [18]. The difference between continuing at a mainline speed of 55 mph and that of coming to a complete stop then accelerating back to 55 mph is .0475 gallons per stop. This translates to just under $0.14 per vehicle per stop [18]. This figure becomes mute when contrasted with the scale of costs involved in accident reduction, time lost to vehicle delay, and construction costs.

3.6.1 Delay Cost

Since the delay measure is the key parameter in calculating lost productive time, it is important to ensure that correct results are found. The Bureau of Labor Statistics releases average hourly earnings of all employees on private, non-farm payrolls. For the month of June 2018 the average hourly earnings were $26.98 an hour [36]. Taking this value as a substitute for the average value of time for delay experienced at the intersection, an annual value can be extrapolated from a typical peak hour delay to the delay experienced annually. Data suggests that the demand volume during the peak hour makes up approximately 15% [37] of the daily volume for this rural intersection. Although it may be an overly conservative assumption, the authors have taken the calculated total delay experienced during the peak hour (multiplying the average delay by the total demand),

3.6.2 Safety Assessment and Associated Costs

The Nebraska Department of Roads (NDOT) uses the KABCO Injury Classification Scale to assess crash data. The literature on crash reduction for alternative intersections uses crash classification schemes that are similar to KABCO, but do not exactly have one-to-one equivalents within each category, such as that used by Edara et al. [14] and Isebrands et al. [34].

The National Highway Transportation Safety Administration (NHTSA) serves as a primary source for estimating economic costs related to crashes, but uses yet another classification scheme. Engineering judgment was used to convert the various accident severity categories so that information can be compared between publications to achieve a uniform result.

The "KABCO" scale was developed by the National Safety Council and is frequently used by agencies to categorize crashes [38]. Each letter stands for a different class: K = Fatal, A = Disabling Injury, B = Visible Injury, C = Possible Injury, O = No Injury. There is also the additional property damage only (PDO) classification when no injury occurred but there is still an economic impact present.

An alternative injury crash based system is the Maximum Abbreviated Injury Scale (MAIS). The Association for the Advancement of Automotive Medicine developed the scale [39]. The injuries have six different levels: 1 = Minor, 2 = Moderate, 3 = Serious, 4 = Severe, 5 = Critical, and 6 = Fatal. Each of the severity levels had a corresponding value of statistical life (VSL), used to monetize the cost of a crash. As of 2010, the Federal Highway Association assessed the VSL, or the cost of a MAIS 6, at just under $1.4 million [40], accounting for the immediate economic person-injury unit costs.

NDOT, as with most state transportation agencies, utilizes the KABCO system. The NHTSA developed a KABCO to MAIS conversion estimate to translate economic costs for crashes in the different classification schemes, as shown below in table 3.1. The cost estimates take into count multiple components besides immediate damage costs (insurance costs, legal costs, medical costs, lost quality of life, etc.).

Table 3.1 Person-injury unit cost by severity [40]

Crash Severity	Economic	Comprehensive
Fatal (K)	$1,542,000.00	$ 10,082,000.00
Disabling (A)	$ 90,000.00	$ 1,103,000.00
Visible (B)	$ 26,000.00	$ 304,000.00
Possible (C)	$ 21,400.00	$ 141,000.00
No Injury (O)	$ 11,400.00	$ 46,600.00
PDO*	$ 4,200.00	$ 4,200.00
		***PDO is measured as per-vehicle**

The KABCO and MAIS person-injury costs were adapted to the NDOT classification, as well as both Edara et al. and Isebrands et al., to examine equivalent crash costs for all alternative designs. The analogous crash types are shown below, in table 3.2. Overall, the cost of Type C injuries is taken to be negligible.

Table 3.2 KABCO description comparison to NDOT [14], [32]

KABCO Conversion	NDOT Injury Scale Description	Edara et al.	Isebrands et al.
K	Killed	Fatal	Fatal
A	Cannot leave scene without assistance (broken bones, severe cuts, prolonged unconsciousness)	Disabling Injury	Incapacitating, serious
B	Visible but not disabling (minor cuts, swelling, etc.)	Minor Injury	Non-incapacitating, evident
C	Possible but not visible (complaints of pain, etc.)	*	*
			*(The average crash reduction rate was used for type C incidents)

Implementing either a roundabout or an RCUT will have a net safety effect for the original TWSC intersection, with CMFs previously discussed and summarized below in table 3.3.

Table 3.3 Crash Severity Impact factors from RCUT and roundabout implementation.

Crash Severity	RCUT	Roundabout
Fatal (K)	100%	100%
Disabling (A)	92%	89%
Visible (B)	68%	83%
Possible (C)	76%	82%
PDO	38%	0%

As each intersection location will be susceptible to different types of crashes, the 10-year crash history will be used to determine site-specific existing crash rates. The costs as defined in table 3.1 are then applied to the existing crash rates to arrive at a monetized annual safety cost for the existing geometric design. The reductions in crash rates for each severity as defined in table 3.2 are then applied to the observed crash rate history at each site, arriving at a weighted score for total monetized annual safety cost associated with the roundabout and RCUT designs.

3.6.3 Construction Cost Estimating

With a general lack of data in the literature regarding construction costs for RCUT mitigation, previous analysis has used an average value listed in the FHWA Information Guide on RCUTs [1], [27]. To supplement this generic value, the researchers reached out to multiple State DOT agencies requesting information on costs experienced in constructing RCUT facilities in practice. Unfortunately, most agencies either did not maintain this information in a way that could be readily shared, or they charged excessive fees to submit the information request. The most useful information was provided by the North Carolina DOT, which provided a list of their RCUT estimated project costs, as shown below in table 3.4.

As noted, the cost value is the estimation and not the completion cost. In calculating an average price for RCUT construction, one modification needed was that two of the projects listed changed more than one junction into an RCUT facility, so these costs were converted to a per-junction rate for inclusion with the average. The average estimated construction cost for an RCUT facility is found to be approximately $860,000, after adjusting construction costs for inflation.

Table 3.4 Construction cost estimates for recent RCUT facilities.

Location	**# of RCUTs in Project**	**Year Completed**	**Total Cost Estimate of Each J-turn**
NC 24 at Hubert Blvd/Waterfront	1	2014	$ 1,001,700
US 17 and Dawson Cabin Road	1	2011	$ 486,080
NC 87 at H. M. Cagle Dr	1	2011	$ 1,310,400
US 74 at Old Pageland-Monroe Road	1	In Progress	$ 1,186,000
US 17 at Kellum Loop Road and Halltown Road	2	2018	$ 398,750
NC 55 Bypass at Avent Ferry Road	1	2016	$ 1,291,500
US 17 and Thomasboro Rd/Pea Landing Rd	1	In Progress	$ 998,000
US 64 at Brown's Crossroads	1	2017	$ 636,540
NC 24/27 and Newt Road	1	In Progress	$ 675,000
US 264 near Neck Road	1	In Progress	$ 1,435,000
US 401 at North Parker Church Rd and Pittman Grove Church Rd	2	In Progress	$ 835,000
US 17 and Hickman Rd/SW Middleton Avenue	1	In Progress	$ 1,760,000
		Avg. Cost:	**$ 858,140**

Due to the roundabout's popularity in use and research, reliable data on average construction costs are easily accessible. The Federal Highway Administration (FHWA) in a 2000 report estimates the average cost at being around $250,000 [41]. This number was reaffirmed by a 2010 FHWA report conducted in Maryland looking at both rural and urban roundabouts [42]. Adjusting for inflation, the estimated construction cost is $365,000.

Chapter 4 Case Study Locations

Nine locations are analyzed as potential candidates for case study analysis, as shown below in table 4.1. All are located in eastern Nebraska and have experienced a higher-than-average crash rate in recent years. Each junction considered includes a four-lane expressway (major road) crossing with a lower-volume two-lane highway (minor road). In deciding which sites to select, the three primary factors considered are the crash history at the site, the traffic characteristics it typically exhibits, and the existing geometry such as median width and upstream and downstream obstructions that would impact locating the u-turn bay.

Table 4.1 List of junctions considered for analysis and pertinent site characteristics.

Major Highway	Minor Road	Near City	Median Width	Entering Left Turn Distance	Sight Distance	Prevalent Crash Type
NE-2	S-66A	Palmyra	40' typ.	92’	Obstructed	Unknown
US-20	NE-110	South Sioux City	40' typ.	85’	Unobstructed	Unknown
US-75	NE-35	Dakota City	40' typ.	84’	Unobstructed	Entering Left Turn
US-77	S-55G	Sprague	40' typ.	96’	Obstructed	Unknown
US-81	NE-13	Hadar	40' typ.	100’	Unobstructed	Rear End
US-81	NE-32	Madison	40' typ. (north) 20' typ. (south)	95’	Obstructed	Angle
US-81	NE-64	Columbus	40' typ. (north) 0' typ. (south)	58’	Unobstructed	Entering Left Turn
US-81	NE-91	Humphrey	40' typ.	55’	Unobstructed	Angle
US-81	S-71B	Platte Center	40' typ.	105’	Obstructed	Unknown

Geometric variety is important because implementation of an RCUT facility can be limited based on the existing median widths and availability of appropriate locations for a U-turn bay. Narrow medians may require a loon to be built, which would affect right-of-way. Downstream obstructions, such as bridges, can interfere with the location of U-turn placement.

U-turn offset has a minimum distance to allow safe lane changes and reaction time for drivers. An offset length too far can incur excessive delays in the form of vehicle rerouting time and costs for right-of-way purchasing and roadway construction. Construction can be inhibited by perceptions from businesses that are located adjacent to the roadway, who may be opposed to its installation [24].

Traffic characteristics analyzed at every intersection include the turn-movement demand flowrates, heavy vehicle percentages, and free flow speed. The proportion of vehicle traffic between the major and minor road has been found to be important [27] to justify the construction of an RCUT intersection. Each location had similar free flow speeds of 65 mph, but during analysis this was raised to an average of 70 mph. This was due to the State of Nebraska uniformly raising all expressway speed limits by 5 mph across the state. This adjustment was made to ensure that the research reflected the conditions of the roadway at the time of implementation of a potential RCUT or roundabout facility.

The crash history is arguably the most important factor in deciding which location to include in case-study analysis. Safety is the first priority for any DOT when designing roadways, and RCUTS have been shown to drastically reduce crashes at TWSC intersections [14]. Locations exhibiting higher than average crash rates, with a high number of crashes associated with through and left-turn movements from the minor approaches are prioritized for selection.

Working in conjunction with NDOT, three locations were chosen, including the intersection of US-81 and NE-91 in Humphrey, the intersection of US-81 and NE-32 in Madison, and the intersection of US-81 and NE-35 in Dakota City. The three cities with sites chosen are shown relative to the map of the state of Nebraska in figure 4.1, below.

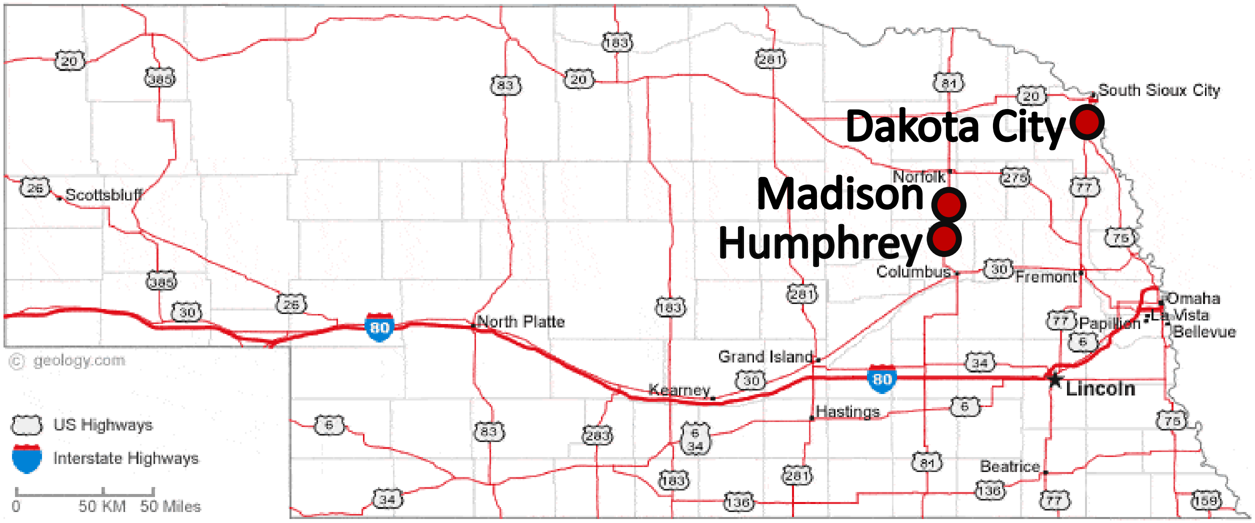


Figure 4.1 Chosen study site locations [43]

<u>4.1 US-81 and NE-91 near Humphrey, NE</u>

The two-way stop-controlled (TWSC) intersection of US-81 and NE-91, east of Humphrey, NE, is shown below in figure 4.2. The intersection has experienced 53 crashes in the last 10 years, five of those being fatal. Nebraska DOT specifically identified Humphrey, NE as a location that they thought of as an ideal location to implement an RCUT facility. During the time the study was ongoing, NDOT further determined to move forward with installing an RCUT facility at this location, scheduled for completion in the summer of 2019.

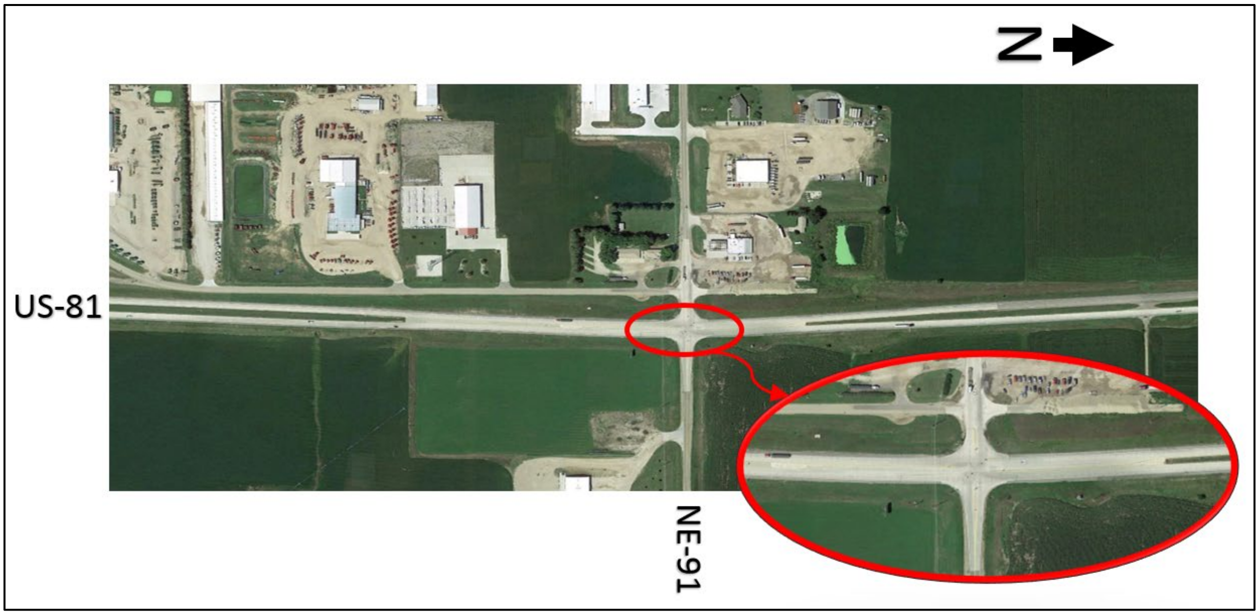


Figure 4.2 Intersection of US-81 and NE-91 near Humphrey, NE [22]

The roadway geometry and traffic data collected from US-81 and NE-91 is shown below in table 4.2. The volumes represent the AM peak period collected on April 12, 2018. It was decided to use the AM peak period instead of the PM because it was identified that high school drivers were a significant portion of the crashes that occurred there. The AM peak period ensures that normal work and school traffic would be collected at the same time, since the school is released at 3:30 p.m. and peak afternoon traffic occurs between 4:00 and 6:00 p.m. The posted speeds on US-81 are currently 65 mph, but have been modeled as 70 mph, anticipating future conditions.

Table 4.2 Roadway geometrics and traffic data for US-81 and NE-91

Movement Group	NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	Aggregate
Base Volume (veh/h)	30	206	19	11	238	41	61	43	50	13	30	5	-
Total Analysis Volume (veh/h)	40	256	28	16	272	48	124	72	100	20	40	8	-
Lane Width (ft)	12	12	12	12	12	12	12	12	12	12	12	12	-
Speed (mph)	70			70			60			60			-
Grade (%)	0			0			0			0			-
Peak Hour Factor	0.75	0.81	0.68	0.69	0.88	0.85	0.49	0.60	0.50	0.65	0.75	0.63	0.87
Heavy Vehicle Percentage (%)	10%	22%	21%	55%	19%	10%	7%	35%	16%	15%	30%	60%	12%

This location has geometric restrictions present. The U-turn offsets could not be placed along US-81 within 1,000 feet of the intersection, due to the narrow median width close to the junction. Further away from the point of intersection, the median returns to the standard width of 40 feet. However, there is an adjacent intersection on US-81 2,500 feet to the south, where it crosses NE-71A. There is also a right-of-way concern south of US-81 and NE-91, with multiple businesses located on the west-side of US-81 that may impact the construction of the RCUT facility. An additional right-of-way concern brought up by NDOT is the presence of central-pivot irrigators that may restrict how far a loon could be extended to the east of US-81, south of NE-91.

The data collection shows the majority of traffic on the major roadway approaches along US-81. Eastbound traffic coming from Humphrey was the third highest approach, with significantly less traffic on the westbound approach. The overall heavy vehicle percentage of 12% is significantly higher than the Highway Capacity Manual (HCM) default value of 2%, with some movements exhibiting greater than 20%.

US-81 and NE-91 had the highest crash rate for any of the intersections studied. The prevalent crash type are angle crashes. The vast majority happening during daylight hours, with a dry road surface and no alcohol involved. This indicates that geometric solutions may be successful at improving safety at this site. The detailed crash history table is not included in this report for privacy reasons.

4.2 US-81 and NE-32 near Madison, NE

The two-way stop-controlled (TWSC) intersection of US-81 and NE-32, near Madison, NE, is shown below in figure 4.3. The intersection has a higher-than-average crash rate and is geometrically unique in this study, as it has a narrow concrete median to the south, providing an example case study location that would incur higher construction costs when remediating the safety concerns with an RCUT design. Additionally, locating multiple RCUT facilities along US-81 follows best practices from other State DOTs such as in North Carolina, where RCUTs are recommended in series along a corridor to help decrease problems that arise from driver expectation if they encounter alternative or unusual intersection designs in an isolated situation [44].

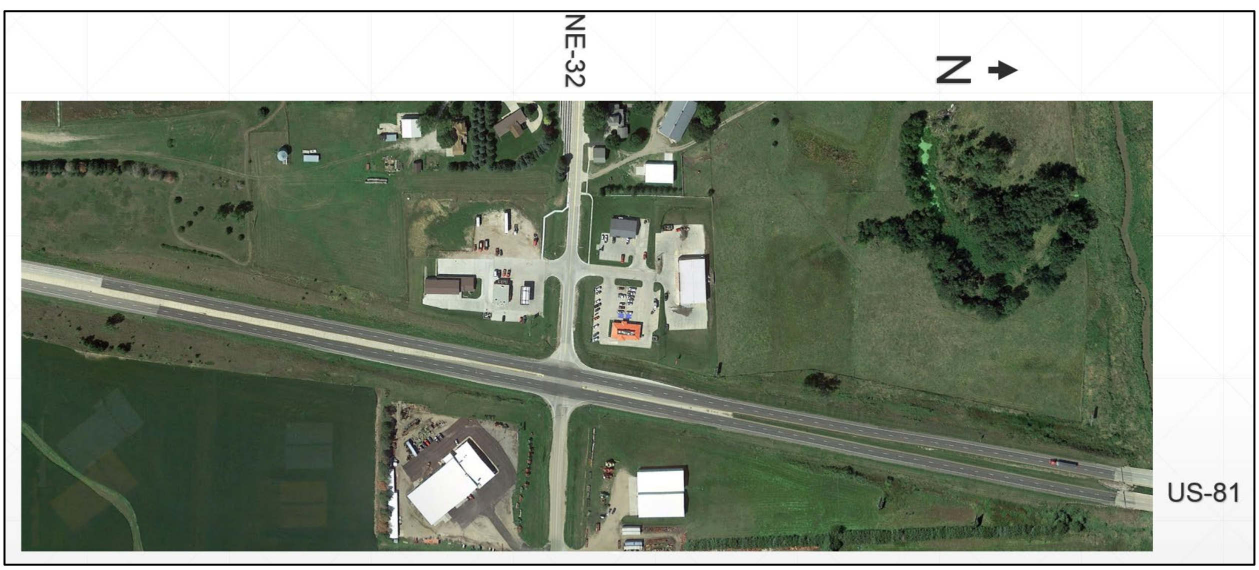


Figure 4.3 Intersection of US-81 and NE-32 near Madison, NE [22]

The roadway geometry and traffic data collected from US-81 and NE-32 is shown below in table 4.3. The volumes represent the AM peak period collected on April 12, 2018, assessing AM rather than PM to incorporate school-related traffic. The posted speeds on US-81 are currently 65 mph, but have been modeled as 70 mph, anticipating future conditions.

Table 4.3 Roadway geometrics and traffic data for US-81 and NE-32

Movement Group	NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	Aggregate
Base Volume (veh/h)	12	382	5	9	215	62	82	19	18	5	10	9	-
Total Analysis Volume (veh/h)	16	440	12	16	248	68	109	28	21	16	16	12	-
Lane Width (ft)	12	12	12	12	12	12	12	12	12	12	12	12	-
Speed (mph)	70			70			60			60			-
Grade (%)	0			0			0			0			-
Peak Hour Factor	0.75	0.87	0.42	0.56	0.87	0.91	0.75	0.68	0.85	0.31	0.63	0.75	0.91
Heavy Vehicle Percentage (%)	0%	15%	20%	11%	19%	3%	1%	5%	6%	40%	10%	22%	10%

The median width is the biggest design challenge for future implementation of the RCUT intersection, being limited to 16 feet at the south leg. The north leg is a 40-foot median, the typical design width for this type of highway in Nebraska. The Green Book suggests at least 12 feet of separation between opposing movements in a rural setting [8]. This means that at least 20 feet is required to provide a turn bay for the U-turn at the south leg of the intersection. Using this guidance, the roadway would require realignment to implement an RCUT at the Madison location, leading to very high construction costs.

Another geometric consideration is the relatively close adjacent obstructions, with an intersection 2,000 feet to the south, and a bridge 1,500 feet to the north. Although the southern u-turn location will easily fit within the 2,000 foot limit, the northern bridge obstruction will cause the u-turn location on that side to either be closer than desired or farther away than is optimal. The closer option can lead to complications with weaving maneuvers from the minor road through and left-turning vehicles, with the further option leading to excessive additional travel time or these rerouted vehicles. The right-of-way in both directions is largely clear of obstructions.

The data collection shows the majority of traffic on the major roadway approaches along US-81. Eastbound traffic coming from Madison was the third highest approach, with significantly less traffic on the westbound approach. The overall heavy vehicle percentage of 10% is significantly higher than the Highway Capacity Manual (HCM) default value of 2%, with some movements exhibiting greater than 20%.

Of the three locations chosen, Madison has experienced the fewest crashes during the period for which data was available. It has similar traffic characteristics and intersection geometry as Humphrey, and exhibits a prevalent crash type of angle as well. Nine of the twenty-two crashes at Madison occurred during either dark or poor weather conditions, and the only fatality involved alcohol. This suggests that Madison's crash patterns might not be as directly benefitted as at other locations, but significant benefits would still be anticipated from the construction of an RCUT facility.

4.3 US-75 and NE-35 near Dakota City, NE

The all-way stop-controlled (AWSC) intersection of US-75 and NE-35, near Dakota City, NE, is shown below in figure 4.4. The intersection has a higher-than-average crash rate and has been discussed in the recent past by NDOT and the local municipalities as an intersection in need of improvements. This site is located in close proximity of Sioux City, NE, a few miles to the north.

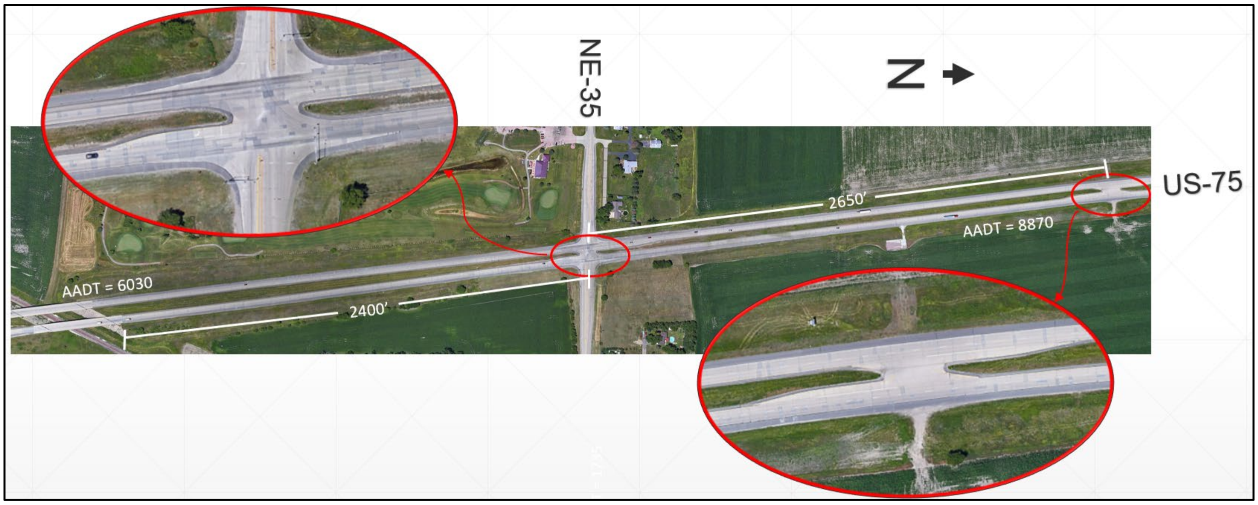


Figure 4.4 Intersection of US-75 and NE-35 near Dakota City, NE [22]

US-75 is a well-traveled corridor that connects Omaha and Sioux City. The intersection at NE-35 is the first stopping point before entering Sioux City, after approximately 65 miles unimpeded to the south. A high crash rate at the site caused the intersection to be changed from TWSC to AWSC, but NDOT is continuing to explore additional measures to improve safety at the site, particularly if the solution were able to retain safe operations while removing the stop condition on through movements along US-75.

Previous investigations of the site determined that volume warrants were not met at the location to further justify signalization. Subsequently, the most effective mediation was determined to be a high speed roundabout that could accommodate the large traffic volumes without forcing all directions to come to a stop. However, this solution had been opposed by the municipal partners in the past.

Data collection for this location was completed on Wednesday May 16, 2018, with good visibility and no precipitation. As with the other locations, the AM peak period was used to capture school and commuting traffic. The posted speed limit of 65 mph along US-75 is being modeled as 70 mph to accommodate anticipated future operations. The roadway geometry and traffic data collected from US-75 and NE-35 is shown below in table 4.4.

Table 4.4 Roadway geometrics and traffic data for US-75 and NE-32

Movement Group	NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	Aggregate
Base Volume (veh/h)	14	340	24	105	255	92	104	21	4	16	31	100	-
Total Analysis Volume (veh/h)	20	408	32	112	304	112	124	40	8	24	48	116	-
Lane Width (ft)	12	12	12	12	12	12	12	12	12	12	12	12	-
Speed (mph)	70			70			60			60			-
Grade (%)	0			0			0			0			-
Peak Hour Factor	0.70	0.83	0.75	0.94	0.84	0.82	0.84	0.53	0.50	0.67	0.65	0.86	0.95
Heavy Vehicle Percentage (%)	0%	8%	4%	2%	13%	17%	14%	5%	0%	0%	0%	1%	7%

This study location is ideal to implement an RCUT design, in terms of the existing geometric considerations, and lack of site constraints. The median to the north is the typical 40 feet and to the south it widens to 50 feet. There are no obstructions to the north or south that pose a concern for the u-turn offset location. There is a bridge directly to the south, but this is 2,400 feet away, giving plenty of room to place a u-turn. There is little in the way of right-of-way interaction.

The data collection shows the majority of traffic on the major roadway approaches along US-75. The next-highest traffic movements come from eastbound left and westbound right traffic, going to work in Sioux City. The overall heavy vehicle percentage of 7% is higher than the Highway Capacity Manual (HCM) default value of 2%, with some movements exhibiting greater than 10%.

Crashes at this intersection are quite prevalent. There have been 35 accidents at this intersection in the last 10 years, leading to 27 injuries. The prevailing crash type is entering left turns, suggesting the RCUT design as a good choice to mitigate the safety concerns, while maintaining throughput on US-75.

Chapter 5 Traffic Operations Analysis

Each location is analyzed with its existing geometric condition and three different alternative geometries. The four intersection types investigated are the two-way stop controlled (TWSC), all-way stop controlled (AWSC), roundabout, and restricted crossing U-turn (RCUT). Vistro, using HCM methodology, analyzed each intersection type with the exception of the RCUT, as the HCM methodology for RCUT analysis had not yet been implemented in Vistro at the time of this study. Manual calculations of RCUT performance ware done using the methodology published in the 6th edition of the HCM, as outlined in the methodology chapter of this report.

Due to a lack of extensive validation of the HCM's RCUT analysis in the literature, the RCUT geometry is additionally modeled using VISSIM microsimulation software, a proven and widely accepted tool within the traffic engineering profession. Calibration of the VISSIM model is done using a TWSC control geometry, comparing the simulated delay results against the equivalent results of HCM's methodology.

A comparative analysis is provided at the end of this chapter to summarize the findings from each of the individual case study sites. However, NDOT has stated that the continual flow of rural highways (such as US-81) is of high priority, investing heavily in building beltways the circumvent cities to reduce stops on the rural highway system. As such, the conversion of any of the case study locations to an AWSC intersection should be considered a last option.

5.1 Operational Analysis Geometric Design

The authors endeavored to lay out the geometric configurations of the intersections based on engineering judgement, past precedent from the literature, and recommendations from NDOT to obtain optimum results. Operational analysis is generally independent of the geometric configuration chosen for most of the intersection designs analyzed, with the exception of locating the median u-turn location on the RCUT junctions.

For both the TWSC and AWSC intersection geometries, the minor approaches in both cases are two-lane highways utilizing a single lane to serve all movements at the intersection without auxiliary turn lanes. The major approaches have a dedicated left turn lane, a through lane, and a shared right-turn/through lane.

The roundabout geometry modeled is based on existing roundabout facilities where a 4-lane highway meets with a 2-lane highway. One key example used is the intersection of highways 544 & 539 southwest of Lynden, WA, as shown below in figure 5.1. Lane-use modifications to the existing geometry is limited to the elimination of the dedicated left turn lane on the major approaches. The two remaining lanes on the major approaches are modeled as a through-left and a through-right, respectively.

Figure 5.1 Roundabout junction of highways 539 & 544 southwest of Lynden, WA [22]

The RCUT intersection provides the most variety and required design decisions in its layout, due to the site-specific constraints upstream and downstream on the major approaches that impact the placement of the median u-turn locations. All other lane movements for the RCUT designs were modeled the same as the existing lane configurations, including number and length of auxiliary lanes, as shown below in figure 5.2.

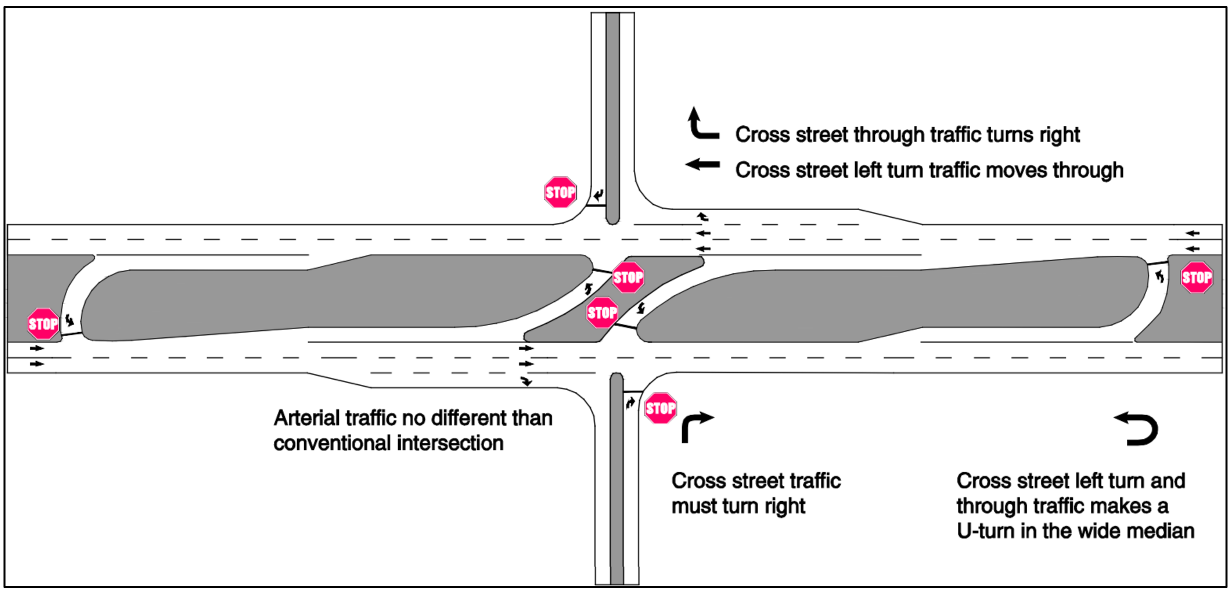


Figure 5.2 Basic stop controlled setup of RCUT used for analysis [1]

The locations of the u-turn bays for each case study site location are indicated below, in table 5.1. Each offset is located between 1,000 and 2,500 feet, with specific locations tied to site constraints at each junction.

Table 5.1 U-turn locations for RCUT geometric design at each locations (feet)

U-turn		US81-NE91	US81-NE32	US75-NE35
Northern	Offset	1350	2400	1150
	Length	300	250	200
Southern	Offset	1650	1350	1100
	Length	275	200	200

5.2Operational analysis of US-81 and NE-91 near Humphrey, NE

The intersection of US-81 and NE-91 is currently TWSC, but is scheduled for conversion to an RCUT junction by the summer of 2019. In addition to the existing condition analysis of the TWSC geometry, three other designs were modeled, including all-way stop-controlled, roundabout, and restricted crossing u-turn (RCUT).

5.2.1 Two-way Stop Controlled

Under TWSC analysis, free movements are modeled as experiencing zero delay. However, best practices, as recommended by the HCM, is to ignore the intersection level of service taking the weighted average of vehicle delays, and instead grade the intersection based on each individual approach. This leads to inequalities when conducting comparative analysis between the various design options. The results for HCM analysis of the TWSC condition is provided below, in table 5.2. The authors have chosen to include the aggregate intersection delay, but not the intersection LOS, in keeping with the recommendation of the HCM.

Table 5.2 TWSC operational analysis of US-81 and NE-91

	NBL	NBT+R	SBL	SBT+R	EBL	EBT	EBR	WBL	WBT	WBR
Movement V/C Ratio	0.0	0.0	0.0	0.0	0.4	0.3	0.1	0.1	0.1	0.0
Delay for Movement (s/veh)	8.2	0.0	8.8	0.0	36.0	37.9	30.0	21.9	20.6	13.3
Movement LOS	A	A	A	A	E	E	D	C	C	B
95th-Pctl Queue Length (veh/ln)	0.1	0.0	0.1	0.0	5.7	5.7	5.7	0.8	0.8	0.8
95th-Pctl Queue Length (ft/ln)	2.6	0.0	1.3	0.0	143.1	143.1	143.1	20.9	20.9	20.9
Approach Delay (s/veh)	1.0		0.4		34.4			20.1		
Approach LOS	A		A		D			C		
Intersection Delay (s/veh)	11.75									
Intersection LOS	N/A									

Although the northbound and southbound left-turn movements did not degrade the operations of the approaches on US-81, the lack of gaps for movements on NE-91 led to significant reductions in level-of-service (LOS) on the minor roadway. All movements on the northbound and southbound approaches experienced an LOS of A. On the eastbound approach, the left and through movements experienced LOS E, with the right-turn movement at LOS D. The westbound approach had the lowest demand volume, and experienced LOS C for the left and through movements, with LOS B for the right-turn movement.

5.2.2 All-way Stop Controlled

The results for the AWSC intersection are proved below in table 5.3. With all movements now experiencing some form of control delay at the intersection, HCM recommends examining an intersection LOS in addition to the individual movement LOS.

Table 5.3 AWSC operational analysis of US-81 and NE-91

	NBL	NBT	NBR	SBL	SBT	SBR	EB	WB
Delay for Movement (s/veh)	10.3	11.8	11.6	10.8	12.1	11.6	16.0	11.2
95th-Pctl Queue Length (veh/ln)	0.3	1.1	1.0	0.1	1.2	1.2	3.0	0.5
95th-Pctl Queue Length (ft/ln)	6.3	26.5	25.7	2.7	30.7	29.2	75.1	11.6
Approach Delay (s/veh)	11.5			11.8			16.0	11.2
Approach LOS	B			B			C	B
Intersection Delay (s/veh)	12.9							
Intersection LOS	B							

Operating under stop control, the northbound and southbound approaches are degraded to an LOS B for the AWSC design, compared with the largely free-flow conditions experienced under TWSC. Introducing gaps in the major movements significantly improves the functionality of the minor approaches, such that eastbound now operates at LOS C, and westbound operates at LOS B.

5.2.3 Roundabout

The results for the roundabout intersection are provided below in table 5.4. All movements are anticipated to operate at LOS A with the roundabout design, including a significant reduction in delay for the main movements.

Table 5.4 Roundabout operational analysis of US-81 and NE-91

	NBL+T	NBT+R	SBL+T	SBT+R	EB	WB
Average Lane Delay (s/veh)	5.39	5.7	4.73	4.79	8.79	6.65
Lane LOS	A	A	A	A	A	A
95th-Pctl Queue Length (veh/ln)	0.58	0.68	0.52	0.59	1.68	0.35
95th-Pctl Queue Length (ft/ln)	14.45	16.96	13.06	14.65	41.99	8.65
Approach Delay (s/veh)	5.56		4.76		8.79	6.65
Approach LOS	A		A		A	A
Intersection Delay (s/veh)	6.30					
Intersection LOS	A					

5.2.4 RCUT

The operational results for the RCUT junction are provided below in table 5.5. The additional travel time on the minor approach left and through movements significantly degrades the operations of the intersection, representing the primary detriment of this design that offsets its significant safety benefits.

Table 5.5 RCUT operational analysis of US-81 and NE-91

	NBL	NBT+R	SBL	SBT+R	EBL	EBT	EBR	WBL	WBT	WBR
ETT for Movement (s/veh)	8.2	0.0	8.8	0.0	78.7	80.7	30.0	57.6	56.3	13.3
Movement LOS	A	A	A	A	E	F	C	E	E	B
Approach ETT (s/veh)	1.0		0.4		62.7			51.6		
Approach LOS	A		A		E			D		
Intersection ETT (s/veh)	11.7									
Intersection LOS	B									

All movements on the major approaches along US-81 operate at LOS A, with the through and right-turn movements unimpeded. The eastbound and westbound approaches on NE-91 experience significant additional travel time caused by the additional distance traveled for through and left-turning vehicles to utilize the u-turns, with the u-turn bay to the south being located further downstream than the one to the north, causing the worst travel times for the eastbound approach. Eastbound through traffic experiencing LOS F, while eastbound left and westbound through and left all experience LOS E. There is some delay due to queuing on the eastbound and westbound approaches as vehicles wait for gaps in the US-81 traffic, as the right-turn movements on eastbound and westbound experience LOS C and LOS B, respectively.

5.3 Operational Analysis of US-81 and NE-32 near Madison, NE

The intersection of US-81 and NE-32 is currently TWSC. In addition to the existing condition analysis of the TWSC geometry, three other designs were modeled, including all-way stop-controlled, roundabout, and restricted crossing u-turn (RCUT).

5.3.1 Two-way Stop Controlled

The results for HCM analysis of the TWSC condition is provided below, in table 5.6. The authors have chosen to include the aggregate intersection delay, but not the intersection LOS, in keeping with the recommendations of the HCM for TWSC intersections.

Table 5.6 TWSC operational analysis of US-81 and NE-32

	NBL	NBT+R	SBL	SBT+R	EBL	EBT	EBR	WBL	WBT	WBR
Movement V/C Ratio	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.1	0.1	0.0
Delay for Movement (s/veh)	7.9	0.0	8.5	0.0	21.1	23.3	15.6	20.8	19.5	11.8
Movement LOS	A	A	A	A	C	C	C	C	C	B
95th-Pctl Queue Length (veh/ln)	0.0	0.0	0.1	0.0	2.0	2.0	2.0	0.5	0.5	0.5
95th-Pctl Queue Length (ft/ln)	1.0	0.0	1.2	0.0	48.9	48.9	48.9	11.6	11.6	11.6
Approach Delay (s/veh)	0.3		0.4		20.7			17.8		
Approach LOS	A		A		C			C		
Intersection Delay (s/veh)	4.3									
Intersection LOS	N/A									

Although the northbound and southbound left-turn movements did not degrade the operations of the approaches on US-81, the lack of gaps for movements on NE-32 led to significant reductions in level-of-service (LOS) on the minor roadway. All movements on the northbound and southbound approaches experienced an LOS of A. All minor movements experienced LOS C, with the exception of the westbound right-turn movement at LOS B.

5.3.2 All-way Stop Controlled

The results for the AWSC intersection are provided below in table 5.7. With all movements now experiencing some form of control delay at the intersection, HCM recommends examining an intersection LOS in addition to the individual movement LOS.

Table 5.7 AWSC operational analysis of US-81 and NE-32

	NBL	NBT	NBR	SBL	SBT	SBR	EB	WB
Delay for Movement (s/veh)	9.0	12.0	11.9	9.4	11.0	10.4	11.8	10.5
95th-Pctl Queue Length (veh/ln)	0.1	1.7	1.7	0.1	1.1	1.0	1.1	0.3
95th-Pctl Queue Length (ft/ln)	2.1	42.4	42.0	2.2	27.0	24.9	28.5	6.8
Approach Delay (s/veh)	11.8			10.6			11.8	10.5
Approach LOS	B			B			B	B
Intersection Delay (s/veh)	11.4							
Intersection LOS	B							

Operating under stop control, the northbound and southbound approaches are degraded to an LOS B, compared with the largely free-flow conditions experienced under TWSC. Introducing gaps in the major movements significantly improves the functionality of the minor approaches, such that eastbound and westbound now operate at LOS B.

5.3.3 Roundabout

The results for the roundabout intersection are proved below in table 5.8. All movements are anticipated to operate at LOS A with the roundabout design, including a significant reduction in delay for the main movements.

Table 5.8 Roundabout operational analysis of US-81 and NE-32

	NBL+T	NBT+R	SBL+T	SBT+R	EB	WB
Average Lane Delay (s/veh)	5.2	5.5	4.4	4.4	5.3	6.8
Lane LOS	A	A	A	A	A	A
95th-Pctl Queue Length (veh/ln)	0.8	0.9	0.5	0.5	0.6	0.2
95th-Pctl Queue Length (ft/ln)	19.1	22.4	11.9	13.2	14.8	5.9
Approach Delay (s/veh)	5.4		4.4		5.3	6.8
Approach LOS	A		A		A	A
Intersection Delay (s/veh)	5.1					
Intersection LOS	A					

5.3.4 RCUT

The operational results for the RCUT junction are proved below in table 5.9. The additional travel time on the minor approach left and through movements significantly degrades the operations of the intersection, representing the primary detriment of this design that offsets its significant safety benefits.

Table 5.9 RCUT operational analysis of US-81 and NE-32

	NBL	NBT+R	SBL	SBT+R	EBL	EBT	EBR	WBL	WBT	WBR
ETT for Movement (s/veh)	7.9	0.0	8.5	0.0	56.9	59.1	15.6	76.1	74.8	11.8
Movement LOS	A	A	A	A	E	E	B	E	E	B
Approach ETT (s/veh)	0.3		0.4		53.8			58.1		
Approach LOS	A		A		E			D		
Intersection ETT (s/veh)	4.3									
Intersection LOS	A									

All movements on the major approaches along US-81 operate at LOS A, with the through and right-turn movements unimpeded. The eastbound and westbound approaches on NE-32 experience significant additional travel time caused by the additional distance traveled to utilize the u-turns, with left and through traffic experiencing LOS E, while right-turning traffic experiences LOS B.

5.4 Operational Analysis of US-75 and NE-35 near Dakota City, NE

The intersection of US-81 and NE-32 is currently AWSC. In addition to the existing condition analysis of the AWSC geometry, three other designs were modeled, including TWSC, roundabout, and restricted crossing u-turn (RCUT).

5.4.1 Two-way Stop Controlled

The results for HCM analysis of the TWSC condition is provided below, in table 5.10. The authors have chosen to include the aggregate intersection delay, but not the intersection LOS, in keeping with the recommendations of the HCM for TWSC intersections.

Table 5.10 TWSC operational analysis of US-75 and NE-35

	NBL	NBT+R	SBL	SBT+R	EBL	EBT	EBR	WBL	WBT	WBR
Movement V/C Ratio	0.0	0.0	0.1	0.0	0.9	0.2	0.0	0.1	0.3	0.2
Delay for Movement (s/veh)	8.2	0.0	8.6	0.0	149.0	143.1	128.9	34.4	34.9	20.3
Movement LOS	A	A	A	A	F	F	F	D	D	C
95th-Pctl Queue Length (veh/ln)	0.1	0.0	0.3	0.0	8.7	8.7	8.7	2.9	2.9	2.9
95th-Pctl Queue Length (ft/ln)	1.3	0.0	8.3	0.0	218.1	218.1	218.1	73.4	73.4	73.4
Approach Delay (s/veh)	0.4		1.8		146.7			25.8		
Approach LOS	A		A		F			D		
Intersection Delay (s/veh)	23.2									
Intersection LOS	N/A									

With higher through volumes on US-75 compared to the other two case study locations, a greater impact is seen due to the lack of gaps for movements on NE-35, leading to significant reductions in level-of-service (LOS) on the minor roadway. All movements on the northbound and southbound approaches experienced an LOS of A. All minor movements on the eastbound approach experienced LOS F. The through and right-turn movements on the westbound approach experienced LOS D, with the westbound right-turn movement experiencing LOS C.

5.4.2 All-way Stop Controlled

The results for the AWSC intersection are provided below in table 5.11. With all movements now experiencing some form of control delay at the intersection, HCM recommends examining an intersection LOS in addition to the individual movement LOS.

Table 5.11 AWSC operational analysis of US-75 and NE-35

	NBL	NBT	NBR	SBL	SBT	SBR	EB	WB
Delay for Movement (s/veh)	10.2	14.3	14.0	11.9	13.9	12.9	14.2	13.2
95th-Pctl Queue Length (veh/ln)	0.1	2.0	2.0	0.8	1.9	1.7	1.6	1.6
95th-Pctl Queue Length (ft/ln)	3.1	50.9	49.6	21.1	46.6	42.9	38.7	38.8
Approach Delay (s/veh)	14.0			13.1			14.2	13.2
Approach LOS	B			B			B	B
Intersection Delay (s/veh)	13.5							
Intersection LOS	B							

Operating under stop control, the northbound and southbound approaches are degraded to an LOS B, compared with the largely free-flow conditions experienced under TWSC. Introducing gaps in the major movements significantly improves the functionality of the minor approaches, such that eastbound and westbound now operate at LOS B.

5.4.3 Roundabout

The results for the roundabout intersection are provided below in table 5.12. All movements are anticipated to operate at LOS A with the roundabout design, including a significant reduction in delay for the main movements.

Table 5.12 Roundabout operational analysis of US-75 and NE-35

	NBL+T	NBT+R	SBL+T	SBT+R	EB	WB
Average Lane Delay (s/veh)	5.6	5.9	4.8	5.4	7.3	7.8
Lane LOS	A	A	A	A	A	A
95th-Pctl Queue Length (veh/ln)	0.8	1.0	0.8	1.0	0.9	1.0
95th-Pctl Queue Length (ft/ln)	20.3	23.7	19.5	24.0	21.9	25.1
Approach Delay (s/veh)	5.8		5.1		7.3	7.8
Approach LOS	A		A		A	A
Intersection Delay (s/veh)	6.0					
Intersection LOS	A					

5.4.4 RCUT

The operational results for the RCUT junction are provided below in table 5.13. The additional travel time on the minor approach left and through movements significantly degrades the operations of the intersection, representing the primary detriment of this design that offsets its significant safety benefits.

Table 5.13 RCUT operational analysis of US-75 and NE-35

	NBL	NBT+R	SBL	SBT+R	EBL	EBT	EBR	WBL	WBT	WBR
ETT for Movement (s/veh)	8.2	0.0	8.6	0.0	180.0	174.1	128.9	66.2	66.6	20.3
Movement LOS	A	A	A	A	F	F	F	E	E	C
Approach ETT (s/veh)	0.4		1.8		176.2			38.0		
Approach LOS	A		A		F			D		
Intersection ETT (s/veh)	23.2									
Intersection LOS	C									

All movements on the major approaches along US-75 operate at LOS A, with the through and right-turn movements unimpeded. The eastbound and westbound approaches on NE-35 experience significant additional travel time caused by the additional distance traveled for through and left-turning vehicles to utilize the u-turns. All eastbound movements experience

LOS F, while westbound through and left experience LOS E, and westbound right-turning traffic experiences LOS C.

5.5 Summary Results of Operational Analysis

Each location is analyzed with its existing geometric condition and three different alternative geometries. The four intersection types investigated are the two-way stop controlled (TWSC), all-way stop controlled (AWSC), roundabout, and restricted crossing U-turn (RCUT). The aggregate intersection average delay per vehicle for each location/design is shown below in table 5.14.

Table 5.14 Summary of operational analysis results: aggregate intersection delay

Aggregate Intersection Average Delay per Vehicle (seconds)	TWSC	AWSC	Roundabout	RCUT
US-81 and NE-91 near Humphry, NE	11.8	12.9	6.3	11.7
US-81 and NE-32 near Madison, NE	4.3	11.4	5.1	4.3
US-75 and NE-35 near Dakota City, NE	23.2	13.5	6.0	23.2

Based on the aggregate intersection delay results, all intersections would operate at an overall level-of-service of C or better, regardless of which one of the four unsignalized geometric designs was implemented at the site. Although some intersection designs consistently perform better than others, such as the roundabout, the cost associated with intersection reconstruction is not justified based on overall intersection operational benefits. Having established that the aggregate average delay is acceptable for each design, we further examine the worst case average vehicle delay by approach for each intersection, shown below in table 5.15.

Table 5.15 Summary of operational analysis results: aggregate intersection delay

Worst Approach Average Delay per Vehicle (seconds)		TWSC	AWSC	Roundabout	RCUT
US-81 and NE-91 near Humphry, NE	Approach	EB	EB	EB	EB
	Average Delay per Vehicle	34.4	16.0	8.8	62.7
US-81 and NE-32 near Madison, NE	Approach	EB	EB	WB	EB
	Average Delay per Vehicle	20.7	11.8	6.8	53.8
US-75 and NE-35 near Dakota City, NE	Approach	EB	EB	WB	EB
	Average Delay per Vehicle	146.7	14.2	7.8	176.2

In contrast to the aggregate average delays, examining the average vehicle delay for the worst approach at each case study location suggests a much more complex picture regarding mitigation design decisions. The AWSC and roundabout geometries are shown to be best at producing uniformly acceptable delays on all approaches, providing LOS A or B on every approach at all three case study locations. However, this reduction in delay for the minor approaches is gained at the cost of creating stops or greatly reduced velocity for the through traffic on the major roadway, a condition that NDOT has stated they wish to avoid. The TWSC intersection performs the third best of the four when it comes to minor approach delay, but this design increases potential for high-speed right-angle crashes, which is a key concern at all of the case study sites investigated. The experienced travel time, an analogous measure of delay for alternative intersections, increases significantly for minor approach traffic at the RCUT design, reducing the LOS to E or F, an unacceptable condition. However, this design is the only one of the four that can meet the dual needs of improving safety while maintaining unimpeded throughput on the major road approaches.

5.6 Validation of RCUT Results

Due to the relatively recent inclusion of a Highway Capacity Manual (HCM) methodology for vehicle delay at a restricted crossing u-turn (RCUT) facility, this research includes validation of the RCUT results using VISSIM traffic microsimulation analysis.

Calibration of the microsimulation model is done using the HCM methodology for TWSC intersection vehicle delay. Vehicle speed distributions, gap acceptance, and follow-up headway are modified based on engineering judgement such that the aggregate delay measures for a simulated TWSC intersection are roughly matching the expected results as predicted by the HCM methodology. The case study location at the intersection of US-81 and NE-91 near Humphrey, NE was modeled as TWSC in VISSIM in order to calibrate the parameters listed. Having calibrated the behavior of vehicles to generate consistent results, these calibrated values (speed distribution, gap acceptance, and follow-up headway) are then applied to the simulated RCUT intersection geometries to attempt to validate the HCM methodology results for the case study sites.

Histograms of the average delay per vehicle results for RCUT designs at each case study site location are provided comparing the HCM and VISSIM results. The average delay per vehicle for US-81 and NE-91 near Humphrey, NE is shown below in figure 5.3. The average delay per vehicle for US-81 and NE-32 near Madison, NE is shown below in figure 5.4. The average delay per vehicle for US-75 and NE-35 near Dakota City, NE is shown below in figure 5.5.

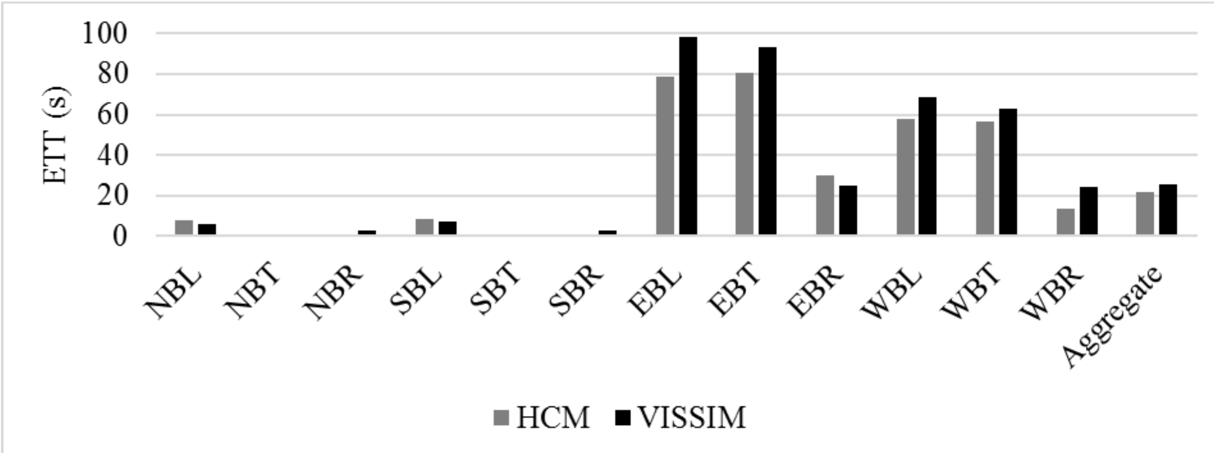


Figure 5.3 Average delay comparison for RCUT at US-81 and NE-91 near Humphrey, NE

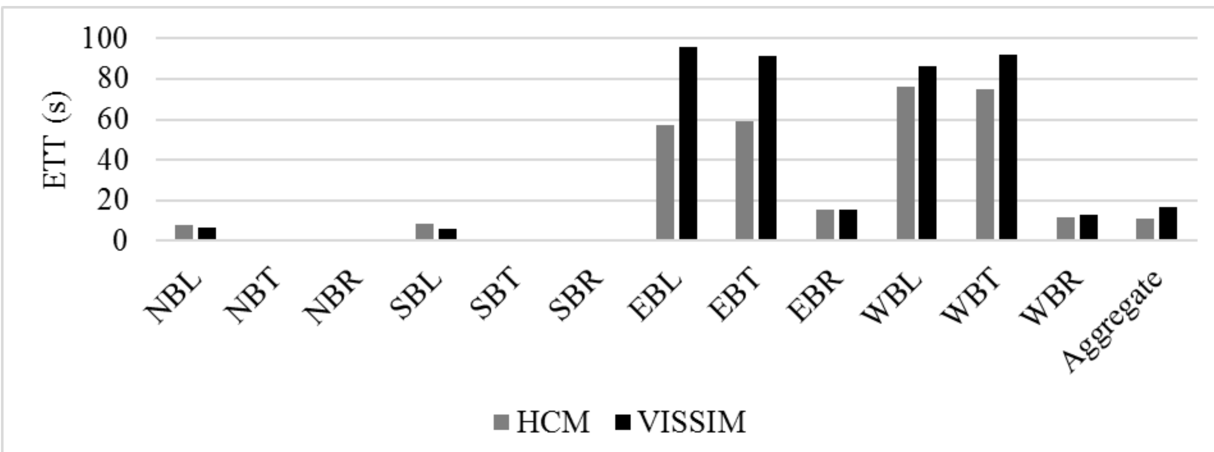


Figure 5.4 Average delay comparison for RCUT at US-81 and NE-32 near Madison, NE

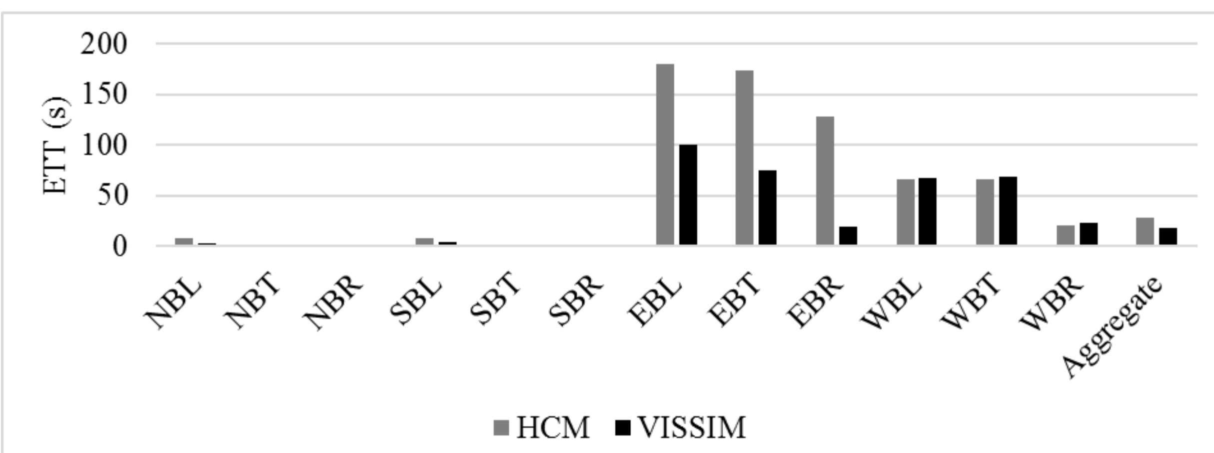


Figure 5.5 Average delay comparison for RCUT at US-75 and NE-35 near Dakota City, NE

The HCM analysis for the case study location at US-81 and NE-91 near Humphrey predicts very similar average experienced travel times (ETT) as those predicted by VISSIM microsimulation. Discrepancies between the two appear for the minor approach left and through movements, where oversaturated conditions occur and the models are very susceptible to varying results based on queue buildup during the time of analysis. The comparison of results between HCM and microsimulation for the intersection of US-81 and NE-32 near Madison are very similar to the results from the case study site location near Humphrey.

At the case study location of US-75 and NE-35 near Dakota City, the ETT predicted by the HCM methodology for the eastbound approach is significantly higher than the VISSIM microsimulation. As with the other two locations this is occurring in oversaturated conditions where demand is in excess of capacity, queues continue to grow over time, and the average delay is dependent upon the length of the analysis period being calculated.

The findings herein suggest that both HCM and microsimulation measures of experienced travel time for restricted crossing u-turns are in agreement for undersaturated conditions. It is the authors' belief that as traffic demands increase toward capacity that site-specific driver behaviors will have a great impact on the actual travel time experienced in the field, and that the driver behaviors themselves will be impacted by the levels of congestion at the site. That is to say, the gap acceptance and follow-up headway of drivers in congested driving conditions are likely to be smaller than those of drivers experiencing no delay; however, at this time neither microsimulation nor the HCM methodology is able to take this interactive behavior into account.

Chapter 6 Cost-Benefit Analysis and Decision Matrix

The cost-benefit analysis of the design alternatives at each location includes the monetized value of delay, the monetized value of crash reduction rates, and the estimated construction costs for the mitigation. As the capital construction costs for unsignalized intersections is essentially a one-time expense, and the monetized delay and safety values see annual returns, the measure of effectiveness for the costs will be presented as estimated return on investment in terms of years to recuperate the initial construction costs.

6.1 Monetized Traffic Delay

Calculating the cost of delay involved estimating the worth of an individual's time. The Bureau of Labor Statistics reports that the average hourly wage for a worker in Nebraska was $21.89/hr for May of 2017 [45]. This rate is used to calculate the cost of delay experienced during the peak hours analyzed. The peak hour is then taken equal to 15% of the average daily traffic [37]. Conversions from delay to monetized traffic delay are displayed below, in table 6.1.

Table 6.1 Monetized delay costs at case study locations

US-81 and NE-91 near Humphrey, NE	TWSC	Roundabout	RCUT
Total ETT (s)	12027	6599	22543
Peak Hour Cost of Delay ($)	$ 73.13	$ 40.13	$ 137.08
Daily Cost of Delay ($)	$ 487.53	$ 267.50	$ 913.83
Yearly Cost of Delay ($)	$ 177,948	$ 97,639	$ 333,550
US-81 and NE-32 near Madison, NE	**TWSC**	**Roundabout**	**RCUT**
Total ETT (s)	4323	5111	11001
Peak Hour Cost of Delay ($)	$ 26.28	$ 31.08	$ 66.89
Daily Cost of Delay ($)	$ 175.23	$ 207.18	$ 445.94
Yearly Cost of Delay ($)	$ 63,958	$ 75,622	$ 162,768
US-75 and NE-35 near Dakota City, NE	**AWSC**	**Roundabout**	**RCUT**
Total ETT (s)	18407	8079	38573
Peak Hour Cost of Delay ($)	$ 111.92	$ 49.12	$ 234.55
Daily Cost of Delay ($)	$ 746.17	$ 327.50	$ 1,563.64
Yearly Cost of Delay ($)	$ 272,350	$ 119,537	$ 570,727

Relative to the existing condition, the roundabout design is predicted to save overall travel time, while the restricted crossing u-turn is predicted to increase it. Although these perceived costs are valued based on the average income per hour in Nebraska, these values are not direct costs experienced by either NDOT or the individual drivers passing through the site. The time itself is experienced as a few seconds by each driver passing through the location as part of a larger trip, which adds up to the totals shown by aggregating those few seconds across every vehicle passing through the intersection. Although these values will be examined in terms of an annual return on investment against the cost of construction at a given site, the benefit itself is experienced by society at large, and will at no point directly offset the construction costs expended by the state and ultimately paid for by taxpayers. This is not to say that intersection improvements are not valued or necessary, but that the benefits stated herein should be understood within the context of being theoretical societal benefits.

6.2 Monetized Safety Benefits

Combining crash severity rates with the crash histories from each location and the crash severity reductions previously discussed in section 3.5, monetized costs for crashes at each location and for each intersection design are calculated. As the TWSC and the AWSC are taken to have similar crash rate profiles, only three types of intersections are analyzed for safety: the current intersection design at each site, the roundabout intersection, and the RCUT junction. Monetized results for crash rates are provided below, in table 6.2.

Table 6.2 Monetized crash costs of each intersection design

US-81 and NE-91 near Humphrey, NE	Historical Crash Rate (per year)	Cost ($/crash)	Current: TWSC ($/year)	Roundabout ($/year)		RCUT ($/year)	
				Red.	Eq. Costs	Red.	Eq. Costs
Fatal (K)	0.5	$10,082,000	$ 5,041,000	100%	$ -	100%	$ -
Disabling (A)	1.3	$ 1,103,000	$ 1,433,900	89%	$ 157,729	92%	$ 114,712
Visible (B)	3	$ 304,000	$ 912,000	83%	$ 155,040	68%	$ 291,840
Possible (C)	1	$ 141,000	$ 141,000	82%	$ 25,380	76%	$ 33,840
PDO	2	$ 4,200	$ 8,400	0%	$ 8,400	38%	$ 5,208
Total Monetized Crash Cost Per Year:			$ 7,536,300	95%	$ 346,549	94%	$ 445,600
US-81 and NE-32 near Madison, NE	**Historical Crash Rate (per year)**	**Cost ($/Crash)**	**Current: TWSC ($/year)**	**Roundabout ($/year)**		**RCUT ($/year)**	
				Red.	**Eq. Costs**	**Red.**	**Eq. Costs**
Fatal (K)	0.1	$10,082,000	$ 1,008,200	100%	$ -	100%	$ -
Disabling (A)	0.7	$ 1,103,000	$ 772,100	89%	$ 84,931	92%	$ 61,768
Visible (B)	0.7	$ 304,000	$ 212,800	83%	$ 36,176	68%	$ 68,096
Possible (C)	0.4	$ 141,000	$ 56,400	82%	$ 10,152	76%	$ 13,536
PDO	0.9	$ 4,200	$ 3,780	0%	$ 3,780	38%	$ 2,344
Total Monetized Crash Cost Per Year:			$ 2,053,280	93%	$ 135,039	93%	$ 145,744
US-75 and NE-35 near Dakota City, NE	**Historical Crash Rate (per year)**	**Cost ($/Crash)**	**Current: AWSC ($/year)**	**Roundabout ($/year)**		**RCUT ($/year)**	
				Red.	**Eq. Costs**	**Red.**	**Eq. Costs**
Fatal (K)	0	$10,082,000	$ -	100%	$ -	100%	$ -
Disabling (A)	1.1	$ 1,103,000	$ 1,213,300	89%	$ 133,463	92%	$ 97,064
Visible (B)	1.1	$ 304,000	$ 334,400	83%	$ 56,848	68%	$ 107,008
Possible (C)	0.5	$ 141,000	$ 70,500	82%	$ 12,690	76%	$ 16,920
PDO	1.4	$ 4,200	$ 5,880	0%	$ 5,880	38%	$ 3,646
Total Monetized Crash Cost Per Year:			$ 1,624,080	87%	$ 208,881	86%	$ 224,638

Both the roundabout and the restricted-crossing u-turn (RCUT) designs provide significant improvements to safety over the existing two-way stop-controlled (TWSC) or all-way stop-controlled (AWSC) intersection designs. The benefits of the roundabout range from an 87% reduction in monetized crash costs up to a 95% reduction, with similar findings for the RCUT design, though the RCUT is currently predicted to have about 10% higher crash-related costs per year than an equivalent roundabout design. One trend that can be implied from the few sample sources studied is that the greatest benefits of constructing these safer designs are seen for intersections currently experiencing the highest crash rates and crash severities, since both the roundabout and RCUT designs are able to completely remove the threat of fatal crashes.

As with the monetized delay results, the monetized safety results represent costs to society at large, and not direct costs to NDOT or the taxpayers, in terms of offsetting the construction costs incurred for building a mitigated intersection geometry at a given site. However, knowing the society costs potentially saved by choosing to construct these alternative intersection designs can help to provide guidance for prioritization of the funding available to NDOT for improving the safety of the surface roadway network.

6.3 Cost-benefit comparison of final results

Assessing return on investment of the various mitigation strategies can be achieved by combining the monetized delay results from table 6.1, with the monetized safety results from table 6.2, and the average construction costs for a roundabout ($365,000) and a restricted crossing u-turn junction ($860,000) as previously discussed in section 3.5 of this report. The results of these computations are provided below, in table 6.3.

Table 6.3 Cost-benefit analysis of design alternatives

US-81 and NE-91 near Humphrey, NE	TWSC (existing)	Roundabout	RCUT
Monetized delay ($/year)	$ 177,948	$ 97,639	$ 333,550
Monetized safety ($/year)	$ 7,536,300	$ 2,495,300	$ 2,495,300
Combined monetized costs ($/year)	$ 7,714,248	$ 2,592,939	$ 2,828,850
Benefit from existing ($/year)	$ -	$ (5,121,309)	$ (4,885,398)
Construction Cost ($ one time)	$ -	$ 365,000	$ 860,000
Years to Recuperate	-	0.07	0.18
US-81 and NE-32 near Madison, NE	**TWSC (existing)**	**Roundabout**	**RCUT**
Monetized delay ($/year)	$ 63,958	$ 75,622	$ 162,768
Monetized safety ($/year)	$ 2,053,280	$ 135,039	$ 145,744
Combined monetized costs ($/year)	$ 2,117,238	$ 210,661	$ 308,511
Benefit from existing ($/year)	$ -	$ (1,906,576)	$ (1,808,726)
Construction Cost ($ one time)	$ -	$ 365,000	$ 860,000
Years to Recuperate	-	0.19	0.48
US-75 and NE-35 near Dakota City, NE	**AWSC (existing)**	**Roundabout**	**RCUT**
Monetized delay ($/year)	$ 272,350	$ 119,537	$ 570,727
Monetized safety ($/year)	$ 1,624,080	$ 208,881	$ 224,638
Combined monetized costs ($/year)	$ 1,896,430	$ 328,418	$ 795,364
Benefit from existing ($/year)	$ -	$ (1,568,012)	$ (1,101,066)
Construction Cost ($ one time)	$ -	$ 365,000	$ 860,000
Years to Recuperate	-	0.23	0.78

Using the monetized delay and safety values for the various intersection case study sites and design alternatives, every site was found to experience a time to return on investment of less than a year, before construction costs were recouped by theoretical societal benefits. The time needed to recoup construction costs for the roundabout design ranged from just 26 days up to three months. Due to the higher construction costs of the RCUT design, and the increased travel time it creates for the minor movements, the time needed to recoup construction costs were significantly higher relative to the roundabout, ranging from two months to nine months.

6.4 Decision Matrix

If the monetized societal benefits associated with the construction of a roundabout or restricted crossing u-turn design are applied directly against the cost of construction, a return on investment can be shown for reconstructing every TWSC or AWSC intersection on Nebraska's rural highway network; this is not the goal of this report. Rather, having justified the benefits of these intersection designs, this research seeks to aid in identifying conditions when these alternative designs would serve well to mitigate a problematic intersection that is experiencing higher-than-average crash severity and frequency. The roundabout design has been in common use by the Nebraska Department of Transportation (NDOT) for some time now, and selection criteria for this design are not necessary. The decision to pursue an RCUT as the intersection of choice is summarized herein as a response to a series of five different questions regarding the potential site, including (1) the safety concerns at the location, (2) the overall levels of traffic demand, (3) the balance between major and minor movement traffic demand, (4) the presence of obstructions along the main roadway that would impact u-turn bay placement, and (5) the available space in the median for the u-turn bay.

The first condition to be met is that the site location under consideration must be operating poorly from a safety standpoint, with significantly higher crash frequency and severity than the average intersection in the state. Although the design would improve safety at every intersection, the State has a limited budget and must prioritize expenditures to optimize the entire surface roadway transportation system.

The second condition is whether the overall levels of traffic are too high to accommodate the interaction between the main approach through traffic and the minor approach weaving traffic utilizing the u-turn to complete left-turn and through movements. If the overall traffic on the roadway is around 50,000 AADT, the performance of the unsignalized RCUT design significantly deteriorates, as does that of the roundabout design, and signalized or grade separated solutions should likely be pursued at the site.

The third consideration is the balance of traffic between the major approaches and the minor approach. With very high experienced extra travel time impacting minor approach left and through movements, the average delay per vehicle and subsequently the LOS of intersection, is largely governed by the ratio of free-moving through traffic on the main road to redirected traffic from the side road. If the AADT of the minor approach is greater than about 80% of the AADT of the major approach, the delay experienced by the minor movements will reduce the overall level of service for the junction below acceptable levels. If overall AADT levels are low, but the volumes are nearly balanced between the major approach and the minor approach, then a roundabout or another unsignalized solution should be pursued.

The fourth consideration is the nature of obstructions downstream of the main intersection along the major roadway. The u-turn bays should be located between 1,000 feet and 2,000 feet downstream of the main intersection. If the location is too close, minor approach cannot safety execute weaving maneuvers in the presence of high-speed through traffic on the major roadway, and if it is located too far away the additional travel time imposed on the minor movements reduces the aggregate level of service for the intersection. The u-turn bay needs approximately 500 feet of unimpeded space with no driveways, cross streets, or major obstructions such as trees or small buildings. If an appropriate stretch of 500 feet cannot be located or created between 1,000 and 2,000 feet from the intersection, an alternative unsignalized design should be considered.

The fifth consideration is the nature of the median available along the major roadway approaches. The design-vehicle turning radius requires a necessary offset between the far lane of the opposing lanes, and the edge of the u-turn bay constructed into the existing median of the site. If the existing median is less than 40 feet in width, the minor approach left-turn and through movements will be unable to safely execute the u-turn within the paved limits of the roadway. In some cases when the existing median is smaller than 40 feet, it is possible to construct a "loon" of pavement into the right-of-way beyond the limits of the traveled way on the opposing lanes, allowing trucks and other large vehicles to execute the u-turn movement. If there are obstructions beyond the travelled way, or if there is a limited width of right-of-way available, it may not be possible to construct the loon. If neither the 40 foot median width nor the "loon" is available at the existing site, the RCUT design might still be an appropriate choice, but additional construction costs should be anticipated due to the realignment of the highway in the vicinity of the junction to allow for the required spacing.

Assuming each of the five conditions as described above have been met, the RCUT geometry represents the safest at-grade intersection design that will allow for unimpeded through-movements along rural highways, and is anticipated to be a widely applied solution for unsignalized rural highway intersections in Nebraska and nationwide. A graphical representation of the considerations as outlined above is provided below, as a decision matrix in figure 6.1.

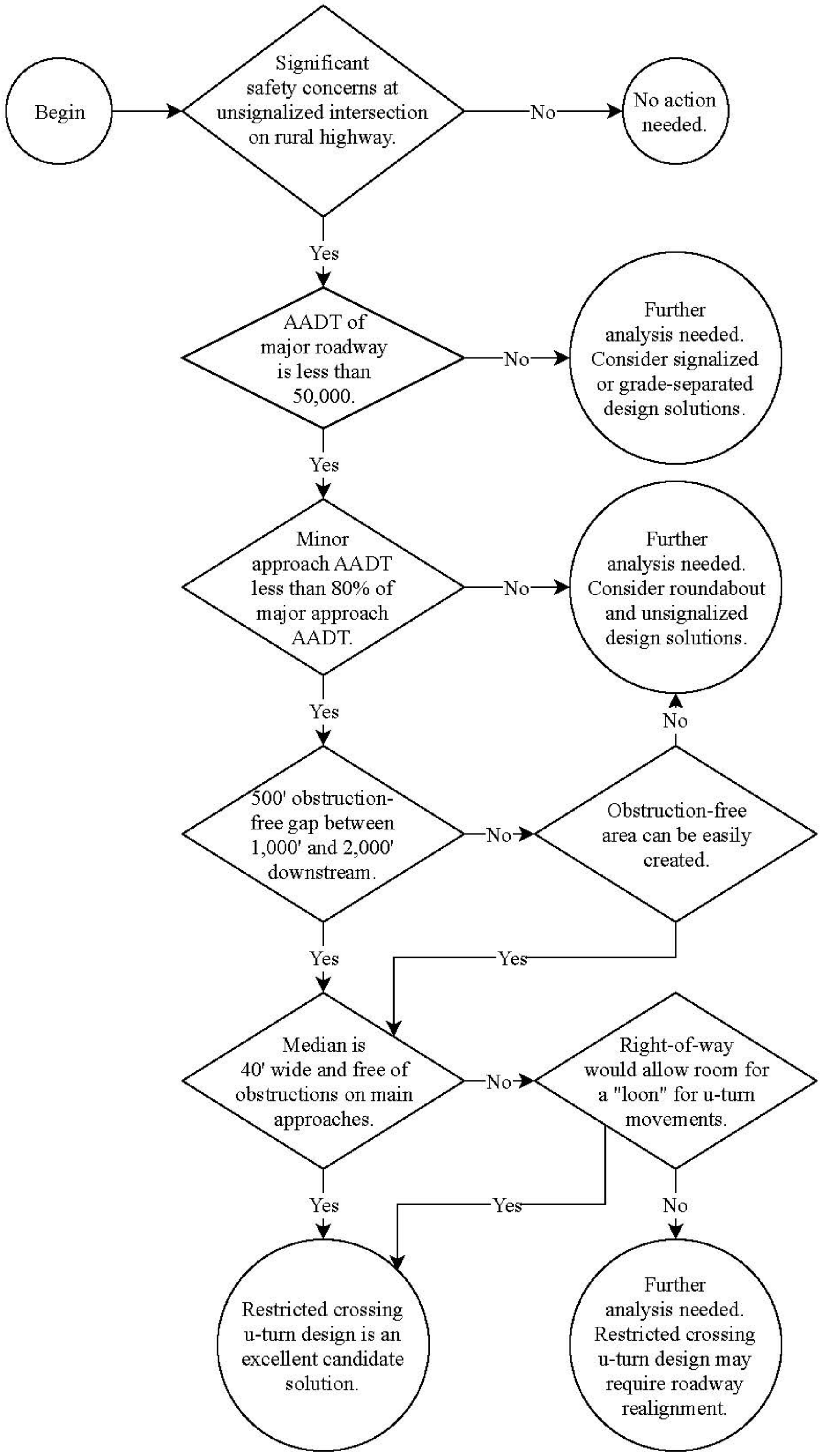


Figure 6.1 Decision matrix for consideration of RCUT geometry

Chapter 7 Limitations of the Study

All research projects are limited both in time and budget, which unfortunately results in limitations on the methodology and findings as well. Some of the key limitations identified by the researchers regarding the current report include (1) the weighting of monetized societal costs for delay and crash measures, (2) the limited number of sites and traffic demand volumes investigated, (3) a decision tool or other methodology for selecting the placement of the u-turn bays, and (4) the inclusion of a grade separated interchange as one of the design alternatives.

The results of the cost-benefit analysis conducted herein relied heavily on comparing monetized societal costs for traffic delay and crashes, against the direct costs to reconstruct the intersection with an alternate geometry. By taking these two different types of values as equivalent to each other, the theoretical result is a justification to reconstruct every unsignalized intersection in Nebraska. The greatest potential improvement for a more nuanced examination of the benefits of reconstructing intersections would be a meaningful way to weight the value of societal costs, to better identify where the tipping point lies between reconstructing an intersection and retaining the existing geometry.

The case studies conducted utilized field-observed traffic demand volumes to predict comparisons of travel delay between intersection designs. A useful additional effort would have been to grow/shrink these volumes and conduct additional analysis for higher and lower levels of AADT. This analysis could then predict, more generally, at what levels of AADT the RCUT design can be expected to fail, relative to other geometries. A large challenge with this type of analysis is that any geometric design can be made to function properly with the addition of extra turn lanes. The ultimate, more nuanced approach, would be to assess the cost of construction for the least number of necessary turn lanes (the geometry as presented in the analysis of this report), and examine the cost increases due to additional lanes as traffic levels increase. This would then provide a way for NDOT to quickly assess site appropriateness for the RCUT design based on costs increasing with higher AADT.

The location of the u-turn bays is currently a topic of debate in the literature. Moving the bays too close to the main intersection creates safety problems with minor approach vehicles making relatively low-speed weaving maneuvers through high-speed major approach through traffic. Moving the bays too far away from the main intersection creates significant increases in experienced travel time, reducing the level-of-service (LOS) of the intersection. The researchers would have liked to systematically move the location of the u-turn bay and simulate the delay results, in order to quantify the monetized delay costs associated with the placement of the u-turn bay, but were unable to do so with the current scope. Each potential site for intersection reconstruction will have site specific limitations that impact the placement of u-turn bays, and it would be beneficial to NDOT to have a decision tool or method to compare the costs required to relocate site obstructions against the costs imparted by moving the u-turn location further down.

The ultimate resolution of an at-grade rural highway intersection experiencing high frequency and severity of crashes is reconstructing the site as a grade-separated interchange. This solution is an order of magnitude more costly than reconstruction using one of the alternative intersection designs, but is still chosen as a preferred solution to maintain unimpeded through movements on the highway. A better understanding on the safety benefits of grade-separation and the construction costs associated with this facility would have provided a more complete review of the options being considered by NDOT when planning intersection reconstruction projects.

Chapter 8 Conclusions and Recommendations

The main finding of this research report is that both the roundabout and restricted crossing u-turn (RCUT) intersection designs improve safety at two-way stop controlled (TWSC) and all-way stop controlled (AWSC) rural highway intersections to such a degree that they are always justified, given that societal costs associated with crashes are taken equal to the cost for intersection reconstruction. The roundabout has the greatest safety performance, as well as the greatest operational performance (lowest vehicle travel times) of all the unsignalized at-grade intersection designs assessed, and should be the design of choice whenever it is permissible to reduce the speed of the main approach through traffic. For cases when it is not acceptable to impede the main approach through traffic, the RCUT design provides excellent safety improvement without significant operational performance degradation of the intersection. Intersection reconstruction of existing TWSC and AWSC intersections should be conducted based on recent crash history, both severity and frequency, with selection between the roundabout and RCUT design determined based on the classification of the roadway location and whether through traffic on major approaches may be impeded.

8.1 Findings Organized by Chapter

Although the main finding of this report, as stated above, is that both roundabouts and restricted crossing u-turn junctions are effective mitigation tools to address safety concerns at TWSC intersections on rural highways, this report includes many other pertinent findings that are spread throughout the chapters, organized by topic.

The literature review conducted in Chapter 2 included some essential findings that may impact the decision making process when selecting an appropriate safety mitigation strategy. There was an initial concern with driver expectancy, which prevented this design from being widely adopted throughout the country. However, a sufficient number of installations have now been completed in states like North Carolina, Maryland, and Minnesota, and safety data from a broad range of these installations has confirmed that the theoretical safety benefits anticipated with the design have been realized in field applications. The RCUT design is frequently implemented as either signalized or unsignalized, with urban applications having signalization and short offsets to u-turn bays (of only a hundred feet), while rural applications of the design use stop-control and have much longer offsets of 1,000 to 2,000 feet due to the conflict between high-speed major street through traffic, and lower-speed weaving maneuvers being performed by traffic from the minor approach. The Federal Highway Administration (FHWA) has provided general guidance on the geometric layout of these designs, but more specific design guidance has been developed by each state agency based on their own internal experience with implementing the design locally; it is anticipated that normalization of the design will occur with upcoming releases of the Manual on Uniform Traffic Control Delay (MUTCD) and A Policy on Geometric Design of Highways and Streets (Green Book). There is some disagreement in the literature regarding the operational impacts of this intersection, particularly for the unsignalized design, as the minor movements experience significant increases in experienced travel time while the unimpeded through movements on the main approaches are not included in the weighted average of the operational analysis. Generally speaking, the RCUT design increases travel times for minor roadway traffic, while reducing or maintaining low or no delays for major roadway traffic. The safety benefit of the RCUT design is the primary reason for its recent embrace by a number of state agencies throughout the country, with a significant reduction in vehicle conflict points, and field-observed crash reduction rates, particularly for the most severe crash types. Two-way stop controlled (TWSC) intersections on rural highways are prone to experiencing fatal right-angle accidents as minor street traffic enters high-speed through lanes, a type of crash that the RCUT design is intended to prevent. There is some difficulty to accommodate high volumes of bicycle and pedestrian movements with the RCUT design, but this becomes a consideration of lower priority when considering rural highway applications.

The methodology of the research conducted, as described in Chapter 3, may have a significant impact on the way in which the findings of this report are interpreted. Comparative analysis was conducted for three site locations with either TWSC or all-way stop control (AWSC) existing geometry, analyzing the anticipated impacts of mitigation with a roundabout or an RCUT design. In designing the simulated intersection geometry, some concerns were raised about the potential cost impacts of implementing RCUT junctions on Nebraska's rural highway system. The typical median width for rural highways in Nebraska is 40' from edge of travelway to edge of travelway, which would leave approximately 28' remaining if a left-turn bay were added to an existing median. However, the recommended minimum median width to accommodate the turning radius of a WB-40 design vehicle would instead be 51' in the absence of a loon, and 41' if a loon were to be constructed. This initial analysis suggests that every potential RCUT location in the state will require some realignment of roadway to achieve the necessary separation, with significant full-depth roadway reconstruction increasing the cost of the project. Regarding the operational analysis of the design, the conversion of delay to level-of-service (LOS) was examined, and concerns were raised regarding the comparative analysis between different intersection geometries, with the potential for one intersection to perform better in terms of average delay, while an alternate design might perform better in terms of level-of-service, due to the way that signalized intersections are allowed more delay than unsignalized ones at the same operational level. Finally, from a methodology perspective, delay and crash rates were converted to equivalent societal costs, but return-on-investment analysis takes these societal cost values as equal to construction costs, with the mismatch between the two measures not resolved at this time.

The case study site locations selected in Chapter 4 were chosen from a list of candidate sites provided by the Nebraska Department of Transportation. Each of these sites met the criteria of being an unsignalized TWSC or AWSC junction between a four-lane rural highway and a minor road arterial, and most of the sites identified have higher than average observed crash rates over the previous five years. Initial implementation of RCUT designs in other states has been done in series along one arterial, to acclimatize local drivers to the new geometry, and it was appealing to examine multiple sites along US-81, such as the chosen sites in Madison and Humphrey, as this highway exhibits the appropriate combination of demand volumes that is well suited to an unsignalized RCUT application.

The operational analysis conducted in Chapter 5 confirmed that the purpose of implementing an alternative design such as a roundabout or an RCUT is for the safety benefits, and not primarily to increase throughput or decrease delay. Assessing TWSC, AWSC, roundabout, and RCUT geometries at US-81 in both Humphrey and Madison, all four geometries are predicted to have average delays of fewer than 15 seconds per vehicle during the peak hour, well below acceptable thresholds. The intersection of US-75 and Nebraska-35 in Dakota City experiences significantly more demand volume than the other two sites, and while it is appropriate to keep this site unsignalized, the TWSC and RCUT designs exhibit much higher average delays closer to 25 seconds per vehicle, with some movements in failure for both designs. The take-away from the operational analysis is that while the roundabout and RCUT designs do no harm for low demand-volume conditions, at higher volumes the traffic experiences significant delay, and the TWSC and roundabout options operate better as volumes climb toward the need for signalization. There was some concern by the researchers in the reliability of the relatively untested RCUT methodology, which has not yet been implemented widely in standard software packages like Synchro and HCS, but validation through calibrated microsimulation models showed that the predicted experienced travel times from the HCM method are at least in line with the predictions from microsimulation.

The costs and benefit analyses from implementing the various intersection geometries were assessed in Chapter 6, which included monetized delay costs, monetized crash costs, and anticipated construction costs. Comparing the TWSC and AWSC intersections against the roundabout, the anticipated delay is sometimes less and sometimes more for the roundabout, but the relative costs for delay over the course of the year are minimal, in the range of $100 to $200 thousand per year. The experienced travel time at the RCUT intersection is anticipated to be around twice that of the existing TWSC and AWSC intersections, but again in a relatively low range of $200 to $600 thousand per year. In contrast, the monetized crash costs for the existing geometries ranged from the low of $1.6 million for the relatively safe AWSC site in Dakota City, to the higher $2 million for the TWSC site near Madison, all the way up to $7.5 million per year for the location in Humphrey, which has experienced a high crash rate in recent years. Mitigating these locations with either a roundabout or an RCUT intersection is anticipated to reduce the monetized safety costs by an order of magnitude, in the range of $200 to $250 thousand at Dakota City, $135 to $145 thousand at Madison, and $350 to $450 thousand per year at Humphrey. Combining the safety and operations data, the combined benefit per year of constructing an RCUT junction compared with the existing condition is around $1.1 million for Dakota City, $1.8 million for Madison, and $4.8 million per year for Humphrey. The roundabout exhibits less delay and has slightly better safety performance than the RCUT, and the anticipated benefits for it are around a 10% improvement over the RCUT. If these monetized delay and safety costs are assumed to be equivalent weight to the construction costs expended to implement the design, both a roundabout and an RCUT design would provide a positive return on investment after less than one year, with an anticipated lifetime of 20 to 30 years before reconstruction may become necessary. In the most extreme case of a roundabout intersection being constructed at Humphrey, the return on investment was calculated at just 0.07 years, or 25 days.

However, despite the potential benefit of reconstructing every unsignalized rural highway intersection to achieve the anticipated safety benefits associated with these designs, there is limited budget for construction in any given year, and an increasing need to spend that limited budget to maintain the aging surface roadway infrastructure, rather than taking on new projects such as roundabout and RCUT reconstruction. State agencies thus need some methodology to triage which intersections to examine for potential mitigation, and the decision matrix provided at the end of Chapter 6 is intended to assist with this process. The decision matrix seeks to assess specifically whether an RCUT intersection would be appropriate; the five factors for consideration identified include: (1) the safety concerns at the location, (2) the overall levels of traffic demand, (3) the balance between major and minor movement traffic demand, (4) the presence of obstructions along the main roadway that would impact u-turn bay placement, and (5) the available space in the median for the u-turn bay. The results of the decision tree lead to multiple potential options, varying from the RCUT being an excellent candidate solution, to no action (mitigation) needed at the site. Other solutions from the decision tree lead to a suggestion to examine grade-separated design solutions, a suggestion to examine roundabouts or other unsignalized designs, or a recommendation for further analysis of the cost for realigning the road to implement the RCUT at a specific site. The primary takeaway from the research is that both a roundabout and an RCUT design can be relied upon to lead to significant safety improvements for unsignalized intersections on rural highways, and that the decision of which one to use should factor in the potential increase in delay to the minor approach at the RCUT design if a high demand volume is anticipated (such as Dakota City), or the consideration of whether it is permissible to interrupt the flow of the major arterial through movement with a roundabout versus leaving it free-flowing with the RCUT.

The final chapter of content in this report, Chapter 7, examines some of the limitations of the research conducted. The major concern that the researchers have regarding the findings of this report is the concept of monetized delay and safety being equal to direct construction costs. While each site will have many constraints to work with and work around, particularly for placement of downstream u-turn bays and realignment of roadways for the RCUT design, it is the justification of whether or not to pursue this solution that is at the heart of this research report, and the weighting of societal costs versus direct costs is unfortunately an ethical question that is beyond the scope of this research to resolve.

8.2 Recommendations for Future Work

Having fully-established the potential benefits from the restricted crossing u-turn intersection regarding the mitigation of safety issues at unsignalized rural highway intersections, further work needs to be done to expand the recommended practice for use of this design within the state of Nebraska.

Between the time of the start of this research and the completion of the report, the Nebraska Department of Transportation conducted design, and will be pursuing construction of the first rural highway RCUT intersection in the state. Codifying the design decisions made during the process of that work will lead to a consistent set of design decisions regarding rural highway RCUT facilities in the state. Key takeaways will be the range of downstream offset that is appropriate for the u-turn bay location, the preferred use of acceleration and/or deceleration lanes for minor street through and left-turning traffic utilizing the u-turn location, and the desired median widths of the reconstructed roadway at the location of the u-turn maneuvers.

Although this report includes a great deal of background information about RCUT intersections in general, the focus has largely been on rural highway applications, and there is a great deal more work to be done to understand potential urban implementation of this design in the major cities within the state, such as Omaha, Lincoln, and Grand Island. Because the Nebraska DOT holds primary responsibility only for the surface roadway network beyond the limits of metropolitan areas, future funding and direction on urban RCUT facilities in the state will likely need to be led by city administrators. Based on the broad implementation of both signalized and unsignalized RCUT facilities in other jurisdictions, it is likely that these design will become a standard option at some point in the near future throughout Nebraska and the great plains states, with much work to be completed between now and then.

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