Evaluating the Benefits and Drawbacks of Intersections with Three-Phase Traffic Signals

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RESEARCH & DEVELOPMENT

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16. Abstract

At four-phase conventional intersections where traffic demand is near or above capacity, alternative intersections may perform better. Alternative designs with two-phase traffic signals such as reduced conflict intersections (RCI, also called RCUT, J-turn, and superstreet) result in shorter travel times, fewer crashes, and better pedestrian service in North Carolina (NC). However, retrofits to designs with two-phase signals may be negatively impactful and unpopular. Higher minor street demand, lack of precedent, and complaints (from neighbors, business owners, politicians, media, etc.) are among the possible obstacles for constructing two-phase intersection designs in many locations. Intersections with three-phase signals might provide some of the two-phase design advantages while also providing more direct movements and alleviating some public concerns.

This study assists Departments of Transportation (DOTs) in addressing questions such as: (1) At what locations are three-phase designs most well suited? (2) How much do they cost, especially compared with other intersections like RCIs? (3) What are the considerations needed for pedestrian and bicyclist safety? (4) What kind of geometric and right-of-way (ROW) limitations are faced during construction? (5) What designs would be most readily accepted by the public?

In this project, the research team completed a state-of-the-art literature review, conducted microsimulation analysis to evaluate operational performance, assessed the safety of three-phase designs using various methods and developing new tools, conducted a cost/benefit analysis, and developed a public acceptance scoring system (PASS). Overall, three-phase intersection designs were found to have significant potential benefits across all measures of effectiveness (MOEs). The traffic operations analysis revealed that six three-phase alternative intersections—offset thru-cut, thru-cut, reverse RCI, partial CFI, CFI/MUT combo, and MUT Redirect Major (MUT #1)—may perform as well as or even better than two-phase designs under certain traffic conditions, such as those with high-turning traffic volumes. The CFI/MUT design outperformed the partial CFI in four MOEs and matched it in traffic operations. As a result, the CFI/MUT could be a promising alternative where there are concerns, such as pedestrian safety or ROW limitations, about implementing a partial CFI.

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Executive Summary

The purpose of this research is to add new insights regarding the benefits and drawbacks of using alternative intersections with three-phase traffic signals compared to other intersection designs and to develop a technical guideline to help designers and policymakers in transportation understand when and where to use three-phase intersection designs.

At four-phase conventional intersections where traffic demand is near or above capacity, alternative intersections consistently improve performance. Intersection designs with two-phase traffic signals such as reduced conflict intersections (RCI, also called RCUT, J-turn, and superstreet) result in shorter travel times, fewer crashes, and better pedestrian service in North Carolina (NC). However, retrofits to designs with two-phase signals may be negatively impactful and unpopular. Higher minor street demand, lack of precedent, and complaints (from neighbors, business owners, politicians, media, etc.) are among the possible obstacles for constructing two-phase designs in many locations. In other words, while two-phase intersections perform very well at many intersections, designers might not be able to select those designs for some projects. On the other hand, intersections with three-phase signals might provide some of the two-phase design advantages while also providing more direct movements and alleviating some public concerns.

This study assists Departments of Transportation (DOTs) in addressing the following questions: (1) At what locations are three-phase designs most well suited? (2) How much do they cost, especially compared with other intersections like RCIs? (3) What kind of traffic control devices are needed? (4) What movement restrictions could cause motorist confusion and violations? (5) How could we minimize those violations? (6) What are the considerations needed for pedestrian and bicyclist safety? (7) What kind of geometric and right-of-way (ROW) limitations are faced during construction? (8) What movements are less impactful for redirecting in different cases? (9) What designs would be most readily accepted by the public?

Current literature on alternative intersections with three-phase signals is limited. Excluding offset T, partial continuous-flow intersections (CFIs), and quadrant intersections, little information is available on the performance of other three-phase intersections. Reviewing the crash modification factors (CMF) Clearinghouse reveals that only a few studies have estimated CMFs for converting four-phase conventional intersections to three-phase intersections. These studies focused on partial CFIs. This research evaluates different three-phase designs to increase the confidence level in selecting the most appropriate design at different locations.

To identify benefits and drawbacks of three-phase intersections, the research team evaluated three-phase designs considering measures of effectiveness (MOE) that include traffic operations, safety, pedestrian and bicycle performance, public acceptance, and construction cost. As a part of the evaluation conducted, three spreadsheet-based tools titled public acceptance scoring system (PASS), conflict point analysis (CPA), and safe system intersections (SSI for new alternatives) were developed by the research team. Our results show that in appropriate situations, three-phase designs will provide significant operations and safety benefits for all users with fewer impacts compared to two-phase intersection designs. Therefore, they may be more palatable to stakeholders. Ultimately, a framework was developed using these results to help decision-makers and stakeholders improve safety, operational efficiency, public acceptance, and cost savings at future intersection projects in NC.

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Chapter 1 Introduction

With regards to safety, intersections are critical components of our national transportation infrastructure. A major component of intersections are traffic signals, whose design has resulted in multiphase control of intersections. A signal phase is defined as "the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements." (MUTCD, 2023). A typical standard signalized intersection has four critical signal phases per cycle: north/south thru movements, north/south left turns, east/west thru movements, and east/west left turns (not necessarily in that order). Four-critical-phase intersections, while the predominant intersection design in the United States, incur safety and operational penalties by allowing left turn movements from all approaches (Luo, 2022).

At four-phase conventional intersections where traffic demand is near or above capacity, alternative intersections may perform better. Intersection designs with two-phase traffic signals such as reduced conflict intersections (RCI, also called RCUT, J-Turn, and superstreet) and median U-turn (MUT) result in shorter travel times, better pedestrian service, and safety benefits compared to conventional designs (Reid et al., 2014; Jagannathan et al., 2007). These improvements in performance are achieved by redirecting left-turns at an intersection. With no left turns at the main intersection, only two signal phases are required: north/south green, east/west red and north/south red, east/west green. Redirecting these movements decreases conflict points, or points where traffic flows from different street approaches intersect (Reid and Hummer, 2020).

However, retrofits to designs with two-critical-phase signals may be negatively impactful and unpopular with local communities. Higher minor street demand, redirecting too many movements, lack of precedent, and complaints (from neighbors, business owners, politicians, media, etc.) are among the possible obstacles to constructing two-phase designs in many locations. In other words, while two-phase intersections perform very well at many intersections, planners might need help selecting those designs for some projects.

An alternate solution is intersections with three-phase signals, which might provide some of the two-phase design advantages while providing more direct movements and alleviating public concerns. Typically, three-critical-phase intersections redirect minor or major street left-turns (or thru movements), but not both, like a two-phase intersection. Since three-phase designs do not redirect all left turns like two-phase intersections, they require one additional signal phase to direct traffic.

As mentioned above, there has been a growing interest in converting existing conventional intersections to alternative intersections (also known as innovative and unconventional designs) in the last two decades (Hughes and Jagannathan, 2009). Past studies have shown valuable benefits for implementation of alternative intersections such as MUT (Reid et. al, 2014; Al-Omari et. al, 2020; El Esawey and Sayed, 2011; Bared and Kaisar, 2022; Jagannathan, 2007), continuous flow intersection (CFI, also known as displaced left turn intersection, DLT) (Hummer and Molan, 2022; Cunningham, 2022; Steyn et. al, 2014), and reduced conflict point intersection (RCI, also known as RCUT, superstreet, and J-turn) (Mishra and Pulugurtha, 2021; Molan et. al, 2022; Sun et. al, 2019; Howard et. al, 2022; Molan et. al, 2021; Hummer et. al, 2010; Hummer et. al, 2007; Ott et. al, 2012). While all these alternative intersections have symmetric geometries, many existing intersections experience asymmetric traffic conditions with higher traffic volumes on one or two legs. Moreover, the available right-of-way (ROW) and its restrictions can vary across different intersection approaches. In other words, implementing an alternative intersection with symmetric geometric features can be challenging or costly for state departments of transportation (DOTs) under certain circumstances. Therefore, more alternative intersection designs need to be introduced to address these situations.

As a possible solution to the concern mentioned above, combination of alternative intersection designs (hereafter called combination intersection designs) with different geometric features on different approaches could be considered to facilitate traffic operations at intersection sites with asymmetric traffic conditions and/or varying ROW on different approaches. In recent years, state DOTs such as North Carolina DOT, Virginia DOT, and Alaska DOT have shown high interests in implementing newer alternatives such as combination intersection designs (Hummer, 2020; AKDOT, undated) therefore, it is expected to see more of these designs in the future. Despite this high interest, the current literature on combination intersection designs is limited to only a few research articles, and many transportation professionals are not yet familiar with these intersection designs.

1.1 Problem Statement

Despite the advantages of alternative intersection designs with two signal phases, their implementation can be challenging in some locations with high side street demand, ROW restrictions, unbalanced traffic demands, or due to objections from local stakeholders, including neighbors, businesses, and politicians. Therefore, state DOTs might not be able to consider these alternatives in some circumstances.

1.2 Objective

The objective of this final report is to enable traffic engineers and decision makers to make informed decisions about where three-phase intersections could work well. This objective is accomplished by informing readers about the safety and operational performance of intersections with three-phase traffic signals. Specifically, this report includes a state-of-the art literature review, data collection, simulation modeling, public acceptance analysis, and safety analysis of intersections with three-phase traffic signals. It also presents condition diagrams of existing three-phase intersections across the country. The results of this research will hopefully assist state DOTs in their future intersection improvement projects at locations with potential for new combination intersection designs.

1.3 List of Abbreviations

The following abbreviations are utilized throughout the review/report:

- **AASHTO:** American Association of State Highway and Transportation Officials
- **AADT:** Annual Average Daily Traffic
- **ASCE:** American Society of Civil Engineers
- **B/C:** Benefit/Cost
- **CFI:** Continuous Flow Intersection
- **CMF:** Crash Modification Factor
- **CPA:** Conflict Point Analysis
- **DDI:** Diverging Diamond Interchange
- **DLT:** Displaced Left Turn
- **DOT:** Department of Transportation
- **FHWA:** Federal Highway Administration

- **FITS:** Framework for Intersections with Three-phase Signals
- **LOS:** Level of Service
- **MOE:** Measure of Effectiveness
- **MUT:** Median U-Turn
- **MUT #1:** Median U-Turn with Redirected Lefts Only from the Major Road
- **MUT #2:** Median U-Turn with Redirected Lefts Only from the Minor Road
- **MUTCD:** Manual on Uniform Traffic Control Devices
- **NCDOT:** North Carolina Department of Transportation
- **NCHRP:** National Cooperative Highway Research Program
- **PASS:** Public Acceptance Scoring System
- **PDO:** Property Damage Only
- **QR:** Quadrant Roadway Intersection
- **RCI:** Reduced Conflict Intersection
- **REDIRECT L&T (or RLT):** Redirect Left and Thru
- **REDIRECT 2L&T (or R2LT):** Redirect Two Lefts and One Thru
- **ROW:** Right-of-Way
- **SaFID:** Safest Feasible Intersection Design
- **SSAM:** Surrogate Safety Assessment Model
- **SSI:** Safe System Intersections
- **TRB:** Transportation Research Board
- **TRR:** Transportation Research Record
- **V/C:** Volume over Capacity

1.4 List of Definitions

1. **At Grade Intersection:** When two or more surface streets intersect at grade level.
2. **Alternative Intersection:** An intersection design where at least one traffic movement is strategically redirected from a "conventional" signalized intersection to remove or reduce conflict points and to improve traffic signal operation and pedestrian performance at signalized intersections.
3. **Signal Phase**: A traffic phase is defined as the green, change, and clearance intervals in a cycle assigned to specified movement(s) of traffic.
4. **Crash Modification Factors**: A crash modification factor (CMF) is derived from crash studies related to a particular change made to a site by comparing crashes before and after the change. A CMF is then used to compute the expected number of crashes after implementing a similar change on a different road or intersection. This CMF value allows traffic engineers to estimate the effectiveness of a given countermeasure at a particular site.
5. **Surrogate Safety Measures:** Surrogate measures of safety are indirect measures that reflect the crash experience of a facility.
6. **Combination Design:** An intersection design that combines elements of at least two other intersection designs. Example: CFI/MUT Combo which combines the partial MUT and partial CFI designs.

Chapter 2 Literature Review

This literature review was developed as part of NCDOT Research Project 2023-20 in order to investigate how to advance the implementation of three-phase intersections and identify some possible responses to current questions related to three-phase intersections, such as: (1) At what locations are three-phase designs most well suited? (2) How much do they cost, especially compared with other intersections like RCIs? (3) What kind of traffic control devices are needed? (4) What movement restrictions could cause motorist confusion and violations? (5) How could we minimize those violations? (6) What are the considerations needed for pedestrian and bicyclist safety? (7) What kind of geometric and right-of-way (ROW) limitations are faced during construction? (8) What movements are less impactful for redirecting in different cases? (9) What designs would be most readily accepted by the public?

Current literature on alternative intersections with three-phase signals is limited, but some of these questions have been studied more using two-phase intersections. The FHWA Displaced Left Turn (Steyn et al. 2014), the FHWA Median U-Turn (Reid et al. 2014), and the FHWA Quadrant Roadway (QR) Intersection (Reid and Hummer 2020) Informational Guides provide general details, planning techniques and strategies, evaluation methods (for evaluating operational and safety performance), geometric design guidelines, and principles to be considered when choosing and implementing CFI, MUT, and quadrant intersections. The FHWA guidelines also presented construction costs of a few past projects implementing those designs. According to the information provided, construction costs varied from $1.7M to $5.1M, from $4.4M to $7.5M, and from $1.8M to $3.2M for MUTs, CFIs, and quadrants, respectively, constructed in the 2000s and the 2010s.

Excluding offset T, partial CFIs, and QRs, (three three-phase designs with real-world examples in NC) little information is available on the performance of other three-phase intersections. Reviewing the Crash Modification Factors (CMF) Clearinghouse reveals that only a few studies have estimated CMFs for converting four-phase conventional intersections to three-phase intersections. These studies focused on partial CFIs, and MUTs with two-phase traffic signals (no CMF for the three-phase version, though).

Specific three-phase designs discussed in this literature review are: partial MUT (two versions), partial CFI, reverse RCI, CFI/MUT combination (combo), thru-cut, offset-T, seven-phase signal, redirect left and through (redirect L&T or RLT), and QR. There are also other three-phase designs with no publications in the current literature: redirect two left and one through (redirect 2L&T or R2LT, proposed by one of the authors, Amir Molan) and offset thru-cut (proposed by Joseph E. Hummer). The design geometry for each of these intersections is provided in section 3.1 of this report.

The sources collected in this report are mainly publications and technical reports by the North Carolina Department of Transportation (NCDOT), National Cooperative Highway Research Program (NCHRP), Federal Highway Administration (FHWA), Transportation Research Board (TRB), Elsevier, American Society of Civil Engineers (ASCE), and other State DOTs.

2.1 Overview

This literature review comprises twelve subheadings summarizing works written about alternative intersections with three-phase signals. Specific areas of discussion include (a) design descriptions, (b) traffic operations, (c) safety performance, (d) pedestrian performance, (e) public and stakeholder acceptance, and (f) construction costs. These topics are presented to help readers obtain a full understanding of existing literature on alternative intersections with three signal phases, and what the study needs are to advance three-phase intersections.

The literature reviewed includes journals, reports, articles, proceedings, state DOT documents, and presentations. The entire list of publications is presented in the reference section at the end of this report. This literature review is broken up into two main sections: the performance of specific three-phase intersection designs (16 studies), and public acceptance of all alternative intersections (10 studies) as shown in Table 2.1.

Table 2.1 Publication Category

Publication Category	Number
Three-Phase Intersection Performance	16
Public Acceptance of Alternative Intersections	10
Total	26

2.2 Three-Phase Intersection Performance

This section presents literature related to the safety, pedestrian, and operational performance in three-phase intersection designs. Tables 2.2 and 2.3 provide a breakdown of the works we found by the focus of the study and design type of the three-phase intersections, respectively. The main findings of these studies are highlighted in this section (2.2) of this literature review. Additionally, section 2.7 provides a consolidated summary of these findings.

Table 2.2 Summary of Three-Phase Intersection Publications by Focus of Study

Focus of Study	Yang et al. (2023)	Cunningham et al. (2022)	Luo et al. (2022, 2024)	Ahmed et al. (2021)	Ingle and Gates * (2021)	Schroeder et al. (2021)	Qu et al. (2021)	Cunningham et al. (2020)	Hummer (2020)	Reid and Hummer (2020)	Rouphail et al. (2020)	Hummer et al. (2019)	Zlatkovic (2015)	Hughes et al. (2010)	Inman (2009)	Total
Safety Performance		X	X		X	X					X		X	X		7
Operational Performance	X		X	X			X	X			X	X	X	X		9
Design Guidelines						X			X	X		X	X	X	X	7
Total	1	1	2	1	1	2	1	1	1	1	2	2	3	3	1	23

*Only unsignalized offset T intersections

Table 2.3 Summary of Three-Phase Design Publications by Geometric Design

Three- Phase Intersection Geometric Design	Yang et al. (2023)	Cunningham et al. (2022)	Luo et al. (2022, 2024)	Ahmed et al. (2021)	Ingle and Gates* (2021)	Schroeder et al. (2021)	Qu et al. (2021)	Cunningham et al. (2020)	Hummer (2020)	Reid and Hummer (2020)	Rouphail et al. (2020)	Hummer et al. (2019)	Zlatkovic (2015)	Hughes et al. (2010)	Inman (2009)	Total
Partial MUT**			X													1
Partial CFI		X	X	X			X				X		X		X	6
Reverse RCI			X													1
CFI/MUT Combo			X						X							1
Thru-cut			X													1
Offset-T					X			X								2
Seven-Phase Signal												X				1
Quadrant Roadway	X					X			X	X				X		6
Total	1	1	5	1	1	1	1	1	2	1	1	1	1	1	1	19

*Only unsignalized offset T intersections
**With three signal phases

2.2.1 MUT Redirect Major (Partial MUT #1) and MUT Redirect Minor (Partial MUT #2)

2.2.1.1 Design Description

There are two versions for the three-phase MUT. The MUT redirect major (partial MUT #1) redirects only the left-turn traffic from the major road, while MUT redirect minor (partial MUT #2) redirects the left-turn traffic from the minor street. In these designs, except for the redirected left-turn traffic, all other traffic movements follow conventional routes. Note that a two-phase MUT redirects all the left-turn movements to U-turn crossovers. Figures 2.1 and 2.3 show the design geometry for both partial MUT configurations.

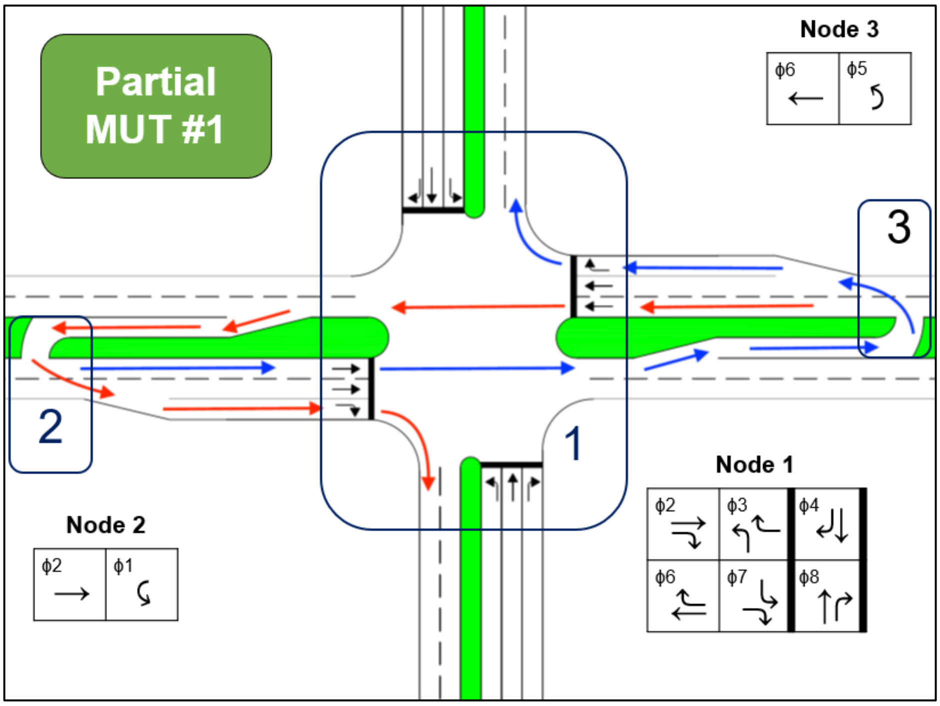

Figure 2.1 MUT Redirect Major (Partial MUT#1) Design Geometry and Signal Phasing

In Figure 2.1, the routes of left-turn traffic from the major street are shown with red and blue lines. It should be noted that in Figure 2.1, as well as in subsequent figures depicting the geometry of other three-phase signal designs, only the redirected movements are illustrated; conventional traffic movements are not shown. To the best knowledge of the authors, there are at least three real-world examples like the concept of MUT #1: one intersection site in Boise, ID, and two sites in New Orleans, LA. Figure 2.2 shows a satellite view of one of the MUT #1 examples in Boise, ID.

Figure 2.2 MUT Redirect Major (Partial MUT#1) at State Street/Veterans Memorial Parkway, Boise, Idaho

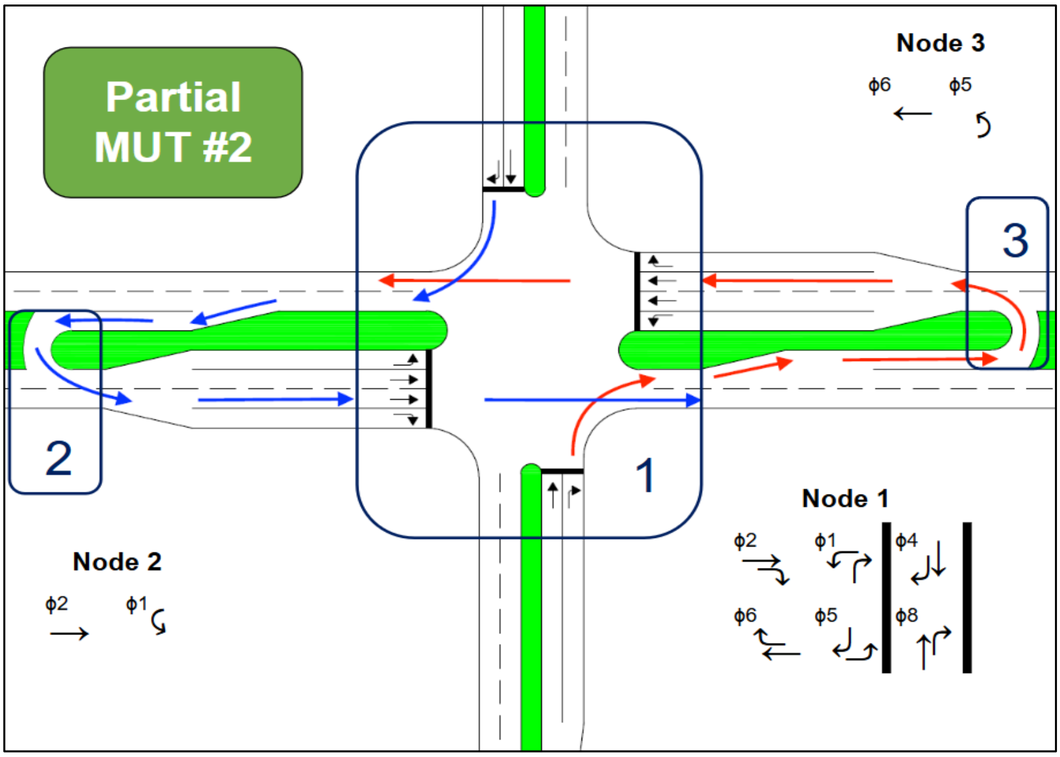

Figure 2.3 MUT Redirect Minor (Partial MUT#2) Design Geometry and Signal Phasing

Along the same corridor in New Orleans that has a few real-world examples of the MUT #1 (redirect major Rd), there are also two examples similar to the MUT #2 concept. Figure 2.4 presents a satellite view of one of these MUT #2 examples in New Orleans, LA.

Figure 2.4 MUT Redirect Minor (Partial MUT#2) Located at W Napoleon Ave/N Causeway in New Orleans, LA

2.2.1.2 Performance

According to Luo et al. (2024), the partial MUT #1 is advantageous when turning demand is low, where the through movement could receive longer green indications than in the conventional design, and the total cycle length can be effectively reduced due to removing one of the signal phases. Partial MUT designs include 24 conflict points, eight conflict points fewer than the four-legged conventional design.

Pedestrians should experience a safer service applying the new 20-flag method published in the NCHRP Report 948 (Schroeder et al., 2021) at both partial MUT #1 and partial MUT #2. It should be noted that the 20-flag method evaluates the expected safety and comfort pedestrians will experience at a particular intersection. Luo (2022) found that partial MUT #1 intersections had 2 yellow flags and 10 red flags for pedestrians compared to 14 red flags at a conventional intersection. This was the lowest number of flags of the three-phase designs in that study which also analyzed partial CFI, CFI/MUT combo, reverse RCI, and thru-cut.

Luo (2022) also provided the information regarding pedestrian and vehicle travel times summarized in Tables 2.4 and 2.5, respectively. For both tables, an assumed volume/capacity ratio of 1.0 was used. Also, high turning conditions were 5,200 total vehicles per hour per lane (vphpl) with equal turning and through volumes, moderate turning conditions were 5,000 total vphpl with turning volumes set to 66% of through volumes, and low turning conditions were 4,800 total vphpl with turning volumes set to 50% of through volumes (Luo 2022). According to Tables 2.4 and 2.5, partial MUT #1s have the lowest pedestrian travel times of the six intersections included and provide an improvement in vehicle travel time compared to conventional intersections as shown in Table 2.5 (Luo 2022).

The completed tests statistic in Table 2.5 reflects the percentage of scenarios in which at least 90% of vehicles successfully reached their intended route destinations by the time the network simulation ended (Luo 2022). Notably, the conventional design exhibited the longest average travel times across all the turning ratios and also had the lowest rate of completed tests. This lower completion rate shows its capacity limitations, particularly when compared with the three critical phase alternative designs (Luo 2022).

Table 2.4 Pedestrian Travel Times for Three-Phase Intersections (Luo, 2022)

Intersection Type	Overall		High Turning		Moderate Turning		Low Turning	
	Travel Time (sec)	No. of stops/vehicle	Travel Time (sec)	No. of stops/vehicle	Travel Time (sec)	No. of stops/vehicle	Travel Time (sec)	No. of stops/vehicle
Conventional	84	0.46	89	0.47	88	0.46	76	0.45
Partial MUT #1	70	0.8	75	0.92	66	0.92	70	0.74
Partial CFI	107	1.78	106	1.79	107	1.79	110	1.77
MUT/CFI	118	1.13	131	1.15	109	1.13	115	1.07
Reverse RCI	75	1.37	73	1.39	73	1.39	80	1.37
Thru-cut	81	1.28	83	1.29	85	1.29	74	1.27

Table 2.5 Average Vehicle Travel Time Based on VISSIM (Luo, 2022; Luo et al., 2024)

Intersection Type		Overall		High Turning		Moderate Turning		Low Turning	
		Travel Time (sec)	Completed Tests (%)	Travel Time (sec)	Completed Tests (%)	Travel Time (sec)	Completed Tests (%)	Travel Time (sec)	Completed Tests (%)
Four-Phase	Conventional	301	19	326	4	316	17	292	38
Three-Phase	Partial CFI	176	100	191	100	171	100	164	100
	MUT/CFI	184	100	207	100	176	100	168	100
	Partial MUT #1	192	89	249	67	181	100	166	100
	Thru-cut	206	76	242	50	201	79	192	100
	Reverse RCI	251	38	N/A	0	241	13	252	100
Two-Phase	RCI	176	61	258	17	181	67	168	100

The partial MUT in Boise, ID, was constructed in 2018 at State Street and Veterans Memorial Parkway (Figure 2.2) (Parris, 2018). This intersection represents the partial MUT #1 with redirected traffic from State Street making downstream U-turns in the median. Given its recent construction, no long-term studies have yet analyzed the safety or operational benefits of the intersection. Our research team reached out to Idaho DOT for information regarding this intersection, and they provided ten years' worth of crash data and AADT data for the intersection as shown in Tables 2.6 and 2.7. There is only three years' worth of crash data following the redesign of the intersection in 2018, so it is difficult to draw a definitive conclusion about the effectiveness of the change. However, there appears to be little to no change in the total number of collisions per year.

Table 2.6 Crash Data Summary for State Street/Veterans Memorial Parkway, Boise, ID

Year	Total Collisions
2012	8
2013	16
2014	16
2015	8
2016	11
2017	16
2018	10
2019	16
2020	8
2021	11

Table 2.7 AADT (veh/day) Data for State Street/Veterans Memorial Parkway, Boise, ID

Street Name	AADT (2021)
State Street (East)	27,500
State Street (West)	33,500
Veterans Memorial Pkwy (North)	9,700
Veterans Memorial Pkwy (South)	21,000

Additionally, as mentioned earlier, there are four partial MUT's constructed in New Orleans, LA. The research team reached out to Louisiana DOT regarding these specific intersections and received multiple years of crash data for two of them as shown in Table 2.8. Of note, the authors do not know what year these partial MUTs were implemented.

For these partial MUTs in New Orleans, the predominant crash type is rear-end crashes followed by side-swipe and angle crashes. Of the total angle crashes at each partial MUT, left turning angle crashes make up between 24%-29%. The most common crash severity was PDO followed by injury crashes. There were no fatal crashes reported at either location between 2018 and 2023.

The FHWA MUT Informational Guide (2014) focuses solely on two-phase MUTs, but some of the information covered could be helpful for analyzing three-phase partial MUTs. For example, this guide recommends using the same MUTCD standard signage for MUTs that is used for conventional intersections, but with the addition of "No Left Turn", "One-Way", and "Do Not Enter" signs where appropriate to guide drivers through the intersection. These guidelines, while direct towards two-phase MUTs should also be applicable to their three-phase equivalents.

Table 2.8 Crash Data for W Napoleon Ave/N Causeway Blvd and W Napoleon Ave/David Drive in New Orleans, LA

		Crash Severity			Crash Type						
Intersection (Date Range)	Total Crashes	Fatal	Injury	PDO	Rear-End	Angle (Total)	Angle (Left Turn)	Head-On	Side-Swipe	Fixed Object	Other
N Causeway Blvd at W Napoleon Ave (2018-2023)	200	0	38	162	89	34	10	2	45	8	22
W Napoleon Ave at David Dr (2018-2023)	161	0	36	125	85	41	10	4	20	4	7

2.2.2 Partial CFI

2.2.2.1 Design Description

The partial CFI incorporates left-turn crossovers at both the major and minor roads, where left-turning traffic crosses over to the left-hand side of the road at a secondary intersection located before the main intersection. The partial CFI design is particularly advantageous when it comes to high demand from the major street, where it could operate all through and left-turn movements simultaneously, particularly when the left-turn crossover is on the major road. The design does not have a U-turn crossover. This feature allows it to have the same traffic flow at the main intersection as the conventional design. Figure 2.5 shows a partial CFI. There are multiple options for sidewalk placement at partial CFIs: traditional, midblock, and offset. Traditional crosswalks are standard pedestrian crossings located at intersections, aligned directly with the roadway. Midblock crosswalks are placed between intersections to improve pedestrian access and safety. Offset crosswalks have a staggered design, requiring pedestrians to cross one approach at a time, which enhances visibility and safety.

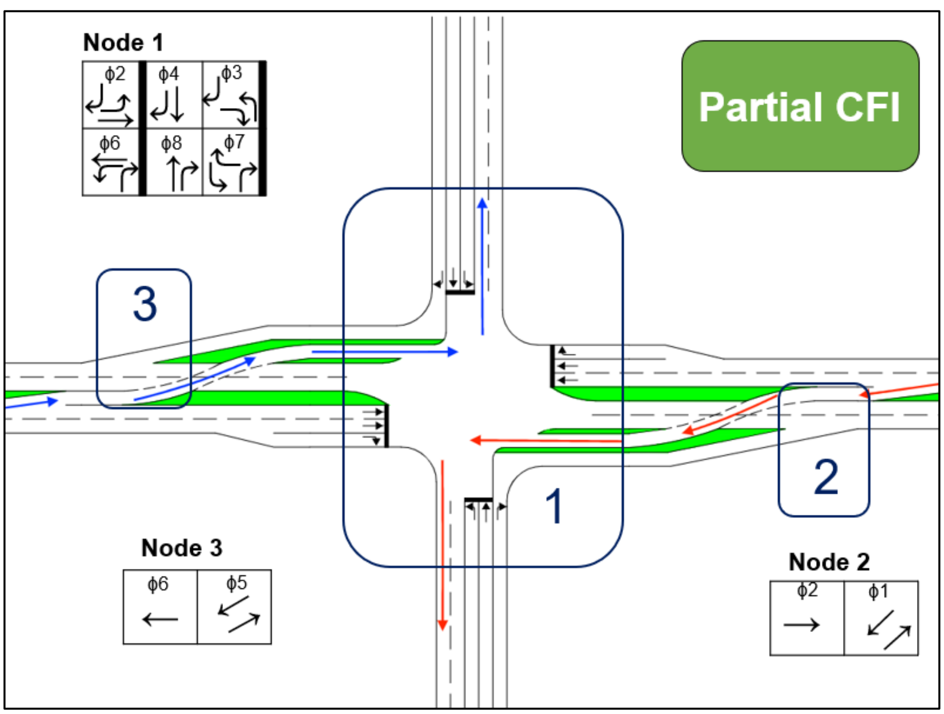

Figure 2.5 Partial CFI Design Geometry and Signal Phasing

2.2.2.2 Performance

Partial CFIs might not be pedestrian-friendly at some intersections because they create long walking distances, multiple crossings, the concept might be confusing for pedestrians, and they have six (6) yellow flags and 14 red flags using the 20-flag method. In terms of traffic safety, partial CFIs have 30 conflict points, only two conflicts fewer than the conventional design.

New CMFs were developed for the conversion of conventional signalized intersections to CFIs in a recent NCDOT report (Cunningham et al. 2022). The research team chose nineteen CFIs across eight states with four reference intersections for each CFI, however three treatment sites were dropped due to lack of data or an unexpected situation. Of note, none of the case study sites were in North Carolina. For each crash type, researchers found that the CMFs were all less than one with the range being 0.616-0.960. Rural CFIs were found to have larger crash reductions than urban sites. Cunningham et al. (2022) also found that implementing CFIs resulted in a decrease in total crashes (12.1%), fatal & injury crashes (13.8%), property damage only crashes (11.8%), angle crashes (29.4%), and rear-end crashes (12.9%). The researchers examined the results for each crash type and determined that while there was a significant reduction in angle and rear-end crashes, there was a 10.50% increase in all other crash types combined. Additionally, CFIs with parallel right turns had greater crash reductions than CFIs with standard right turns. The introduction of skew to CFI design was found to increase the rate of angle crashes.

According to Luo (2022) (Tables 2.4 and 2.5), partial CFIs have an estimated pedestrian travel time of 107 seconds, and an average simulated vehicle travel time is 176 seconds. Although partial CFIs result in the lowest vehicle travel time among the six intersections studied in Luo et al. (2022), they increase pedestrian travel time by 23 seconds compared to conventional intersections (see Table 2.5).

Rouphail et al. (2020) found that traditional pedestrian crossings had the least number of stops, and offset had the shortest stopped delay. Midblock performed well when routes started and ended near the midblock crossing.

Qu et al. (2021) developed a methodology for constructing signal timing at CFIs. They suggested using the following steps:

1. Determine signal phase timing at the main intersection based on traffic volume at the main intersection.
2. Determine the timing of the signal phase at the minor intersections to meet the progression requirements.
3. Check the following constraints:
    a. Green splits for left-turning traffic at the crossover or “minor” intersection should be sufficient for the left turning volume.
    b. The green thru phase for the minor intersection should be greater than the green thru at the main intersection.
4. Adjust signal timing as needed if constraints are not met.

According to Qu et al. (2022), following these steps consistently led to improved performance over the signal timing optimization software, SYNCHRO (24% reduction in traffic delay, 8.5% reduction in vehicle travel time, and 28.8% reduction in queue length on average).

The FHWA DLT Intersection Informational Guide (Steyn et al. 2014) provides design guidelines for pavement markings and signage for two-phase CFIs (synonymous with DLT). Specifically, this guide highlights the need to make drivers aware of the differences in traffic flow from conventional intersections, namely the crossover portion. Additional signal heads need to be positioned above the crossover lanes at the intersection in addition to overhead and post-mounted signs to help drivers navigate the intersection. Appropriate lighting should also help reduce driver errors. While specifically intended for two-phase CFIs, these guidelines should be mostly applicable for three-phase partial CFIs.

Inman (2009) concluded that advanced signing ahead of a partial CFI was an important navigational consideration given the design differences from a conventional intersection. Inman (2009) also found that signs mounted on the ground were just as effective in promoting proper navigation of the partial CFI as overhead signage.

2.2.3 Reverse RCI

2.2.3.1 Design Description

The reverse RCI redirects the left-turn traffic from the major street and through traffic from the minor street. Figure 2.6 shows the geometry of reverse RCI design. Based on the best knowledge of the authors, there are at least five reverse RCIs in North Carolina. Figure 2.7 shows one of these real-world examples in NC.

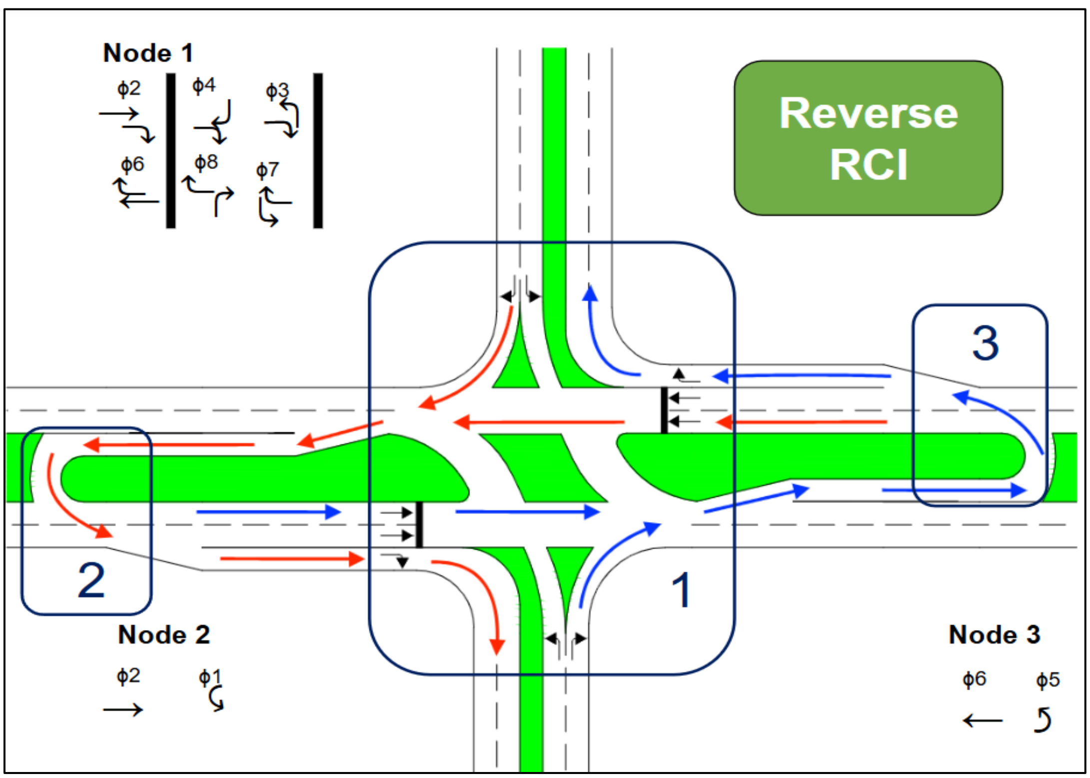

Figure 2.6 Reverse RCI Design Geometry and Signal Phasing

Figure 2.7 Reverse RCI at GB Alford Highway/Avent Ferry Road in Holly Springs, NC

2.2.3.2 Performance

According to Luo (2022) and Luo et al. (2024), the extra travel distances required to navigate a reverse RCI intersection could negatively impact traffic operations. Regarding safety, the design has 14 conflict points, which is the lowest number among all the three-phase designs included in this literature review. Good service for pedestrians could also be expected with 4 yellow flags and 10 red flags based on NCHRP Report 948's (2021) flag method.

Based on Tables 2.4 and 2.5, estimated pedestrian travel time for reverse RCIs is 75 seconds, and average vehicle travel time is 251 seconds (Luo, 2022). While reverse RCI has the second-best pedestrian travel time and good pedestrian safety characteristics, it has the longest vehicle travel time of all three-phase intersections studied in Luo (2022).

2.2.4 Partial CFI/MUT Combo

2.2.4.1 Design Description

The partial CFI/MUT combo has features of both the partial MUT and partial CFI designs. Major street lefts in one direction are redirected with a paved "crossover" while the major street lefts in the opposite direction are redirected with a downstream U-turn. Based on the best knowledge of the authors, there are at least two full CFI/MUT Combo intersections in the USA. The first is in Virginia Beach, VA; in which the CFI left-turn ramp and the U-turn crossover are located on two separated approaches (they are located on the same EB approach in the example illustration in Figure 2.8). The second is located in Fairbanks, AK as shown in Figure 2.9.

As an advantage of the partial CFI/MUT combination, it only requires additional right-of-way (ROW) on one of the approaches. This should be particularly beneficial in terms of public acceptance, as no changes are required on three of the intersection approaches.

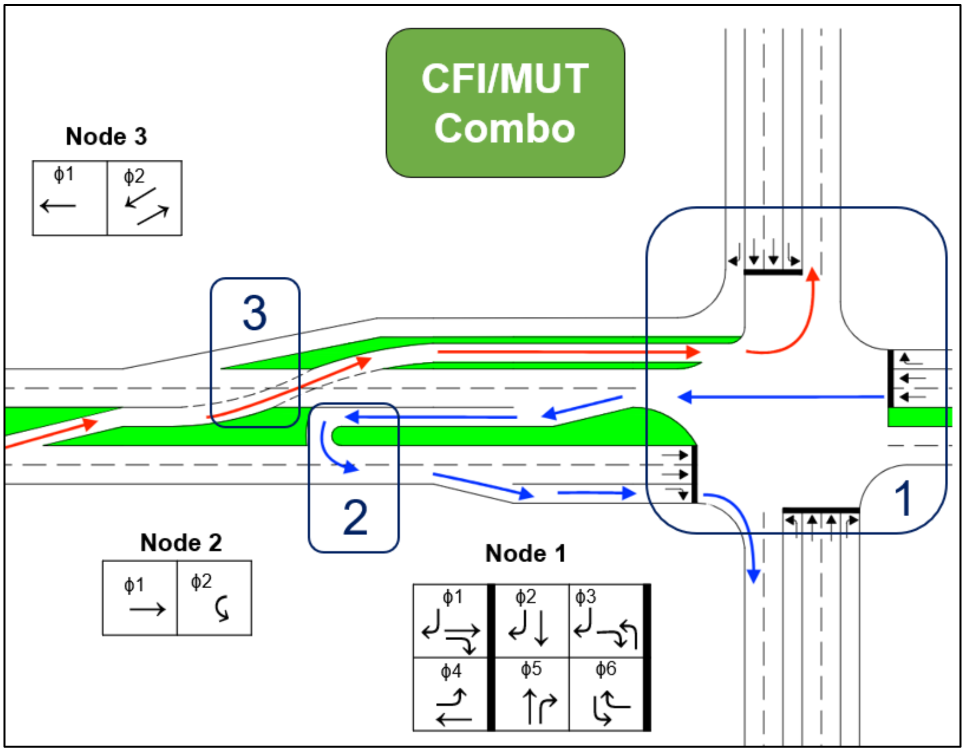

Figure 2.8 Partial CFI/MUT Combo Design Geometry and Signal Phasing

Figure 2.9 Full CFI/MUT Combo at Gaffney Road and Richardson Highway in Fairbanks, AK

2.2.4.2 Performance

Based on Hummer (2020), the partial CFI/MUT combo could increase the network's capacity due to the removal of left-turn/through traffic conflicts in the center of the major road. The design also reduces the number of conflict points to 27, which is five conflicts fewer than conventional and partial CFI. Regarding pedestrian safety, this design has 4 yellow flags, and 10 red flags based on NCHRP Report 948's (2021) flag method.

The CFI/MUT combo has the longest pedestrian travel time of the three-phase designs included in Tables 2.4 and 2.5 for all turning conditions, but has the second best vehicle travel time behind the partial CFI for all turning conditions (Luo et al., 2022).

2.2.5 Thru-Cut

2.2.5.1 Design Description

Figure 2.10 shows the geometry of a thru-cut intersection. The thru-cut design redirects only minor street through movements, retaining the left-turn lanes for major street approaches. These redirected thru movements would need to make a U-turn at the next safe available downstream location. As shown in Figure 2.11, there are at least two existing thru-cut intersections in Holly Springs and Charlotte, North Carolina. However, it should be noted that the one in Charlotte, North Carolina has a prohibited major street left turn which is unrelated to the thru-cut concept. Also, there is one example in Virginia and three examples in Maryland. It should be noted that Virginia DOT has planned to build seven thru-cut intersections along US-220. It is expected that the thru-cut intersection could be considered at signalized intersections with low demand on side street through movements. The thru-cut design should be uniquely good for progression systems on major roads because it can fit along an arterial almost anywhere and does not subtract from the through progression bands. It should be attributed to the fact that it is probably the only three-phase design that serves one short minor street phase.

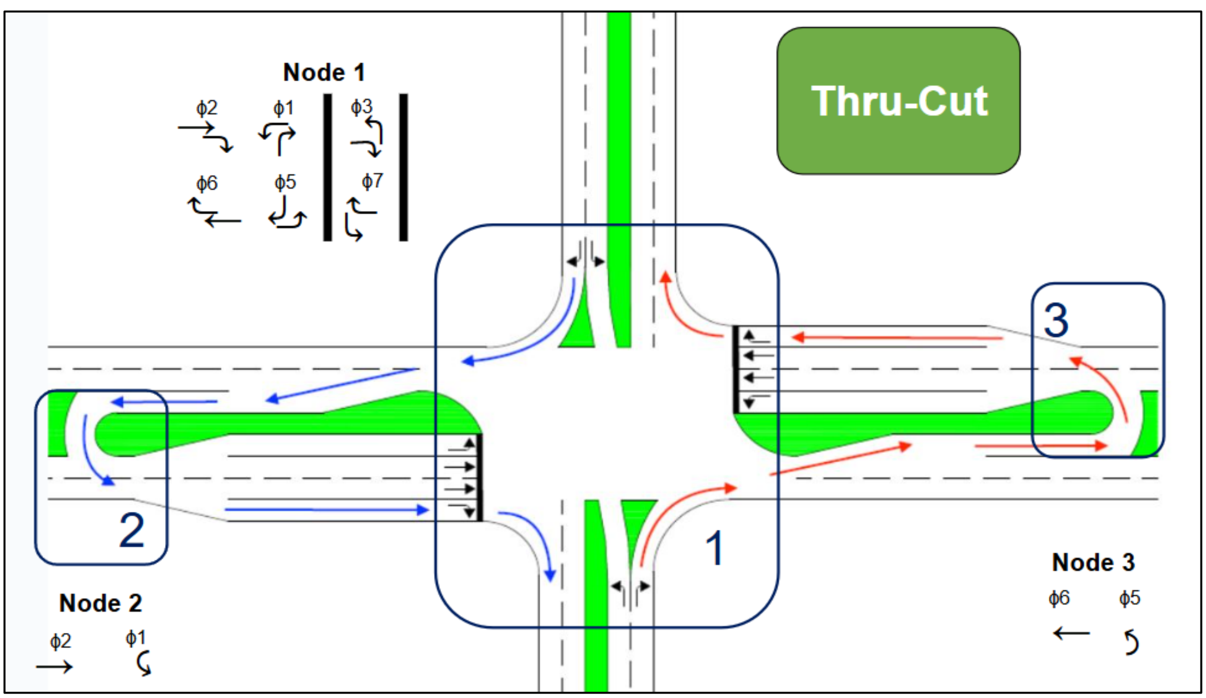

Figure 2.10 Thru-Cut Design Geometry and Signal Phasing

Figure 2.11 Thru-Cut Intersections at Village Walk Dr/S Main St, Holly Springs, NC (Left) and Arrowood Rd/Arrowpoint Blvd, Charlotte, NC (Right)

2.2.5.2 Performance

Thru-cut intersections have fewer conflict points (24) than a conventional intersection (32). According to Luo (2022) and Luo et al. (2024), thru-cut intersections have one of the lowest average cycle lengths (106 seconds) compared among the three-phase designs compared to conventional intersections (173 seconds). Therefore, the thru-cut is expected to have shorter delay and better progression on the major roads, especially because traffic movements from the minor roads are involved with only one of the signals phases (out of three).

According to Luo (2022), thru-cut designs are towards the middle of three-phase intersections in terms of pedestrian and vehicle traffic times (3rd and 4th out of 5, respectively). Of note, the thru-cut design does provide improvements over conventional intersection in both categories.

As previously mentioned, VDOT is constructing seven thru-cut intersections on a corridor along US-220. The research team contacted VDOT about the intersections and they provided five years' worth crash data (September 2017-2022) and AADT data from 2019 for each of the seven intersections that will eventually be converted to a thru-cut design. While this data (summarized in Tables 2.9 and 2.10) does not allow for advanced safety evaluations, it provides insight into where suitable locations for implementing thru-cut intersections might be based on VDOT plans. According to Table 2.9, rear-end collisions are the most common collision type on average throughout the Virginia thru-cut corridor followed by angle collisions. While an average of 42 total crashes occurred at each of the seven thru-cut intersections along US-220 from 2017-2022, there were no fatal collisions. Additionally, the average AADT values for US-220 and the minor road for each intersection were 27,143 and 3,851 vehicles per day (veh/day), respectively.

Table 2.9 Summary of US-220 Thru-Cut Corridor Crash Data (2017-2022)

Intersection	Total Crashes	Fatal Crashes	Rear End	Angle	Head On	Side Swipe	Fixed Object	Other
US-220 at Route 619-816 Sontag Road	39	0	14	18	1	1	2	3
US-220 at Route 675 Indian Grave Road	53	0	30	11	0	8	2	2
US-220 at Route 679 Buck Mountain Road	47	0	20	17	1	4	2	3
US-220 at Route 697 Wirtz Road	60	0	30	26	0	1	1	2
US-220 at Route 862 Home Depot-Lowes	41	0	27	11	0	1	1	1
US-220 at Route 1210 Dyer Street	19	0	4	12	0	1	2	0
US-220 at Route 1290 Crossbow Circle	35	0	20	9	2	2	1	1
Average	42	0	21	15	1	3	2	2

Table 2.10 Summary of US-220 Thru-Cut Corridor 2019 AADT Data

Intersection	US-220 AADT	Secondary Road AADT
US-220 at Route 619-816 Sontag Road	16,000	3,460
US-220 at Route 675 Indian Grave Road	32,000	5,700
US-220 at Route 679 Buck Mountain Road	32,000	6,700
US-220 at Route 697 Wirtz Road	26,000	3,800
US-220 at Route 862 Home Depot-Lowes	33,000	3,100
US-220 at Route 1210 Dyer Street	18,000	1,100
US-220 at Route 1290 Crossbow Circle	33,000	3,100
Average	27,143	3,851

According to the initial evaluations done by NCDOT, the thru-cut intersection illustrated in Figure 2.11 (left) at SR 1114 (S Main St.) and Village Walk Dr. in North Carolina showed great safety potential with a 67% reduction in total crashes per year and a 61% reduction in injury crashes per year (Nye 2023). This reduction in crashes occurred despite traffic volumes along SR 1114 more than doubling during the period of study. However, the installation of the signal would have led to some crash reduction by itself (the before condition was two-way stop-controlled intersection).

2.2.6 Offset T Intersections

2.2.6.1 Design Description

Figure 2.12 shows the geometry of an offset T intersection, while Figure 2.13 shows a real-world example of the design. For offset intersections, minor street approaches do not align directly and are instead skewed. Drivers on these approaches can turn right or left. In order to make a thru movement from the minor leg, left turn followed by a right and vice versa depending on the orientation of minor road is required.

2.2.6.2 Performance

Offset T intersections should result in higher safety for both vehicle users and pedestrians due to having only 18 conflict points and mitigating safety concerns such as the conflict between pedestrians and the right-turn demand. On the other hand, traffic movements coming from minor streets could experience longer travel distances. Also, the offset T intersection can be considered as a candidate only in specific geometry configurations with enough ROW.

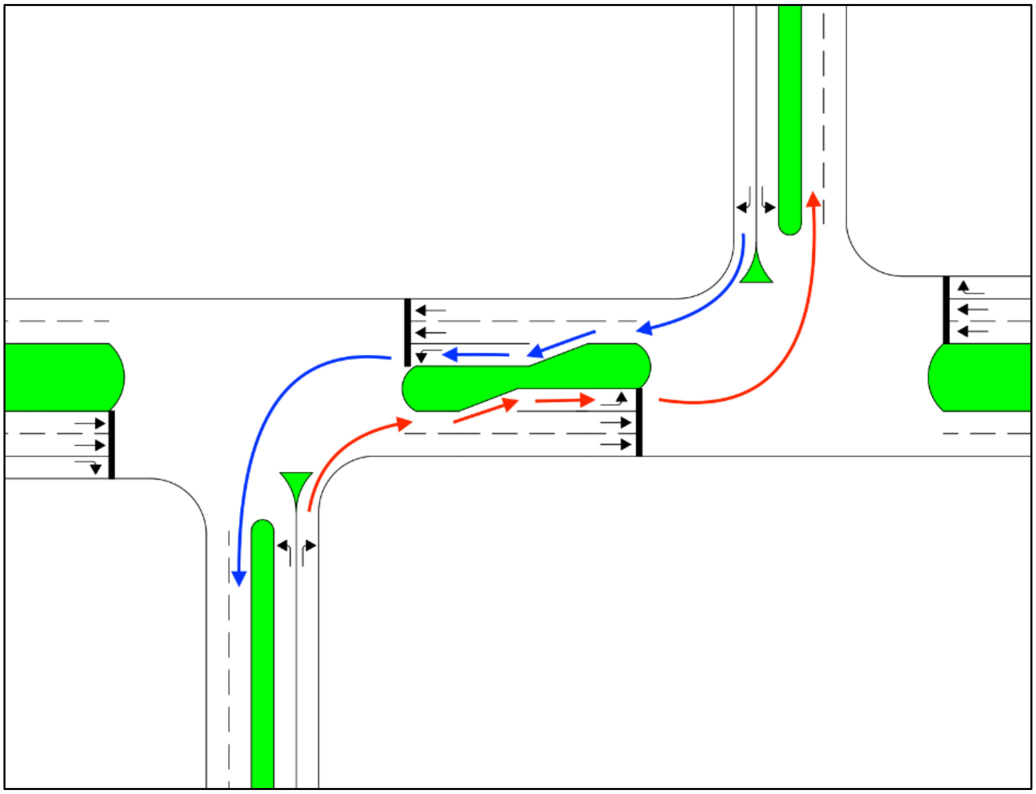

Figure 2.12 Offset T Intersection Design Geometry

Figure 2.13 Offset T Intersection Example

Yang et al. (2023) found that offset intersections consistently performed better than conventional intersections in terms of average delay time under various simulated traffic volume, time of day, and surrounding infrastructure conditions.

According to Cunningham et al. (2020), the offset T-intersection could reduce crashes by half in comparison to the four-leg intersection because of the fewer number of conflict points. Also, in almost half of the simulation tests, offset T intersections performed better in terms of reducing delay compared to conventional design. Fewer angle crashes were predicted at offset T intersections, especially in locations where both the major and minor roads have low demands. The researchers recommended specific combinations of left-right versus right-left and offset spacing for various scenarios with differing infrastructure/customers being served.

After a meta-analysis, Cunningham et al. (2020) discovered that the offset T-intersection greatly reduced travel time by a range of 5-20 seconds. Lastly, after a microsimulation modeling, the study revealed that there was a reduction in traffic delay and maximum queue length by up to 29.7% and 26.9% respectively. Right-left offset-Ts were generally found to have shorter queue lengths. Ingle et al. (2021) found a 35% increase in the number of crashes at rural, unsignalized offset-T intersections compared to conventional intersections in Michigan. Specifically, single vehicle and rear-end crashes increased and angle crashes decreased at unsignalized offset-T intersections. Overall, the researchers found that converting an unsignalized offset-T to a conventional intersection would result in an estimated CMF of 0.74.

2.2.7 Seven-Phase Signal

2.2.7.1 Design Description

As shown in Figure 2.14, the seven-phase signal intersection redirects one of the minor through movements to a U-turn crossover. This design was introduced by Hummer et al. (2019) who indicated that there are no existing seven-phase signal intersections anywhere. However, there are a few thru-cut examples in Maryland (Figure 2.15) that could provide guidance in designing appropriate traffic control devices (TCDs) for the seven-phase signal design.

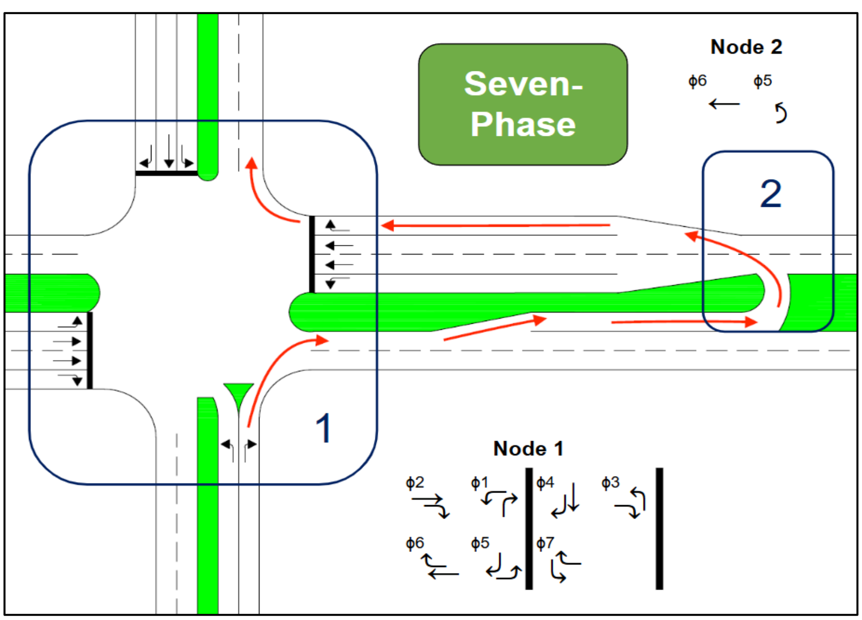

Figure 2.14 Seven-Phase Signal Design Geometry

2.2.7.2 Performance
Possible benefits include higher capacity and shorter travel times at intersections with very low through traffic demand on one of the minor roads due to reducing one of the phases by only increasing the travel distance of one movement. No significant safety improvement is expected in terms of traffic and pedestrians since there will be 28 conflicts with concerns related to pedestrian-vehicle interactions.

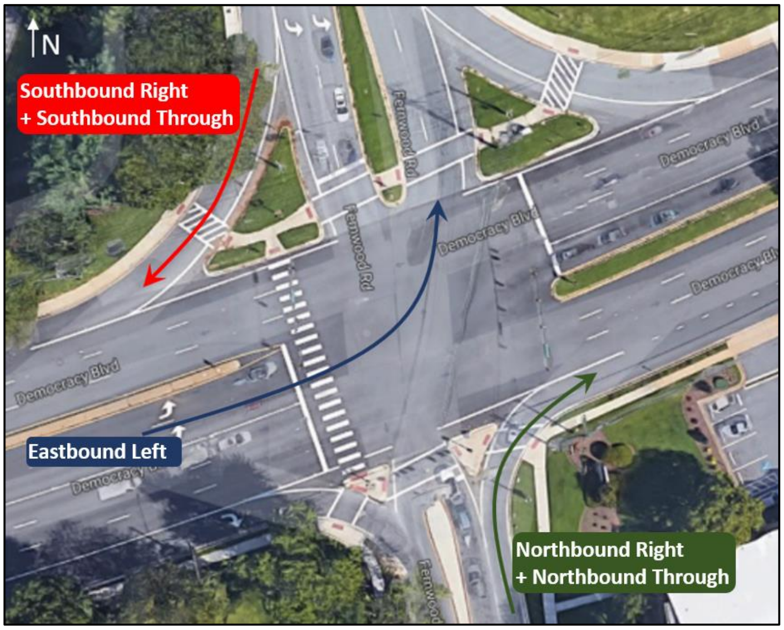

Figure 2.15 Democracy Boulevard at Fernwood Road, Bethesda, Maryland

In Hummer et al. (2019), researchers developed and analyzed the seven-phase design. To compare the seven-phase signal to a conventional intersection, the researchers used SYNCHRO modeling software with the following assumptions for the seven-phase signal intersection: three-legged intersection with an east-west four-lane major street with an AADT of 30,000 veh/day, and a north-south minor street with an AADT of 15,000 veh/day. Additionally, this intersection was in a 1.4-mile-long corridor which included four other signalized intersections. With this framework, Hummer et al. (2019) found that the seven-phase signal had a decrease in delay for all movements except for the southbound through and right compared to a conventional intersection. A LOS of D or better was expected for all movements except for eastbound lefts. The travel time for the northbound through traffic was estimated at nearly 150 seconds with only 17 vehicles completing this movement during peak hour. The optimized cycle length in SYNCHRO was shorter for the seven-phase (120 seconds) versus the eight-phase (145 seconds). Due to this cycle length, some of the other signals in the network saw increases in delay up to about 7 seconds while others saw a decrease in delay up to about 6 seconds.

2.2.8 Single Quadrant Roadway
2.2.8.1 Design Description
This design, as shown in Figure 2.16, redirects all left turns on the minor road. An additional roadway connects a downstream major leg to an upstream minor leg at a second, three-legged intersection. To make a left from the minor approach, traffic is redirected to the single quadrant as shown in blue and red lines in Figure 2.16.

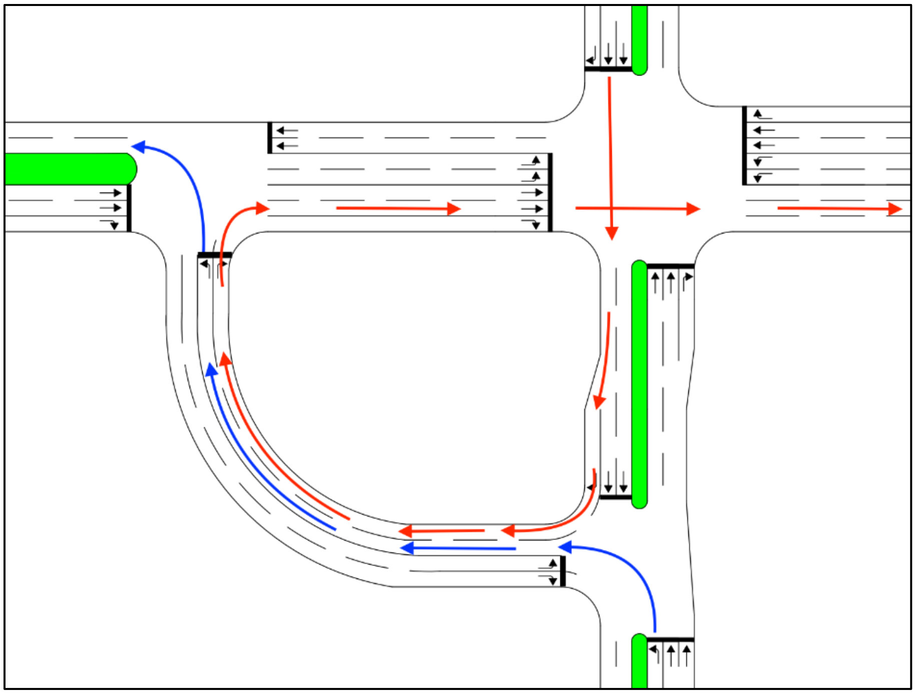

Figure 2.16 Single QR Design Geometry

Figure 2.17 Single QR at US-340/522 and SR-55 in Front Royal, Virginia (Reid et al., 2020)

The FHWA Quadrant Roadway Intersection Informational Guide (2020) provides guidance regarding signals and pavement markings. Specifically, they recommend providing adequate signage and pavement markings to ensure that drivers are aware of redirected left turns, and to guide drivers through the intersection. Additionally, bicycle left turns and lighting at conflict points should also be addressed when designing a quadrant roadway intersection.

2.2.8.2 Performance

According to The FHWA Quadrant Roadway Intersection Informational Guide (2020), the quadrant (with two signal phases at middle node and three signal phases at the other nodes) is appropriate for an intersection with two busy roads. The single quadrant could reduce travel times and increase capacity due to redirecting all left-turn demands. Pedestrians should also feel safer using a single quadrant intersection compared to the conventional design. However, the design includes 30 conflict points, which is the highest number among all the three-phase intersections in this study (partial CFI also has 30 conflicts). In addition, extra ROW is needed for constructing a single quadrant.

Hughes et al. (2010) provided different design concepts for QRs, including geometric design, access management, traffic signals, traffic signage and marking, safety, traffic operations, and the accommodation of non-motorized users in multiple alternative designs. They state that quadrant could be a good design both in terms of vehicular traffic operation and pedestrian performance; however, the possibility of violation of drivers turning left and the extra ROW needed are some of the main drawbacks of the quadrant design. Overall, Hughes et al. (2010) suggests that QRs could perform well at intersections with high through volumes and low to moderate left-turn volumes.

QRs have a smaller footprint at the main intersection than conventional intersections (Reid and Hummer 2020). This narrow roadway footprint is also beneficial for traffic calming and the prioritization given to through traffic could open the opportunity to reduce the number of through lanes. This may seem counterintuitive given the additional connecting road required for this intersection type. The decrease in overall ROW comes from removing the left turn lanes at the main intersection.

2.2.9 Redirect One Left and Thru (Redirect L&T) from a Minor Road

2.2.9.1 Design Description

This design is a derivation of the seven-phase signal. However, in addition to redirecting one of the minor through movements, it also redirects the left-turn demand of the same leg to a downstream U-turn crossover. Figure 2.18 illustrates the geometry with routes of through (in black and blue) and left turn demands (in black and red) from NB of major street and signal phasing diagram for each node.

To the best knowledge of the authors, there are at least three real-world examples for the redirect L&T in Lafayette, LA. Figure 2.19 shows one of these examples. Based on conversations with the Louisiana DOT (LaDOTD), the three identified redirect L&T intersections were implemented as a part of the US-90 widening project (424-02-0088) in 2013. Also, not a single complaint had been made since the new intersection was implemented over ten years ago. Table 2.11 summarizes the crash data for one year (200) before and one year after (2013) on this 7.14-mile-long corridor.

Table 2.12 also presents crash data for the intersection shown in Figure 2.19 from 2006 to 2015. Of note, this intersection was converted from a conventional design to redirect L&T in 2013. From Table 2.12, rear-end collisions were the predominant crash type followed by angle and side swipe. Left turn angle crashes made up roughly 28% of all angle crashes. Most crashes were PDO or injury, but there was one fatal crash in 2013.

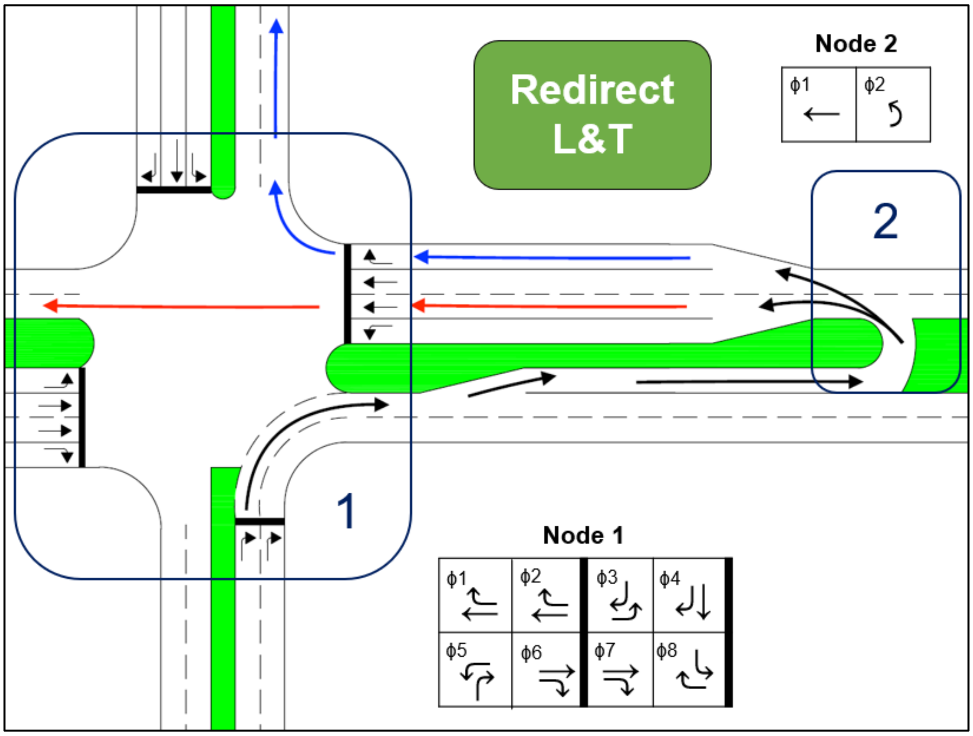

Figure 2.18 Redirect One Left and Thru Design Geometry

Table 2.11 Louisiana RLT Crash Data

Crash Type	2008	2013	Percentage reduction /increase (%)
Rear End	247	167	32% Reduction
Side Swap	44	54	23% Increase
Median Openings	47	23	51% Reduction
Total Crash	379	297	22% Reduction

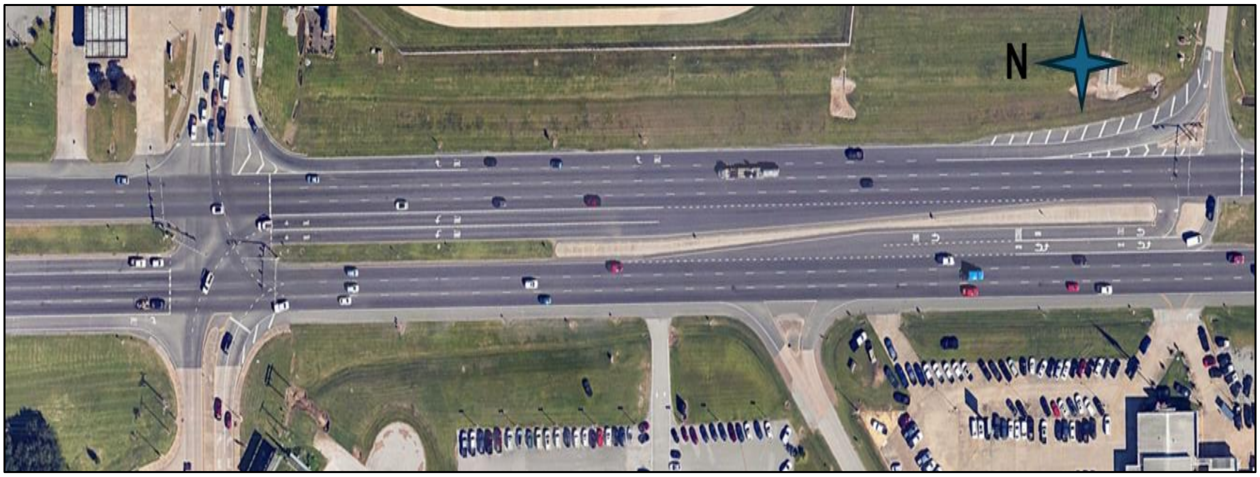

Figure 2.19 A Satellite View of a Redirect L&T Design at the Intersection of University Ave/Surrey St and US-90 in Lafayette, LA

Table 2.12 Crash Data for SE Evangeline Thruway/E University Ave in New Orleans, LA

		Crash Severity			Crash Type						
Year	Total Crashes	Fatal	Injury	PDO	Rear-End	Angle (Total)	Angle (Left Turn)	Head-On	Side-Swipe	Fixed Object	Other
2006	33	0	7	26	11	8	2	0	10	1	3
2007	31	0	5	26	21	4	2	0	2	2	2
2008	20	0	5	15	12	6	3	0	1	1	0
2009	23	0	5	18	19	1	0	0	2	0	1
2010	22	0	5	17	15	2	0	1	4	0	0
2011	23	0	6	17	19	2	2	0	2	0	0
2012	39	0	15	24	21	8	1	0	9	0	1
2013	54	1	7	46	38	7	1	0	6	1	2
2014	29	0	8	21	18	7	2	0	4	0	0
2015	48	0	16	32	27	13	3	0	7	1	0
Total	**322**	**1**	**79**	**242**	**201**	**58**	**16**	**1**	**47**	**6**	**9**

It should be noted that the phasing diagram shown in Figure 2.18 allows both major through traffic movements (EB and WB in Figure 2.18) to have a green light during two of the four total phases. The phasing diagram in Figure 9 is particularly advantageous for the progression system on the major road. Based on a field visit done by one of the research team members on September 27, 2023, the same phasing diagram is used at the existing redirect L&T intersection in Lafayette, LA (shown in Figure 2.19).

Another advantage of the redirect L&T design is that it requires only one U-turn crossover. This makes it an ideal solution for locations with right-of-way (ROW) constraints on one side of the approach, such as limited space for a U-turn crossover or short distances to adjacent signalized intersections. Pedestrian safety performance in this design is expected to be better than that of a conventional intersection. This improvement can be attributed to the reduced number of pedestrian-vehicle conflict points—20 in this design compared to 24 in the conventional type. Additionally, this design eliminates free-flow conflicts, further enhancing pedestrian safety.

2.2.9.2 Performance

Other than the information provided by LaDOTD above, there are no other past studies evaluating the performance of redirect L&T intersections. However, by redirecting one of the minor left-turn demands, the number of conflict points is reduced to 22. A potential downside of the design is that it increases travel distances for two traffic demands coming from one minor road.

2.3 Existing Three Phase Intersection Examples

As previously discussed throughout section 2.2 of this report, there are multiple examples of three-phase intersections that have already been constructed nationally. Table 2.13 summarizes all of the currently existing three-phase intersections that are known to the authors as well as AADT and speed limit data at those locations. Note that Table 2.13 does not include any partial CFIs, offset T, and QRIs, as FHWA informational guides and past studies have included a long list of those intersections. Additionally, there are no real-life examples of the offset thru-cut, seven-phase, and redirect 2L&T designs yet; therefore, they were also excluded from Table 2.13.

Table 2.13 AADT Data and Speed Limit at Existing Intersections with Three-Phase Signals

No.	Design	Major Road	Minor Road	City	State	AADT (veh/day)		Speed Limit (mph)	
						Major Rd	Minor Rd	Major Rd	Minor Rd
1	Thru-cut	Fernwood Road	Democracy Blvd	North Bethesda	MD	10,198	6.601	35	35
2	Thru-cut	MD-355 (Rockville Pike)	Edson Lane	North Bethesda	MD	11,198	5,431	35	35
3	Thru-cut	D-45 (York Road)	Galloway Avenue	Cockeysville	MD	9,899	NA ***	35	25
4	Thru-cut	S Main Street	Village Walk Dr	Holly Springs	NC	25,901	NA	35	10
5	Thru-cut	W Arrowood Rd	Arrowpoint Blvd	Charlotte	NC	22,140	NA	45	35
6	Thru-cut	Christenbury Pkwy	Lidl Driveway	Concord	NC	23,545	NA	45	10
7	Thru-cut	US-220	Valley Ave/ Southern Lane	Roanoke	VA	30,000	3,100	NA	25
8	Redirect L&T	W 12 Mile Rd	Bunker Hill Dr	Troy	MI	25,266	NA	45	25
9	Redirect L&T	US-90	E University Ave	Lafayette	LA	61,933	15,901	55	40
10	Redirect L&T	US-90	E Verot School Rd	Lafayette	LA	54,745	17,075	55	NA
11	Redirect L&T	US-90	Southpark Rd	Lafayette	LA	47,529	10,846	55	45
12	CFI/MUT Combination	Airport Way/Gaffney Rd	Richardson Hwy/Steese Expwy	Fairbanks	AK	26,100	16,000	35	35
13	CFI/MUT * Combination	Indian River Rd	Kempsville Rd	Virginia Beach	VA	54,943	25,039	45	45
14	Reverse RCI	GB Alford Hwy	Avent Ferry Rd	Holly Springs	NC	38,182	16,164	55	35
15	MUT #1 **	Mack Ave	Vernier Rd	Grosse pointe Woods	MI	25,272	23,504	35	35
16	MUT #1	State Street	Veterans Memorial Pkwy	Boise	ID	33,500	21,000	35	35
17	MUT #1	W Napolean Ave	David Dr	New Orleans	LA	24,336	NA	35	35
18	MUT #1	W Napolean Ave	Transcontinental Dr	New Orleans	LA	20,271	NA	35	35
19	MUT #2	W Napolean Ave	N Causeway Blvd	New Orleans	LA	36,537	NA	35	35
20	MUT #2	W Napolean Ave	Clearview Pkwy	New Orleans	LA	NA	NA	35	NA

*DLT and U-turn crossovers are located on two different intersecting roads
**Three of the left-turn movements are redirected (one more than a typical MUT #1)
***NA = Not Available (AADT or speed limit data was not available)

Out of the 20 intersections listed in Table 2.13, the thru-cut and redirect L&T have the highest number of real-life examples, with seven and four examples in the US, respectively. According to Table 2.13, maximum AADTs on major and minor roads of about 26,000 and 11,000 vehicles per day (veh/day) were identified for the thru-cut examples. To provide more information on thru-cut examples, Table 2.13 also includes AADT data of the US-220 thru-cut corridor under construction. On the other hand, all redirect L&T intersections in LA were located on a six-lane corridor (US-90) with a speed limit of 55 mph and an AADT range between 47,000 and 62,000 veh/day. Based on our discussions with District 5 at Louisiana DOT (LaDOTD), all redirect L&T intersections have performed very well on US-90 since their implementation in 2013, resulting in significant operational and safety benefits on the corridor. This demonstrates the capacity potential of the redirect L&T design in accommodating high AADTs. Similarly, CFI/MUT combination intersections should perform very well at higher AADT rates.

Regarding three-phase MUTs and reverse RCIs, AADTs of up to 38,000 and 23,000 veh/day on the major and minor roads, respectively, were found in existing examples based on Table 2.13. Like all thru-cut intersections listed, most of the existing three-phase MUTs and reverse RCI designs are implemented on four-lane roads. Therefore, their performance should also be acceptable at higher AADTs if they are implemented on six-lane roads.

According to Table 2.13, similar to the FHWA guide for RCIs (FHWA 2014), a maximum AADT of 25,000 veh/day should be recommended on the minor road in the reverse RCI design. However, the thru-cut, MUT #1 (MUT redirect major), MUT #2 (MUT redirect minor), and partial CFI/MUT designs have only one movement at each U-turn crossover, which allows the minor street AADT to exceed 25,000 vehicles per day. Additionally, the redirect L&T only redirects traffic on one of the minor streets, potentially resulting in significantly higher AADT on the other leg of the minor street. Further investigations are necessary to identify AADT thresholds.

2.4 Unpublished Designs

2.4.1 Redirect Two Lefts and a Thru

Using a left-turn ramp and a U-turn crossover, the design redirects two left-turns (one left from one minor and one from a major leg) and one minor through to eliminate one of the signal phases. This is a new design proposed by one of the authors, Amir Molan.

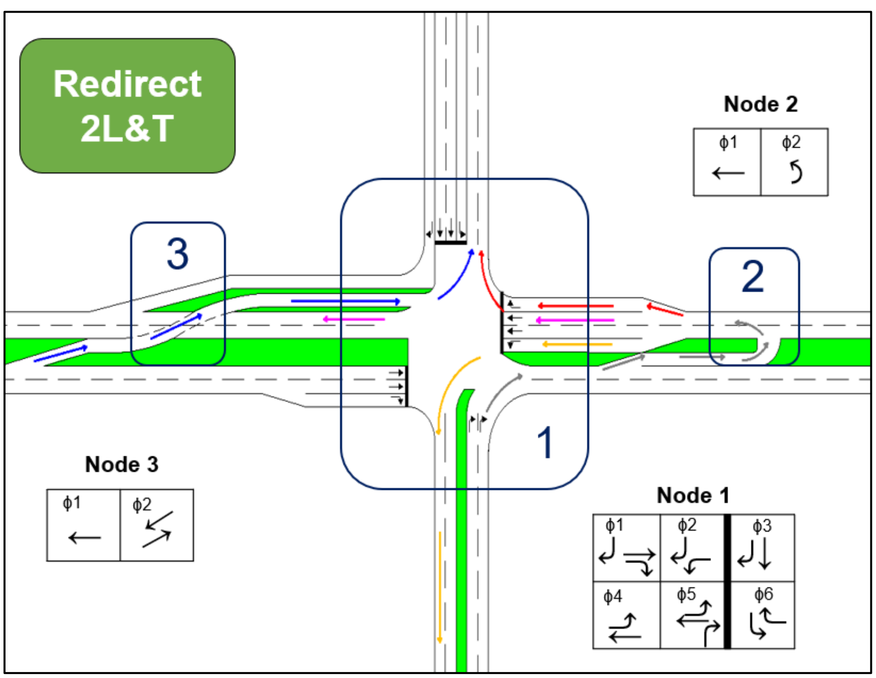

Figure 2.20 Redirect Two Lefts and One Thru Design Geometry

There are no past studies evaluating the performance of the redirect 2L&T intersection. However, based on the proposed phasing diagram, one of the major streets left-turns and one of the major through traffic movements would receive a green indication in two out of the total three-phases. Therefore, the intersection should have great capacity, even with only one left-turn lane for the redirected major left-turn movement. It should also improve signal progression on the major street.

This design has 22 conflict points, which is ten fewer than a conventional design, eight fewer than a partial CFI, and five fewer than the CFI/MUT combo. Among all the three-phase designs included in this study, only reverse RCI (with 14 conflict points) and offset T (with 18 conflict points) have fewer conflict points. In terms of pedestrian service, there should be a few concerns such as a higher number of conflicts between pedestrians and right-turn demand on one of the minor roads; however, the design should not result in an inappropriate service for pedestrians.

2.4.2 Offset Thru-cut

The offset thru-cut, proposed by Joseph E. Hummer, is a new version of the thru-cut design and has not been published in past studies. This design enhances pedestrian performance due to the placement of a crosswalk between minor legs as shown in Figures 2.21 and 2.22. The difference between Figure 2.21 and Figure 2.22 is that the design in Figure 2.22 includes channelized right turns for the minor street approaches to reduce wrong-way potential and driver confusion. Compared to a thru-cut, the main disadvantage of the offset thru-cut design is the potential driver confusion.

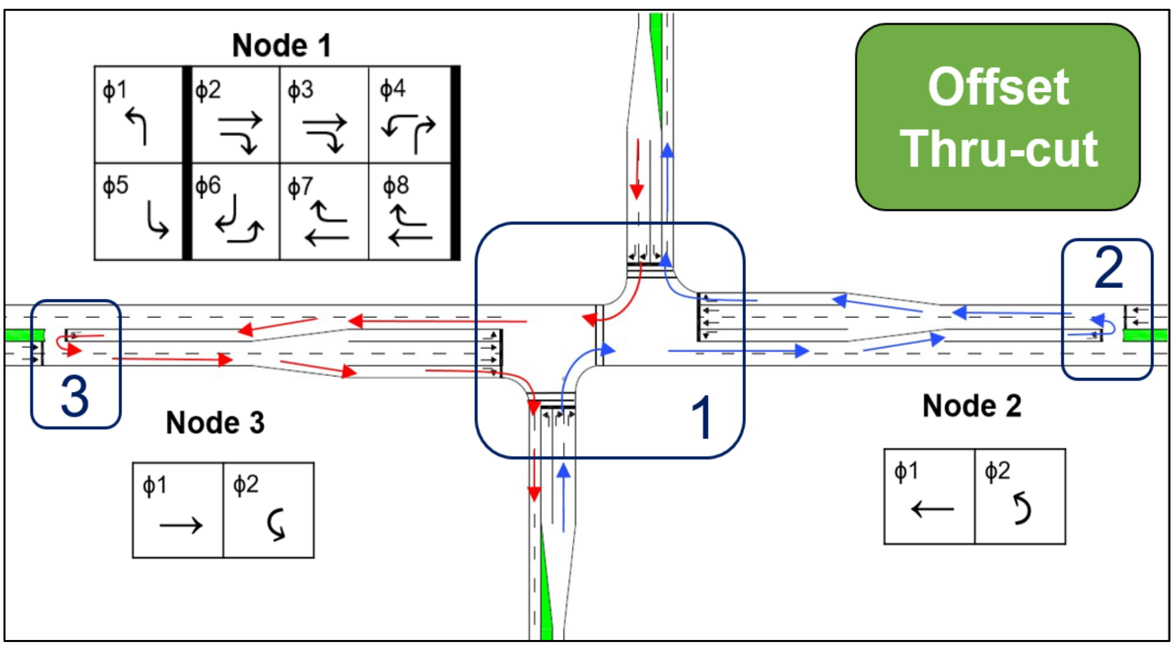

Figure 2.21 Offset Thru-Cut Design Geometry and Signal Phasing

This offset thru-cut has the same number of conflict points as a thru-cut at 24 total. Similar to a thru-cut design, this design is also expected to provide substantial improvement to travel times in traffic conditions with higher turning ratios due to the reduced impact of redirected through traffic movements from the minor road.

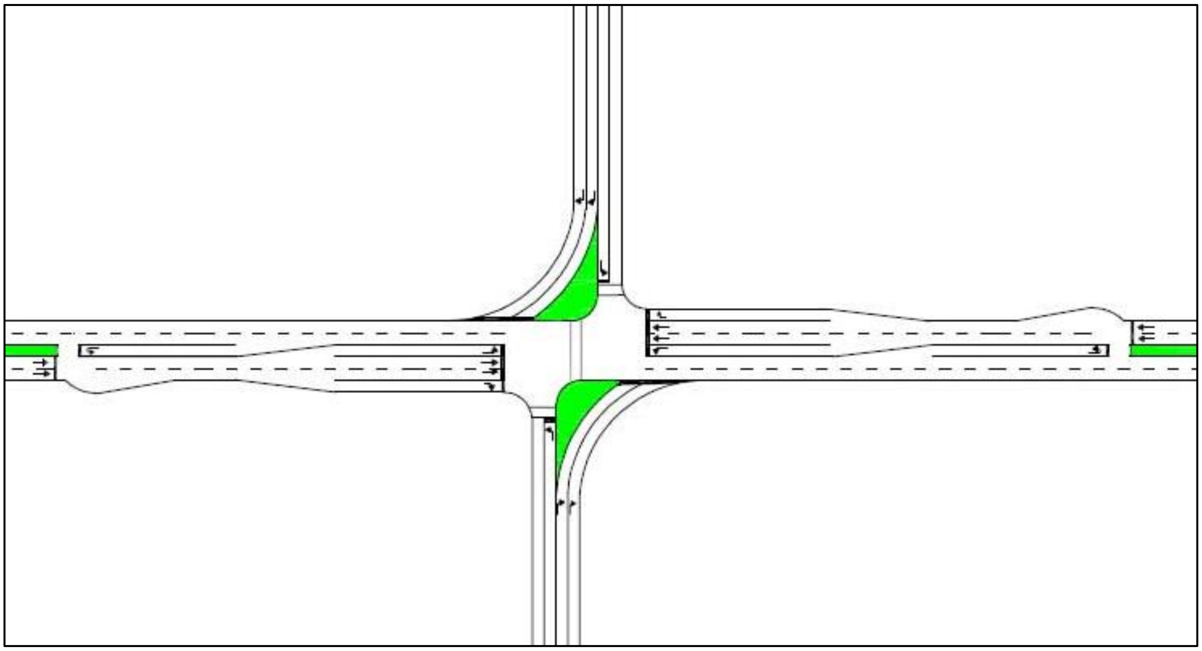

Figure 2.22 An Alternative for Offset Thru-Cut Design Geometry

2.5 Public Acceptance

Several past studies have assessed the public acceptance of new intersection designs and roundabouts. Some of these studies are highlighted in Table 2.14. However, there is limited literature focusing specifically on the public acceptance of three-phase designs. In other words, partial CFI should be the only three-phase design included in past studies on public acceptance. For the purposes of this literature review, studies on the public acceptance of non-three-phase alternative intersection designs are included to provide context for how the public reacted to the implementation of other alternative intersections.

Several studies showed mixed public perceptions towards alternative intersections. According to Ott et al. (2015) commuters, residents, and businesses in NC recognized the operational and safety benefits provided after implementing the new RCI; however, each group had its concerns. Commuters did not feel complete confidence in navigating the intersection. Residents noticed an increase in travel time. Businesses felt that the new RCI negatively affected their business.

Surveys from Jackson et al. (2014) revealed that, in regard to general knowledge, safety, and comfort with DDIs (diverging diamond interchange), users generally thought the interchange was an improvement over the existing facility. Savolainen et al. (2012) found mixed feelings about roundabouts through public surveys, with 38.9% strongly opposing roundabout usage, 30.6% strongly supporting their usage and 52.7% merely finding roundabouts efficient. Pochowski et al. (2010) found a strong positive correlation between the number of roundabouts in the state and the strength of the roundabout policy in that state.

Table 2.14 Summary of Alternative Intersection and Roundabout Public Acceptance Studies by Geometric Design

Type of Intersection	Barnes et al. (2022)	Adsit et al. (2022)	Rodgers et al. (2020)	Schneider et al. (2019)	Ott et al. (2015)	Jackson et al. (2014)	Veneziano et al. (2013)	Savolainen et al. (2012)	Chilukuri et al. (2011)	Pochowski et al. (2010)	Total
Quadrant			X								1
CFI		X	X								2
MUT			X								1
RCI	X		X	X	X						4
Roundabouts		X	X				X	X		X	5
DDI		X				X			X		3
Total	1	3	5	1	1	1	1	1	1	1	16

Based on surveys conducted in an FHWA project by Adsit et al. (2022) in Indiana, the CFI was identified as the least accepted design after the DDI. It should be noted that over 40% of the participants were unfamiliar with the concept of CFIs. Conclusions from the surveys include vast unawareness of the new designs, large doubt in being able to navigate the foreign designs and the persistence to stick to the usual designs. Chilukuri et al. (2011) found that, following the implementation of a DDI, as traffic operation and safety conditions improved, a high percentage of the public was satisfied with the innovation.

To attain more public acceptance, Adsit et al. recommended that more outreach efforts be made to increase awareness, simplification of intersections geometry to reduce confusion and debunking misconceptions about the new designs. Pochowski and Myers (2010) noted that the general public's negative perception towards roundabouts hinders advanced implementation, and that public education should be exerted to minimize oppositions.

Regarding the effects of alternative intersection design on businesses, Barnes et al. (2022) found that implementing RCIs had no negative effects (and in some cases a minor positive effect) on economic activity near the intersection. Likewise, Schneider et al. (2019) found that there was no proof that RCIs were detrimental to business sales as the average sales improved after the installation of RCIs despite issues like traffic congestion, construction inconveniences and even left turn issues being reported on a patron survey. A summary of all of the public acceptance studies included in this literature review is available in Table 2.15.

2.6 Construction Costs

The FHWA Displaced Left Turn (2014), the FHWA Median U-Turn (2014), and the FHWA Quadrant Roadway Intersection (2020) Informational Guides presented construction costs of a few past projects implementing those designs. According to the information guides, construction costs varied from $1.7M to $5.1M, from $4.4M to $7.5M, and from $1.8M to $3.2M for MUTs, CFIs, and QRs, respectively, constructed in the 2000s and the 2010s (Steyn et al. 2014; Reid et al. 2014; Reid and Hummer 2020).

Table 2.15 Summary of Public Acceptance Studies

Researchers/Year	Design	Methods Used	Sample Size	Location	Results Summary
Barnes (2022)	RCI	Surveys	310 surveys	North Carolina	Residents more likely to shop when traffic is improved
Adsit (2021)	Roundabouts, RCI, CFI, DDI	Surveys, online comment boxes	1000 surveys	Indiana	Age, gender, and education impact public acceptance
Rodgers (2020)	Roundabouts, RCI, MUT, CFI, QR	Interviews in public meetings	167 interviews	Georgia, Atlanta	Multiple meetings led to increased acceptance
Schneider (2019)	Raised non-traversable medians, RCI	Questionnaires and interviews	Over 500 questionnaires	Louisiana	Concerns about construction impacts
Ott (2015)	RCI	Interviews and surveys	145 out of 500 surveys/interviews	North Carolina	Businesses are concerned with access and driver confusion
Jackson (2014)	DDI	Surveys	1,649 surveys	-	DDI was considered an improvement over the previous interchange
Veneziano (2013)	Roundabouts	Interviews and surveys	30 surveys/interviews	Montana	Respondents who have used roundabouts tend to view them more favorably
Savolainen (2012)	Roundabouts	Surveys	11,972 surveys	Michigan	Respondents felt that roundabouts were less safe than conventional intersections
Chilukuri (2011)	DDI	Surveys	53 surveys	Missouri	Majority of respondents felt that DDIs increased safety and traffic operations
Pochowski (2010)	Roundabouts	Guides and interviews	-	Multiple States	The first few roundabouts installed in an area will likely meet resistance from the public

According to Luo et al. (2024), the estimated ROW cost for implementing three-phase designs (converting four-phase intersections to three-phase designs) in California ranged from $5 million to $10.2 million in residential districts and $43,00 to $99,200 in rural areas. These values are listed in Table 2.16 which shows that partial MUT, reverse RCI, and thru-cut were estimated to cost the least to implement. CFI/MUT combo and partial CFI were found to be the most expensive.

Table 2.16 Estimated ROW Cost for Replacing a Conventional Intersection in California (Luo et al., 2024)

Intersection Type	Extra ROW (sq ft)	ROW Cost ($)	
		Rural Areas	Residential Districts
Partial MUT	48,000	43,000	5,000,000
Partial CFI	99,200	89,000	10,200,000
CFI/MUT Combo	73,600	66,000	7,600,000
Reverse RCI	48,000	43,000	5,000,000
Thru-cut	48,000	43,000	5,000,000

As mentioned before, VDOT is also constructing a corridor of seven thru-cut intersections along US-220. The cost estimates for the project are highlighted in Table 2.17.

Table 2.17 Anticipated Project Costs for Seven Thru-cuts on VDOT US-220 Corridor

Phase	Cost
Preliminary Engineering	$2.4M
Right of Way	$3.9M
Construction	$9.8M
Total	$16.1M

Based on conversations with Alaska DOT, construction cost of the full CFI/MUT combo was about $20 million, which was a third of the cost estimated for building a DDI at the same location. Some three-phase designs such as redirect two lefts and one thru (2L&T) and offset thru-cut designs have not yet been constructed and do not have cost estimates. Regarding geometric and ROW limitations, the FHWA Quadrant Roadway Informational Guide (2020) provides insight into the benefits (smaller main intersection) and drawbacks (additional ROW for redirecting loop) of constructing Quadrant Roadways.

2.7 Literature Review Summary

This section aims to summarize the possible answers found to the nine main questions proposed in the introduction (and listed in Table 2.18), as well as to highlight other findings of note. This table has been updated at the end of the report to reflect the focus questions addressed by this study and those that require further research.

From a general point of view regarding performance, all three-phase intersection types (with the exception of redirect L&T and redirect 2L&T due to lack of research) were found to improve both traffic operation and safety improvements over conventional intersections with four legs. However, a few of the designs such as the partial CFI might create concerns in terms of pedestrian performance (due to the higher number of flags compared to the conventional design based on the NCHRP Report 948's 20-Flag method).

A few studies address what locations three-phase designs are best suited for. A partial CFI should be considered in situations of high demand from the major street. Quadrant roadways also perform well when both the minor and major legs have high traffic volumes (Reid and Hummer 2020). According to Luo et al. (2024), the MUT redirect major (partial MUT #1) is advantageous in the case of low or moderate turning demands. The partial MUT #1 should be also safer (in terms of vehicular traffic and pedestrian safety) than the partial CFI due to the fewer conflict points and fewer red flags based on the NCHRP Report's 20-Flag method. Thru-cut design should be one of the best alternatives for corridors with shorter intersection spacings due to its good signal progression performance. The CFI/MUT combo resulted in similar (insignificantly longer) travel times as the partial CFI; however, it requires a smaller ROW compared to partial CFIs. The reverse RCI could perform well in urban areas with higher pedestrian volumes. Hummer et al. (2019) provided seven criteria for where a seven-phase signal could perform well. This includes when there is an existing three-legged intersection, a proposal to add a fourth leg to an intersection, and the through demand from the newly added fourth leg can be accommodated while being redirected to a downstream U-turn.

Table 2.18 Summary of Focus Questions

#	Question	Any Available Past Studies Related to These Questions?									
		Partial MUT	Partial CFI	Reverse RCI	CFI/MUT Combo	Thru-cut	Offset T	Seven-Phase	Quadrant	Redirect L&T	Redirect 2L&T
1	At what locations are three-phase designs most well suited?	Yellow	Yellow	Yellow	Red	Yellow	Green	Yellow	Green	Red	Red
2	How much do they cost, especially compared with other intersections like RCIs?	Green	Green	Yellow	Yellow	Green	Red	Red	Green	Red	Red
3	What kind of traffic control devices (pavement markings, signs, and signals) are needed?	Yellow	Green	Red	Red	Red	Green	Yellow	Green	Red	Red
4	What movement restrictions could cause motorist confusion and violations?	Yellow	Yellow	Red	Red	Red	Red	Red	Yellow	Red	Red
5	How could we minimize those violations?	Yellow	Yellow	Red	Red	Red	Red	Red	Yellow	Red	Red
6	What are the considerations needed for pedestrian and bicyclist safety?	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red
7	What kind of geometric and right-of-way (ROW) limitations are faced during construction?	Red	Green	Red	Red	Red	Red	Red	Green	Red	Red
8	What movements are less impactful for redirecting in different cases?	Red	Red	Red	Red	Red	Red	Yellow	Red	Red	Red
9	What designs would be most readily accepted by the public?	Red	Yellow	Red	Red	Red	Red	Red	Red	Red	Red

Relatively Good, *Limited*, *No Publication*

Regarding construction costs, Luo et al. (2024), found that the ROW costs for converting an intersection with four phases to five of three-phase alternative intersections ranged from $5 million to $10.2 million in California. According to VDOT, the anticipated cost of construction and right of way for the US-220 thru-cut corridor (seven thru-cut intersections) is $9.8 million and $3.9 million, respectively. According to multiple FHWA guides, construction costs varied from $1.7M to $5.1M, from $4.4M to $7.5M, and from $1.8M to $3.2M for MUTs, CFIs, and quadrants, respectively.

There is minimal literature available regarding specific traffic control devices for three-phase intersections. Hummer et al. (2019) provided recommendations for the signal timing of seven-phase signal intersections. Additionally, the FHWA Quadrant Roadway, DLT (CFI), and MUT Intersection Informational Guides generally recommend providing additional signage, signals, and pavement markings where appropriate to ensure drivers are aware of redirected left turns, crossovers, and other non-conventional movements. Some of these recommendations should be also applicable to alternative intersection designs with three-phase signals. Motorist confusion is addressed as a precursor to traffic control device implementation in most cases and is included in the FHWA Quadrant Roadway, DLT, and MUT Intersection Informational Guides. The minimization of motorist violations is also addressed in the FHWA Quadrant Roadway, DLT, and MUT Intersection Informational Guides when discussing suggested signage and signals.

Several studies address pedestrian and bicyclist safety at intersections, but few specifically address three-phase designs. NCHRP report 948 introduced the 20-flag method to assess pedestrian safety at various intersection designs (Schroeder et al. 2021). Luo (2022) applied this 20-flag method for partial MUT, partial CFI, reverse RCI, CFI/MUT combo, and thru-cut intersections, and found that partial MUT had the lowest number of flags (concerns) for pedestrians. On the other hand, partial CFI had the highest number of flags. Reid and Hummer (2020) highlight that quadrant roadway intersections provide some advantages to pedestrians and bicycles like the reduction of most crossing movements between vehicles and pedestrians. Hummer et al. (2019) addresses some of the challenges of pedestrian accommodations at seven-phase signal intersections such as usually not having a sidewalk across one of the major legs.

Even though public acceptance of three-phase designs should be higher than alternatives with two-phase designs (as drivers became more accustomed to navigating the intersection), there are no studies citing this yet. In fact, partial CFI is the only three-phase design included in past studies on public acceptance.

Chapter 3 Methodology

This section presents the methodology employed to investigate the benefits and drawbacks of three-phase alternative intersections. It outlines the data collection process, case study selection, simulation modeling approach, surrogate safety assessments, and methods used in the public acceptance assessment, benefit-cost analysis, and the development of a framework for selecting alternative intersections.

3.1 Data Collection and Case Study Selection

To better understand the possible locations where alternative intersections with three-phase signals might work well, the research team requested data on alternative intersections from each of the 14 NCDOT Highway Division engineers. Specifically, we requested location data, intersection type, and any issues/concerns experienced with the alternative intersections within their division. The data we received included: the locations of RCIs throughout the state of North Carolina, the type of each RCI, construction date, estimated construction costs, and safety data. Table 3.1 summarizes the data received from NCDOT.

Table 3.1 Summary of Data Received from NCDOT

Data Source	Location Data	Construction Date	Intersection Type	Safety Data	Public Perception	AADT	Turning Counts	Crash Numbers
NCDOT Highway Division 1	X							
NCDOT Highway Division 2	X		X	X				
NCDOT Highway Division 3								
NCDOT Highway Division 4	X	X	X	X	X			
NCDOT Highway Division 5	X		X					
NCDOT Highway Division 6								
NCDOT Highway Division 7	X		X					
NCDOT Highway Division 8								
NCDOT Highway Division 9	X		X					
NCDOT Highway Division 10								
NCDOT Highway Division 11	X		X					
NCDOT Highway Division 12								
NCDOT Highway Division 13								
NCDOT Highway Division 14								
Dr. Joseph Hummer (statewide NC)	X	X	X					

In the next step, the research team collected AADT and geometric data at 160 intersections from four cities in North Carolina: Raleigh, Cary, Durham, and Chapel Hill. After evaluating these sites, and with guidance from Dr. Hummer from NCDOT regarding ongoing improvement projects at the sites, eight sites were selected for further evaluations. Six of these sites were included in simulation modeling, while the other two sites (sites 3 and 6) were considered for the remaining evaluations, such as pedestrian safety analysis. The process of how and why this decision was made is explained throughout this section.

As shown below in Table 3.2 and Figure 3.1, the eight preliminary case study sites are located throughout Wake and Durham counties. These sites were chosen after an evaluation of the existing intersection conditions based on factors like available right-of-way (ROW) and average annual daily traffic (AADT) rates. Additionally, the exclusion of the intersection from any future projects in the North Carolina State Transportation Improvement Program (STIP) was a mandatory requirement for selection.

Table 3.2 Preliminary List of Case Study Sites

#	County	EB/WB Road	NB/SB Road	GPS Coordinates
1	Wake	New Bern Avenue	NB - N Peartree Lane. SB - Donald Ross Drive	35.783074228, -78.592489070
2	Wake	Chapel Hill Road	Trinity Road	35.794746185, -78.750892139
3	Durham	NC-54	Davis Drive	35.890932871, -78.862158808
4	Wake	Old Wake Forest Road	Capital Blvd	35.870778937, -78.580486663
5	Wake	Capital Blvd	NB - Trawick Rd. SB - Huntleigh Drive	35.820810036, -78.591773197
6	Wake	Capital Blvd	Brentwood Road	35.818938110, -78.595904196
7	Wake	Brier Leaf Ln	Brier Creek Parkway	35.908832568, -78.785192188
8	Wake	NC-55	O'Kelly Chapel Road	35.845791480, -78.89083777

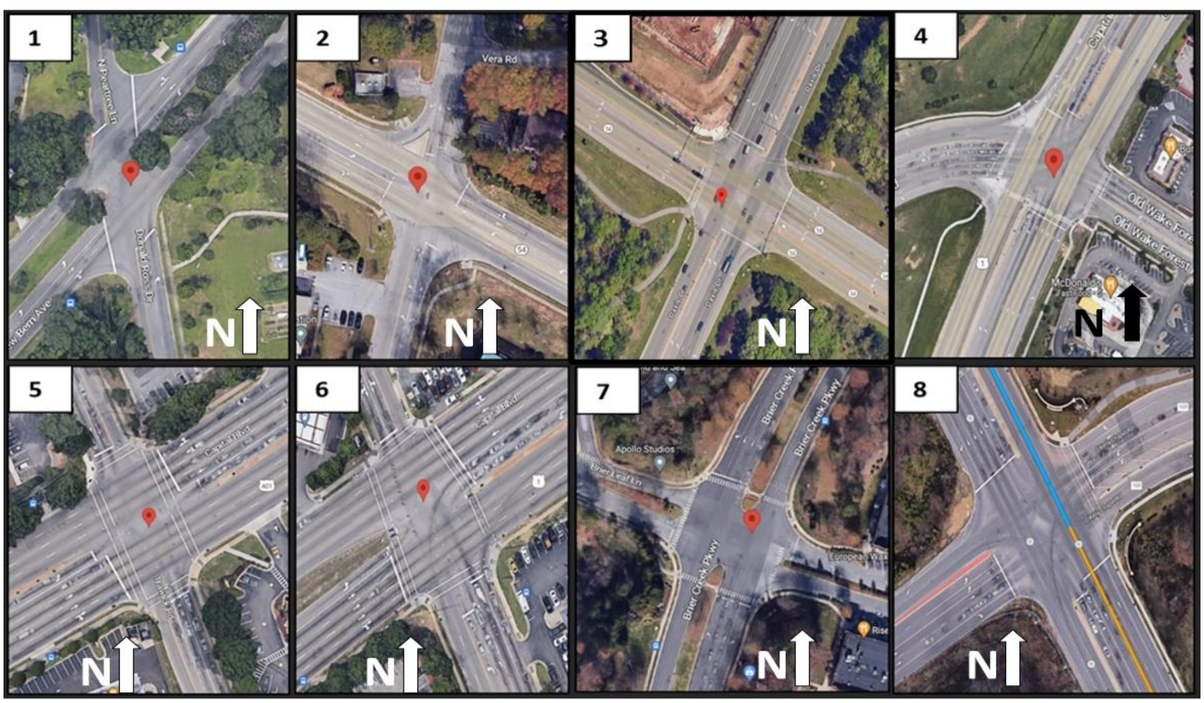

Figure 3.1 Aerial Photos of Preliminary Case Study Sites (Google Maps)

Table 3.3 shows the statistical summary of the data collected on the case study intersection sites, which have no existing plans for future improvement in Wake and Durham counties. The different categories of data displayed in the summary are AADT (veh/day), speed limit (mph) and spacing to the adjacent signalized intersections (ft).

Table 3.3 Statistical Summary of Preliminary Intersection Sites

	Minimum	Maximum	Average	S. Deviation
Major Street AADT (veh/day)	16,500	75,000	36,714	23,480
Minor Street AADT (veh/day)	670	63,000	17,981	21,308
Major Street Speed Limit (mph)	35	55	44 (Mode = 35)	9.9
Minor Street Speed Limit (mph)	35	45	36 (Mode = 35)	3.54
Spacing to Adjacent Intersection (ft)	850	6,000	2,314	2,089

Following studies done by Hummer (2020 and 2021), the research team also conducted analysis to determine the safest feasible intersection design (SaFID) based on total crashes and injury crashes, pedestrian optimum feasible intersection design (POFID), and bicycle optimum feasible intersection design (BOFID) as shown in Table 3.4.

Table 3.4 Study Site SaFID (All Crashes), SaFID (Injury Crashes), POFID, and BOFID

Site #	Number of Thru Lanes		AADT		SAFID (All Crashes)	SAFID CMF (All Crashes)	SAFID (Injury Crashes)	SAFID CMF (Injury Crashes)	POFID	BOFID
	Major	Minor	Major	Minor						
1	4	2	23,000	5,000	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
2	4	2	27,000	5,500	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
3	4	2	27,500	14,000	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
4	7	3	53,500	25,500	MUT	0.8	MUT	0.7	MUT	MUT
5	8	2	73,000	9,000	Sig. RCI	0.8	MUT	0.7	Bowtie or MUT	Sig. RCI
6	8	2	75,000	10,000	Sig. RCI	0.8	MUT	0.7	Bowtie or MUT	Sig. RCI
7	4	2	25,500	NA	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
8	6	4	17,500	17,000	Sig. RCI	0.8	MUT	0.7	Bowtie or MUT	Sig. RCI

(“Unsig.” is short for unsignalized, “Sig.” is short for signalized)

According to Table 3.4, the suitable intersection types (depending on the safety considerations) included in the recommendations are: unsignalized/signalized RCI, TWSC (two way stop signal), MUT (Median U-Turn), and Bowtie. While the two-phase RCI and MUT perform well in terms of safety, they cannot be recommended for most case study sites included due to ROW restrictions such as limited space for constructing an appropriate U-turn crossover.

Peak hour traffic data counts were provided by NCDOT for most of the case study sites. Where this data was unavailable, peak hour traffic data was collected on site by the research team. For those intersection sites, the data was collected by hand tallies for 07:45-08:45 (AM peak), 11:30-12:30 (MD peak), and 16:30-17:30 (PM peak). All of the traffic volume data for each case study site is attached as Appendix 1.

After collecting traffic data, the anticipated traffic for the design year of 2043 was estimated by developing a linear regression relationship based on the latest 20-year AADT data. For example, at site 1 the trendline equation of previous AADT data was found to be y = -66.67x +156,567 with x being the year and y being the AADT value. Using this trendline, the AADT value for 2023 and 2043 were calculated (21.7k and 20.4k, respectively) at site 1, which resulted in a growth rate of -0.3%. Table 3.5 shows the growth rates used at each case study site. The full process of developing these growth rates is available in Appendix 2.

Table 3.5 Growth Rates Used at Case Study Sites

Case Study Site	Heavy Vehicle Annual Growth Rate
Site 1: Peachtree Ln @ New Bern Ave	-0.3%
Site 2: Chapel Hill Rd @ Trinity Rd	1.5%
Site 4: Capital Blvd @ Old Wake Forest Rd	1.4%
Site 5: Capital Blvd @ Trawick Huntleigh	-0.3%
Site 7: Briar Creek @ Briar Leaf	2.3%
Site 8: NC 55 @ O'Kelly Chapel Rd	4.1%

The six sites included in Table 3.5 were modeled using TransModeler. As mentioned earlier, sites 3 and 6 were not included in the simulation modeling. Table 3.6 provides the final list of case study intersections used for simulation modeling. Of note, the same numbering convention was kept for the final list of study intersections that was used for the preliminary list.

Table 3.6 Final List of Study Intersections

Site #	Intersection
1	Peachtree Ln @ New Bern Ave
2	Chapel Hill Rd @ Trinity Rd
4	Capital Blvd @ Old Wake Forest Rd
5	Capital Blvd @ Trawick Huntleigh
7	Briar Creek @ Briar Leaf
8	NC 55 @ O'Kelly Chapel Rd

3.2 Simulation Modeling Approach

As previously noted, there are limited real-world examples of most alternative intersection designs (and no real-world examples of the offset thru-cut, partial CFI/MUT, seven-phase, and the redirect 2L&T designs), so vehicle travel time measurements and historical traffic crash data are unavailable for conducting analyses, such as before-and-after evaluations. Consequently, simulation modeling was the only viable option for the research team to conduct a comprehensive evaluation under similar geometric features, traffic characteristics, and driver behaviors. Two groups of simulation testing were considered: 1) hypothetical modeling using VISSIM, and 2) modeling case study sites using TransModeler. These simulation packages were used because TransModeler is the first choice for modeling in North Carolina based on NCDOT policies. On the other hand, for hypothetical tests, the research team has extensive experience in PTV VISSIM, and VISSIM allows modeling pedestrians and obtaining trajectory files needed for surrogate safety assessments. The following paragraphs detail the simulation modeling approach used in this study.

3.2.1 Simulation Modeling of Hypothetical Scenarios in VISSIM

The following subsections describe the type and number of hypothetical simulation scenarios considered for testing each intersection design, and the various inputs and assumptions needed for the simulation modeling of hypothetical scenarios using VISSIM.

3.2.1.1 Hypothetical Simulation Scenarios

The input traffic volume for the simulation scenarios was determined using critical lane volume (CLV) calculations, setting the volume-to-capacity (V/C) ratios to 0.9 for the conventional intersection. CLV is a traditional method used by traffic engineers to estimate V/C ratios at signalized intersections and has been widely applied in numerous previous studies (Haq et al., 2022; Molan et al., 2019a; Maji et al., 2013; Molan and Hummer, 2020a; Molan and Hummer, 2020b). The V/C ratio was set to 0.9 to simulate traffic conditions at a near-capacity level.

All the designs featured two through traffic lanes in each direction on the major street and one through traffic lane in each direction on the minor street. Also, each approach had one turning lane per movement on both the major and minor roads. Three turning traffic ratios were considered for each intersection approach: 1) high-turning ratio (the turning lanes had 1/2 of the volume of the through lanes), 2) moderate-turning ratio (the turning lanes had 1/4 of the volume of the through lanes), and 3) low-turning ratio (the turning lanes had 1/10 of the volume of the through lanes). These turning traffic ratios were determined based on discussions with North Carolina DOT experts. Initial simulation tests conducted by the research team also showed that conventional intersections struggle to handle higher volumes of turning traffic at traffic conditions with V/C=0.9 due to capacity limitations.

Truck traffic was set at 4% of the total traffic in all scenarios. Finally, six different traffic distributions were considered to account for various balanced and unbalanced (asymmetric) traffic conditions in the simulation modeling. Table 3.7 details these six traffic distributions along with turning ratios involved in the simulation scenarios.

Table 3.7 Simulation Scenarios Included in this Study

Turning Volume Ratios	Traffic Distribution	
	Major Street (EB/WB)	Minor Street (NB/SB)
Left turn = 0.50 Through = Right turn (High Turning Condition)	EB = WB (Equal traffic on EB and WB)	NB = SB (Equal traffic on NB and SB)
Left turn = 0.25 Through = Right turn (Moderate Turning Condition)	0.5 EB = WB (Higher traffic on EB)	NB = 0.5 SB (Higher traffic on SB)
Left turn = 0.10 Through = Right turn (Low Turning Condition)		0.5 NB = SB (Higher traffic on NB)

Note that for the major road directions, eastbound (EB) and westbound (WB) were considered, while for the minor road directions, northbound (NB) and southbound (SB) were used in all simulation models. Based on the details provided in Table 3.7, 18 simulation scenarios (3 turning traffic ratios*6 traffic distributions= 18) were tested per intersection design. In total, 108 simulation scenarios (each was run ten times) were included for the six intersections included in this research. The input traffic ranged from 3,360 to 4,480 vehicles per hour (veh/hr), with an average of 3,993 veh/hr across the network. Table 3.8 presents the input traffic for each simulation scenario, as explained above.

Table 3.8 Input Traffic Volume per Traffic Movement (Vehicle per Hour) in Each Scenario

		EB			WB			NB			SB			Total
Turning/ Volume Case	Test	Left Turn	Thru*	Right Turn	Left Turn	Thru*	Right Turn	Left Turn	Thru	Right Turn	Left Turn	Thru	Right Turn	
Low Turning Traffic	1	80	1,520	80	80	1,520	80	40	380	40	40	380	40	4,280
	2	80	1,520	80	80	1,520	80	20	200	20	40	400	40	4,080
	3	80	1,520	80	80	1,520	80	40	400	40	20	200	20	4,080
	4	40	800	40	80	1,600	80	40	380	40	40	380	40	3,560
	5	40	800	40	80	1,600	80	20	200	20	40	400	40	3,360
	6	40	800	40	80	1,600	80	40	400	40	20	200	20	3,360
Moderate Turning Traffic	7	165	1,330	165	165	1,330	165	90	335	90	90	335	90	4,350
	8	165	1,330	165	165	1,330	165	50	190	50	95	375	95	4,175
	9	165	1,330	165	165	1,330	165	95	375	95	50	190	50	4,175
	10	90	740	90	180	1,500	180	85	335	85	85	335	85	3,790
	11	90	740	90	180	1,500	180	50	190	50	95	375	95	3,635
	12	90	740	90	180	1,500	180	95	375	95	50	190	50	3,635
High Turning Traffic	13	280	1,120	280	280	1,120	280	140	280	140	140	280	140	4,480
	14	280	1,120	280	280	1,120	280	85	170	85	170	335	170	4,375
	15	280	1,120	280	280	1,120	280	170	335	170	85	170	85	4,375
	16	165	665	165	335	1,340	335	140	280	140	140	280	140	4,125
	17	165	665	165	335	1,340	335	85	170	85	170	335	170	4,020
	18	165	665	165	335	1,340	335	170	335	170	85	170	85	4,020

* There are two lanes for the through traffic on each approach of the major road

3.2.1.2 VISSIM Simulation Modeling

The simulation modeling began with Synchro (version 11) to determine optimal cycle lengths, signal timings, and signal progression (signal coordination) systems for each simulation scenario. Key intersection and traffic data, including lane configurations, hourly traffic volumes, speed limit, and signal phasing information for each intersection were inputted into the software. The software was then used to calculate the ideal cycle lengths and optimize the signal timings for each intersection. Synchro's signal timing optimization feature was used to adjust green times, splits, and offsets. It must be added that the signal timing settings and the phase sequence were also optimized for each simulation scenario. Note that the progression considerations were essential for all alternative designs because they involve signalizing three (four signals at an RCI) different locations on the major road. Signal offsets were also calculated using vehicle average speed and U-turn spacings (distance between U-turn and DLT crossovers and the middle signal). Synchro's default settings were used for ideal saturation flows and lost time. The maximum and minimum cycle lengths were set to 150 sec and 40 sec, respectively, with a minimum green time of 6 sec. Yellow and red clearance (all-red) intervals were set at 4 and 2 sec, respectively, based on the Manual on Uniform Traffic Control Devices (MUTCD, 2023, p. 708).

Next, the traffic signal data were imported into the microsimulation software VISSIM (version 2023) to model the entire intersection network and calculate average vehicle travel times, maximum queue lengths, and the average number of stops for each test scenario. To mitigate the influence of simulation variability, each scenario was run ten times, following recommendations from previous studies (Fries et al., 2017; Lee et al., 2024; PTV, 2018).

In the simulation networks, driver behaviors were modeled with consideration of conflict areas and priority rules based on typical driving regulations in North Carolina. All vehicles had speeds set between 25 mph and 40 mph, with the 85th percentile speed set at 35 mph throughout the network. Turning traffic movements on approaches were modeled with speeds between 15 mph and 25 mph, with the 85th percentile speed set at 20 mph. Turning speeds at the midpoint of turns were specifically set to 15 mph, following real speed data collected from Fitzpatrick et al. (2006). The right turn and U-turn traffic were also allowed to make a turn on the red signal when there was a 4-sec minimum gap for it. Each test lasted 75 minutes, including a 15-minute warm-up period to preload the network with vehicles, followed by 60 minutes of data collection.

The simulation network was configured in a square shape, with each side measuring 5,400 ft in length. Regarding geometric features, the lane width, right-turn radius, U-turn (bulb-out) radius, taper length, and length of the storage lane were consistently set at 12 ft, 30 ft, 45 ft, 100 ft, and 400 ft, respectively, for all intersection designs. The U-turn crossovers were located 800 ft away from the middle intersection for all alternative designs except the CFI/MUT combo. For the CFI/MUT combo and the partial CFI, the distance from the middle intersection to the U-turn and displaced left-turn (DLT) crossovers was approximately 600 ft. These spacings were determined based on recommendations provided in FHWA informational guides (Hummer et al., 2014; Reid et al., 2014; Steyn et al., 2014). Based on the geometric data collected by the research team from 39 U-turn crossovers at RCIs in NC, the average and mode U-turn spacings were found to be 940 ft and 820 ft, respectively. The average and mode for the bulb-out radius were both 45 ft.

In total, 1,080 simulation runs (108 scenarios*10 runs per scenario) were conducted for this study. The average results from the ten tests were selected as the representative outcomes for each scenario. In addition, the research team employed factorial analysis (analysis of variance, ANOVA) to ensure that each comparison between the intersection designs had a substantial sample size. This allowed for statistically significant differences in intersection performance to be identified using ANOVA at a significance level of 0.05.

Trajectory files were generated from the simulation software for use in FHWA's surrogate safety assessment model (SSAM) for safety analysis. SSAM was employed in this study to assess safety by identifying simulated conflicts, also known as near misses or vehicle-vehicle interactions. It is important to note that the simulation modeling approach used in this research aligns with several previous studies that evaluated alternative designs using simulation (Buck et al., 2017; Haq et al. 2023; Haq et al., 2022a; Haq et al., 2022b; Howard et al., 2023; Lee et al., 2024; A. Molan and Hummer, 2020a; Molan et al., 2019b; Schroeder et al., 2014).

3.2.2 Modeling Case Study Sites in TransModeler

Once the final case study locations were selected, the research team analyzed which alternative intersection designs might perform well at each site. Alternative designs were suggested based on AADT rates, available ROW, and safety considerations. The final suggested treatments chosen are shown in Table 3.9. The alternatives and their number of critical phases are listed in the first two columns of the table. Each site is then identified at the top of the remaining columns, and a total number of locations for each treatment is suggested. For example, the ninth row of the table shows that a Redirect 2L&T design was selected for only one location (site 4). Each column of Table 3.9 shows the possible alternative treatments that are being considered at each location.

Overall, there are 21 suggested alternatives for all the sites displayed in Table 3.9. Among the three-phase intersections listed in the literature review, the offset T-intersection, offset thru-cut, and single quadrant are the only designs with no case study sites in Table 3.9. It should be noted that the two-phase CFI was not considered in this project because it is an uncommon design due to its significant cost and ROW requirement for implementation. Based on the best knowledge of the author, to date, there are only a few two-phase CFIs currently built.

Table 3.9 Alternative Intersections Suggested for Case Study Sites

		Intersection #						
Suggested Alternatives		1	2	4	5	7	8	Total
Three-Phase	Seven-Phase	X	X					2
	Redirect L&T	X	X					2
	Thru-cut	X				X		2
	MUT #1	X		X	X			3
	MUT #2	X		X	X			3
	Reverse RCI	X						1
	CFI			X			X	2
	CFI/MUT Combo			X			X	2
	Redirect 2L&T			X				1
Two-Phase	RCI	X						1
	MUT	X		X				2
Total		8	2	6	2	1	2	21

Where possible, the NCDOT Congestion Management Simulation Guidelines for TransModeler was implemented in the creation of the simulation models for this project. One notable exception is that the signals in this project are all pretimed (NCDOT recommends using actuated timing). Using pretimed signal control was necessary to allow for proper signal progression throughout each model.

For each of the six case study intersections, the existing roadway geometry was modeled in TransModeler. Using this geometry as a baseline, the alternative intersections were modeled to fit within the available ROW at the case study site whenever possible. The major road was extended 2,500 feet from the main intersection in both directions and the minor road was extended 1,000 feet from the main intersection. For consistency, CFI crossovers and median U-turns each included two lanes with the exception of the U-turn north of the main intersection at site 8. This decision was made because adding another U-turn lane would drastically alter the geometry of the roadway in a manner that was unrealistic with the existing ROW of the site.

Lane geometry for alternative design models was kept as close as possible to the existing geometry while still allowing for the proper function of the alternative intersection design. Some designs required minimal changes to existing roadway conditions, while others like the CFI required multiple new lanes and a channelized right turn. Crossovers and U-turns were modeled within 500-800 feet of the main intersection and were located at existing median breaks where possible.

Traffic volumes were input as individual turning movements at each intersection. As recommended by the NCDOT simulation guidelines, a warmup period of 15 minutes with 75% of total traffic volume was used for all of the models. Redirected vehicles were added as additional volumes to the requisite movements through which they were redirected. Heavy vehicle percentages were based on the collected traffic data for each study site as shown in Table 3.10.

Table 3.10 Heavy Vehicle Percentages at Case Study Sites

Case Study Site	Heavy Vehicle Percentage
Site 1: Peachtree Ln @ New Bern Ave	2.0%
Site 2: Chapel Hill Rd @ Trinity Rd	3.5%
Site 4: Capital Blvd @ Old Wake Forest Rd	4.5%
Site 5: Capital Blvd @ Trawick Huntleigh	4.5%
Site 7: Briar Creek @ Briar Leaf	1.5%
Site 8: NC 55 @ O'Kelly Chapel Rd	2.0%

Free flow speeds were modeled as the existing speed limit of each site plus 5 mph (HCM 2016). CFI crossovers and channelized turns were modeled with the same classifications of their connecting roadways. Turning delays were set to 10 seconds for right turns, 15 seconds for left turns, 20 seconds for U-turns, and 0 seconds for through movements. Of note, turning movements were restricted to a single lane (for example a car turning right could only turn into the nearest receiving lane). Additionally, no right turns on red were allowed.

Each traffic signal was modeled as pre-timed. For models of existing conditions, signal phases matched the current phasing sequence at the site, but the timing of the phases was based on TransModeler's optimization using Webster's equation. Alternative intersections used the phasing sequences provided in Appendix 3 and were subsequently optimized using TransModeler's optimization feature. Minimum cycle lengths varied depending on the number of phases for each signal: 120 seconds for four phases, 90 seconds for three phases, and 60 seconds for two phases. The maximum cycle length was set to 180 seconds. These restrictions are based on the NCDOT simulation guidelines.

All signals were coordinated to allow for maximum signal progression. For clarity, signal progression is defined as the ability of a car to proceed through more than one adjacent signalized intersection without having to stop. Signal coordination was accomplished by offsetting the beginning of the adjacent intersection signal cycles by the amount of time it would take a vehicle to travel from one intersection to the next. Of note, all CFI crossovers and median U-turns were signalized in this study.

3.3 Surrogate Safety Assessments

The research team opted to use surrogate safety measures to assess safety since the traditional methods, such as the Highway Safety Manual (HSM)-based methods, were not usable due to the low number of existing three-phase intersections. HSM-based evaluations require sufficient data from existing intersections. The following paragraphs describe the surrogate safety assessments included in this study.

3.3.1 SSAM

FHWA's surrogate safety assessment model (SSAM) was employed in this research project to assess safety by identifying simulated conflicts, also known as near misses or vehicle-vehicle interactions. In SSAM, a simulated conflict is defined as a situation where two vehicles approach each other in time and space, posing a collision risk if their movements remain unchanged (Gettman et al., 2008). SSAM determines the type and frequency of simulated conflicts between vehicles, based on thresholds for both time to collision (TTC) and post-encroachment time (PET), derived from the analysis of imported trajectory files. Thresholds of 1.5 seconds for time to collision and 5 seconds for post-encroachment time were selected, following recommendations from previous studies (Fan et al., 2013; Gettman et al., 2008; Haq et al., 2022; Huang et al., 2013). It should be mentioned that SSAM was conducted only for hypothetical scenarios because TransModeler does not provide trajectory files needed for SSAM.

3.3.2 SSI

The FHWA has developed an analytical technique and framework for evaluating crossings that is based on a safe system approach. By emphasizing the prevention of major injuries and fatalities, the Safe System Intersections (SSI) approach represents a substantial divergence from conventional road safety procedures. Its main objective is to create a road environment in which human error does not result in serious consequences for those using the road. During project development, this method enables designers to improve intersection safety with the primary goal of removing traffic fatalities.

A recommended set of SSI scores and a variety of efficacy metrics are the results of applying the SSI approach. These metrics include the average amount of exposure across different types of conflict points, the average probability of fatal or serious injury for different types of conflict points which is represented by the average conflict severity, and the average complexity of movements completed at different conflict locations.

An Excel spreadsheet was developed as a tool (titled “SSI for New Alternatives”) in performing the analysis based on the metrics and formulas provided in the FHWA’s Safe System-Based Framework and Analytical Methodology for Assessing Intersections (2021). Development of a tool was essential as the current FHWA manual (2021) does not include any of the three-phase intersections included except partial CFI. An alternative intersection’s adherence to safe system principles was evaluated using the SSI scores. For every alternative intersection under consideration, a score between 0 and 100 is assigned. Higher scores correlate with improved safety system performance, which in turn translates into decreased risks of major and severe injuries. This spreadsheet is available as Appendix 5.

There were several limitations of the SSI spreadsheet tool developed by the research team in this project. First, it should be noted that the non-motorized conflict type was not included in the analysis using the developed spreadsheet tool. Also, all the left-turns movements were assumed to have a protected only signal phase during the analysis. It is also important to note that the FHWA SSI method does not consider right turns on red.

3.3.3 Conflict Point Analysis (CPA) at Intersections

In addition to FHWA’s SSI analysis, the research team also developed another spreadsheet-based tool titled conflict point analysis (CPA) to compare and rank the intersection designs based on 1) frequency and types of conflict points, 2) traffic volume involved in conflict points, 3) vehicle speeds during conflicts, and 4) distribution of traffic volumes conflicting within the network. The literature review conducted included information regarding the total number of conflict points at each intersection design. The following paragraphs provide a table, and a series of conflict point diagrams to elaborate more on the differences among various intersection designs. However, the results of the entire conflict point analysis (CPA) will be presented in the next chapter. Also, the CPA spreadsheet is available as Appendix 6.

Table 3.11 shows the number of conflict points at all the intersections included. The conventional 4-leg intersection has 32 conflict points, comprising 8 diverging, 8 merging, and 16 crossing points. Based on past studies, there is a strong relationship between the number of conflict points and crashes at intersections. For example, a greater number of crossing conflict points correlates with higher crash severity. This summary seeks to provide a comprehensive conflict point analysis for 14 alternative intersections in comparison to the conventional intersection.

Table 3.11 Number of Conflict Points in Intersections Included

Rank	Name/Type	Diverging	Merging	Crossing	Total
1	Reverse RCI	6	6	2	14
1	RCI	6	6	2	14
3	Two-phase MUT	6	6	4	16
4	Offset T	6	6	6	18
5	Redirect L&T	7	7	8	22
5	Redirect 2L&T	7	7	8	22
7	MUT #2	8	8	8	24
7	Offset Thru-cut	8	8	8	24
7	Thru-cut	8	8	8	24
7	MUT #1	8	8	8	24
11	CFI/MUT Combo	8	8	11	27
12	Seven-Phase	8	8	12	28
12	Single Quadrant	9	9	10	28
14	Partial CFI	8	8	14	30
15	Conventional	8	8	16	32

As illustrated in Table 3.11, all of the alternative intersection designs showed fewer conflict points than the conventional intersection, especially in terms of crossing conflicts which are the most severe type of conflicts.

Figures 3.2-3.16 show the exact location of each of the merging, diverging, and crossing conflict points for a conventional intersection and every alternative design included in this project. Among the alternative intersections, both reduced conflict intersection (RCI) and reverse RCI had the least overall conflicts of 14 with a reduction in crossing conflicts to only two (2). On the other hand, partial CFI (continuous flow intersection) had the highest number of conflicts, totaling 30, slightly lower than the conventional design. MUT redirect major (partial MUT #1), MUT redirect minor (partial MUT #2), thru-cut, offset thru-cut, redirect 2L&T (two left-turn and one through movements), and redirect L&T (left and through) have eight (8) crossing conflict points, which shows a 50% reduction compared to the conventional intersection.

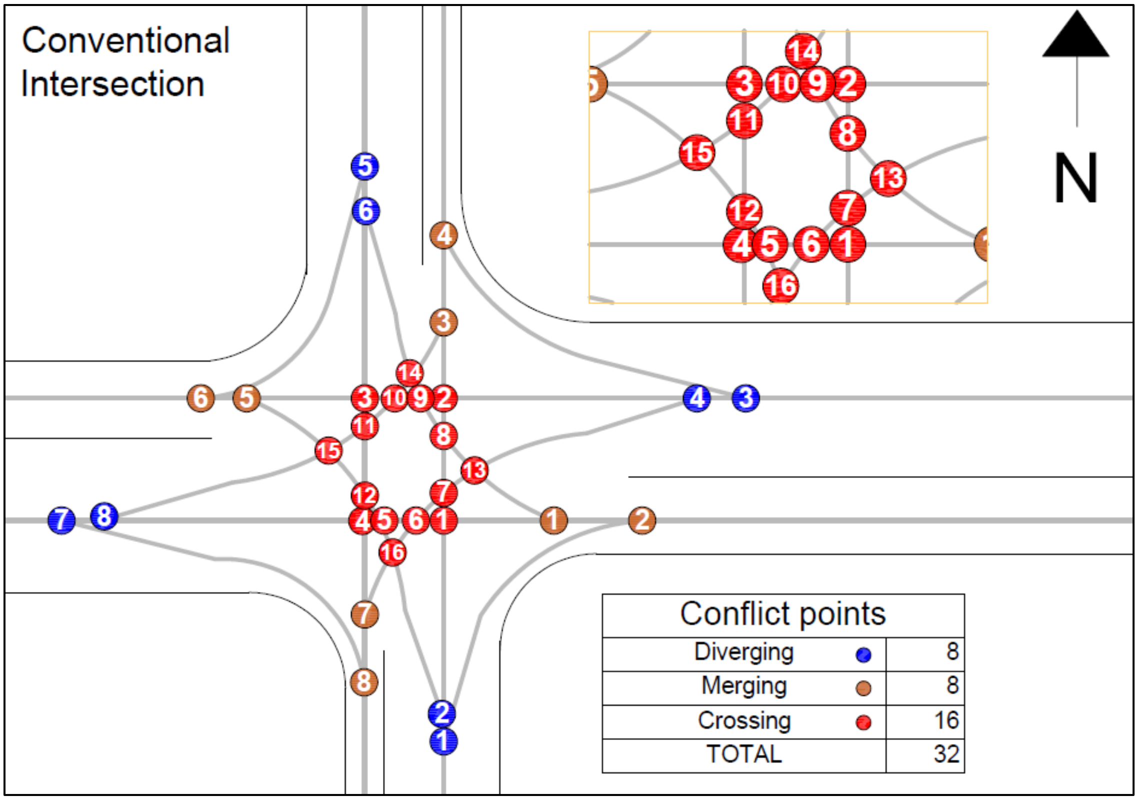

Figure 3.2 Conventional Intersection Conflict Point Diagram

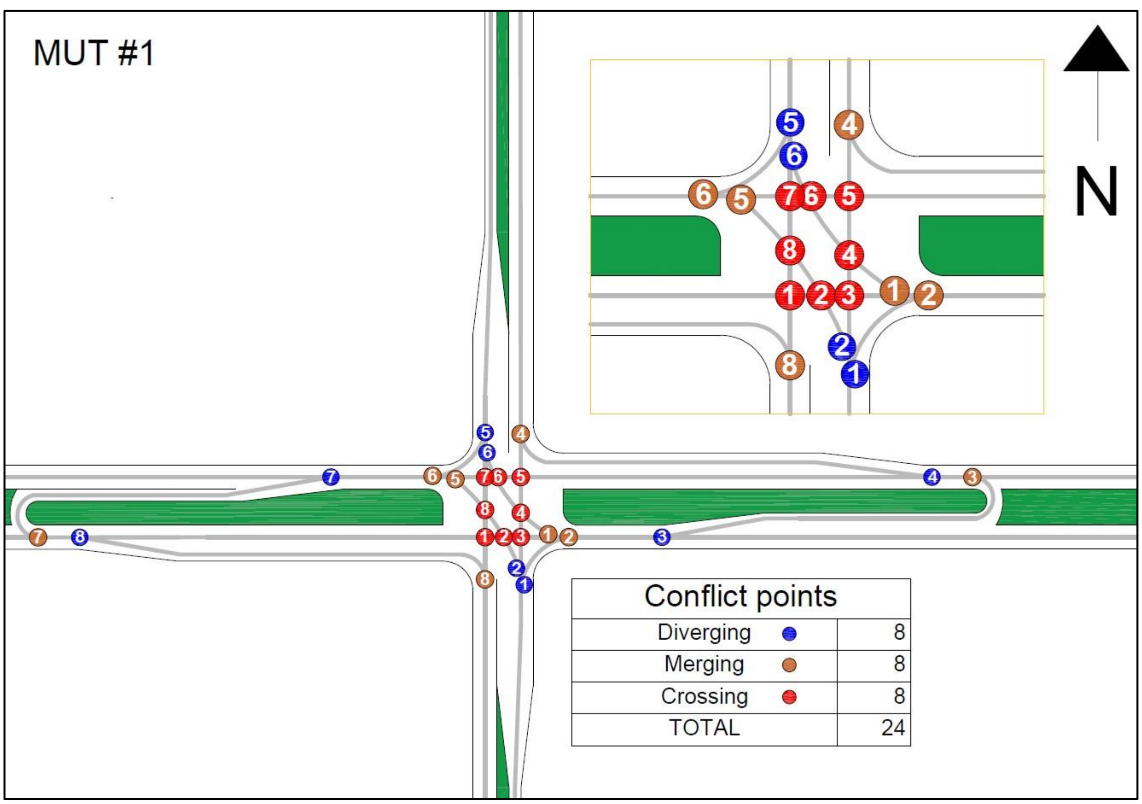

Figure 3.3 MUT Redirect Major (Partial MUT#1) Conflict Point Diagram

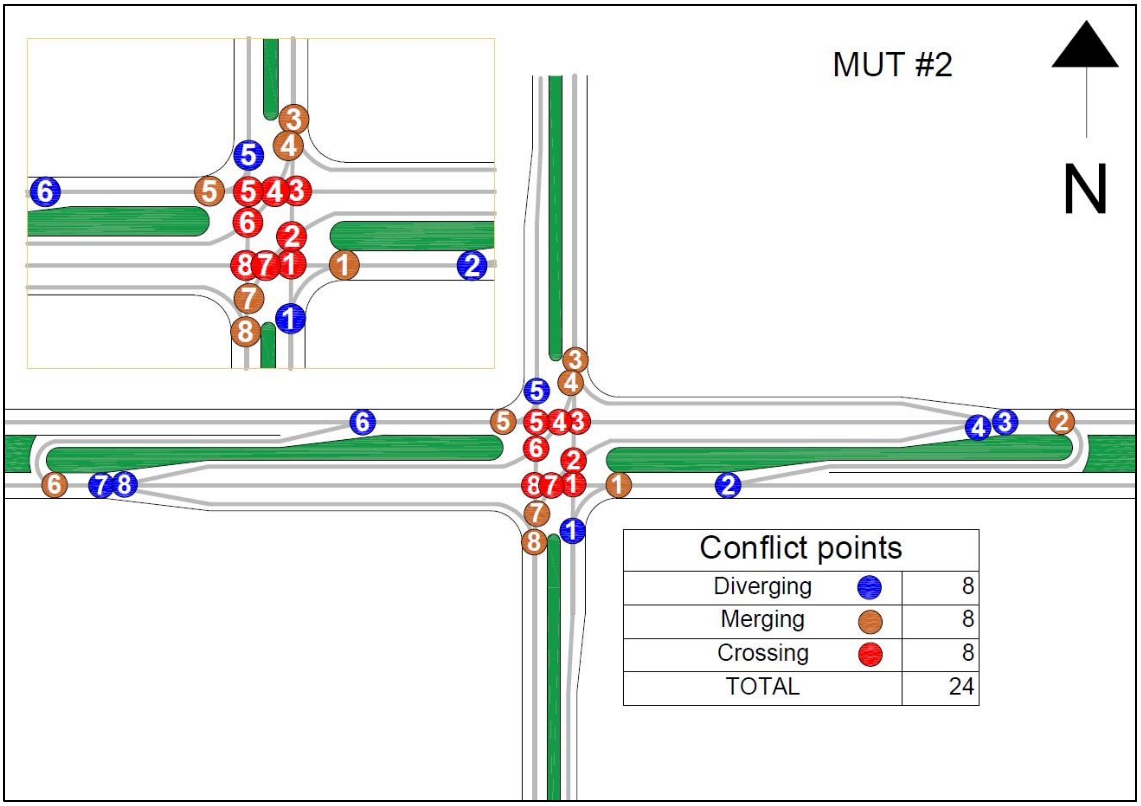

Figure 3.4 MUT Redirect Minor (Partial MUT #2) Conflict Point Diagram

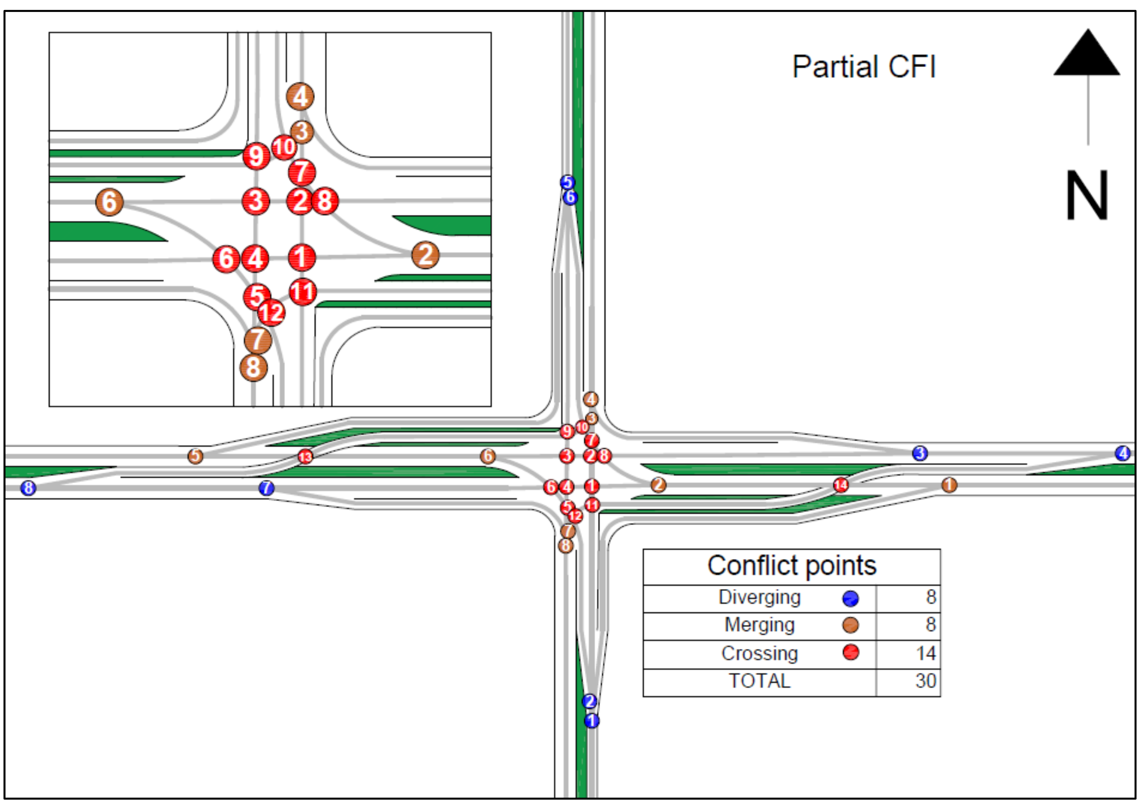

Figure 3.5 Partial CFI Conflict Point Diagram

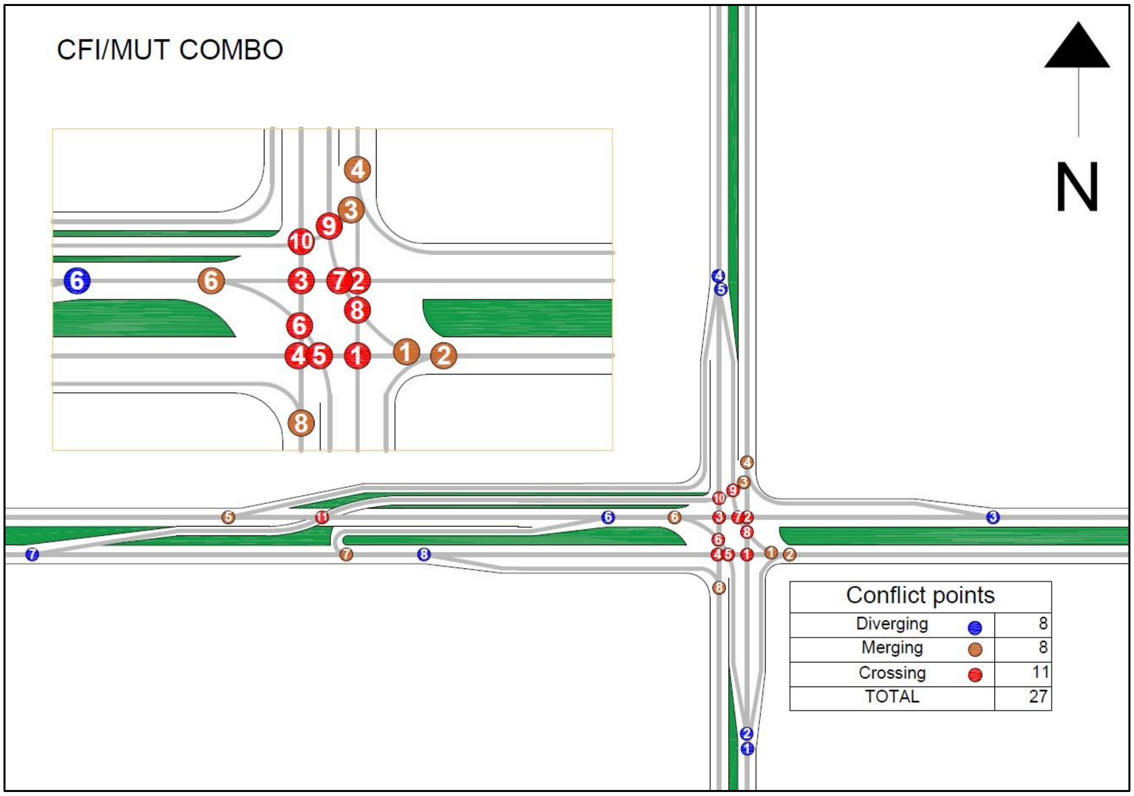

Figure 3.6 CFI/MUT Combo Conflict Point Diagram

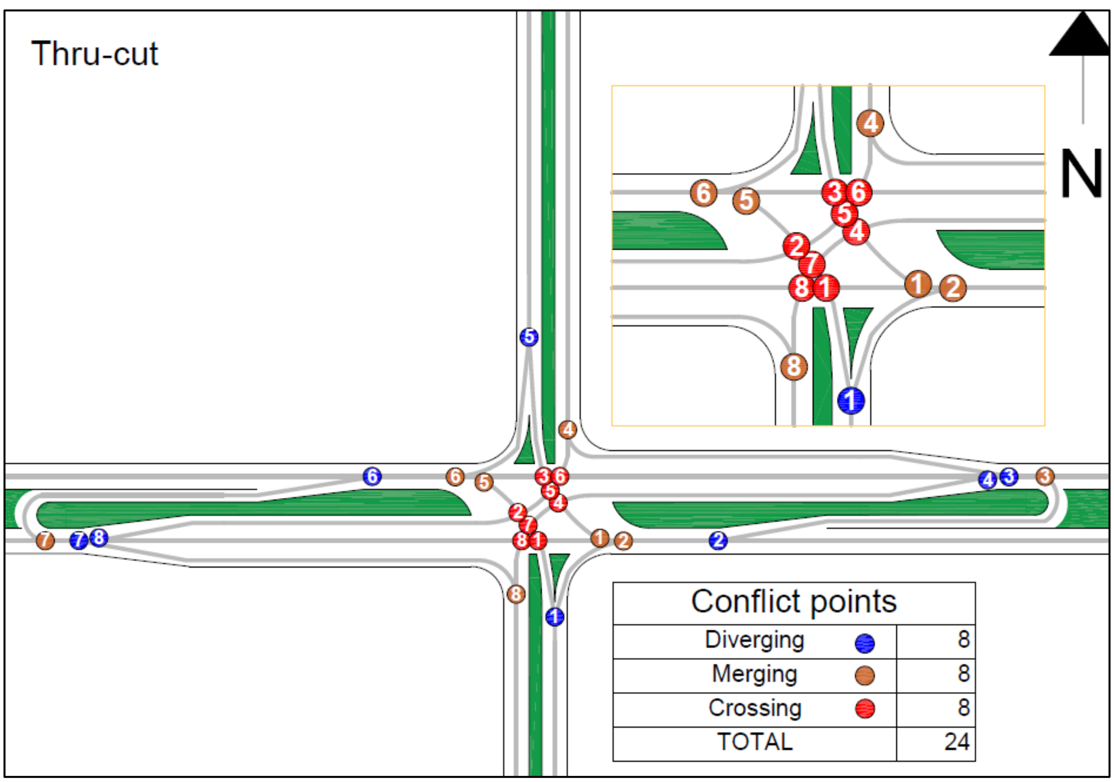

Figure 3.7 Thru-Cut Conflict Point Diagram

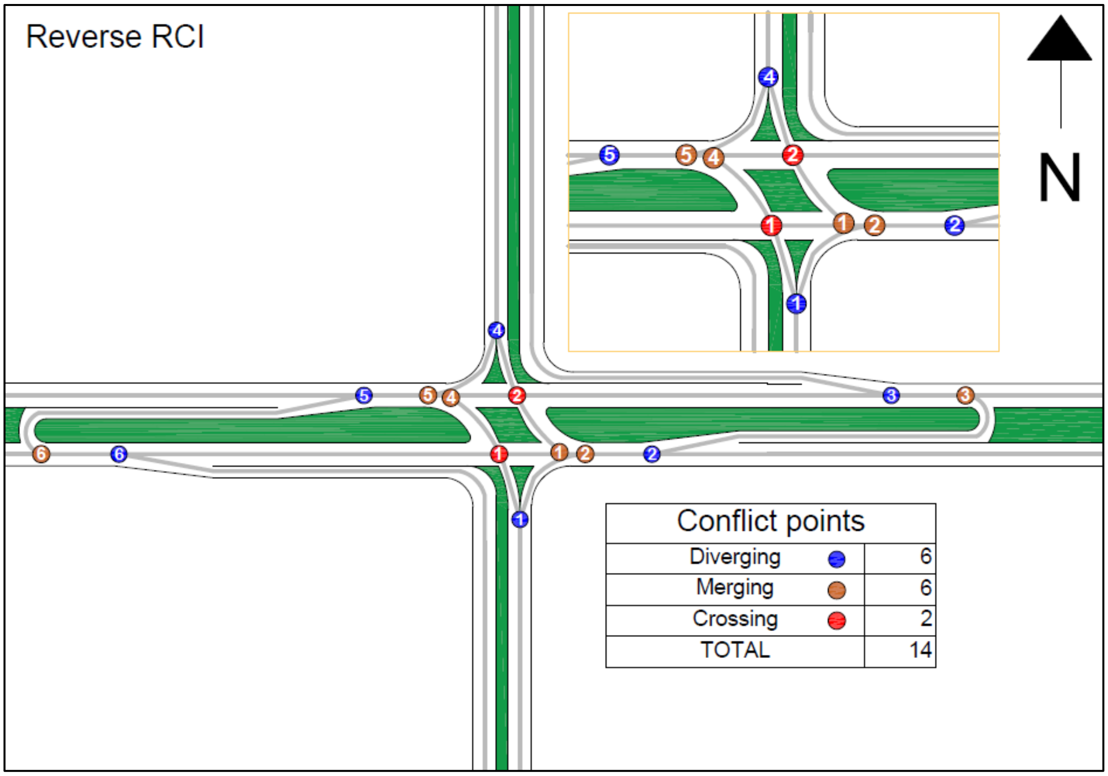

Figure 3.8 Reverse RCI Conflict Point Diagram

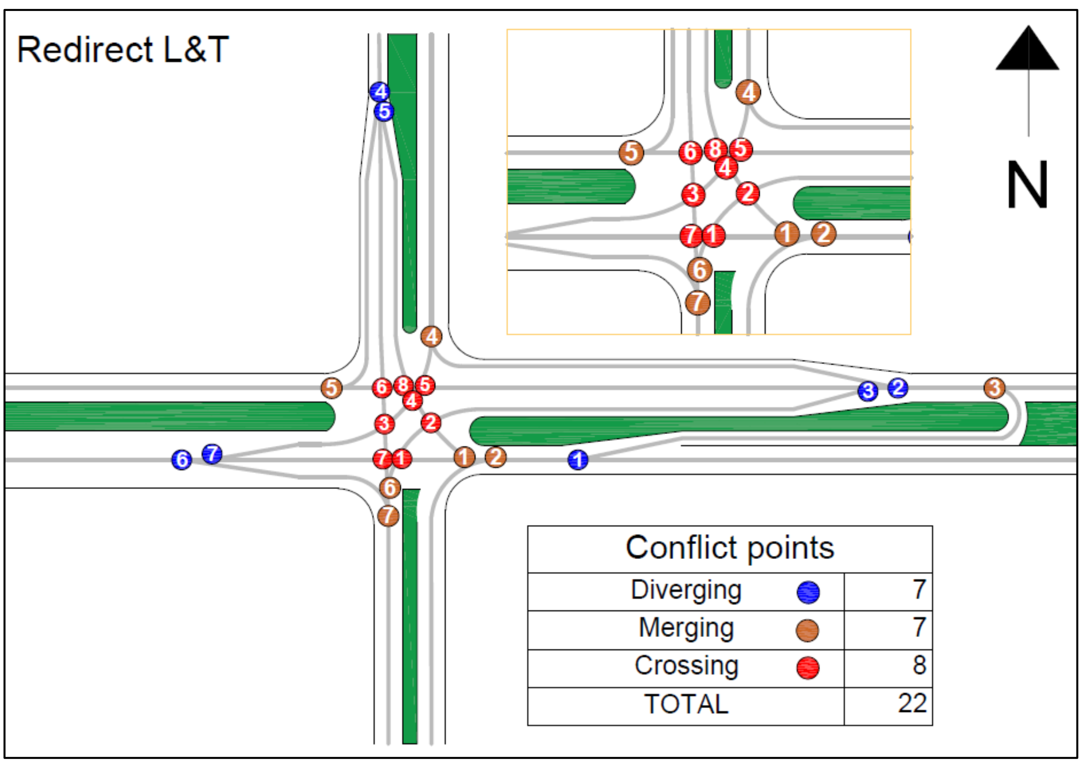

Figure 3.9 Redirect L&T Conflict Point Diagram

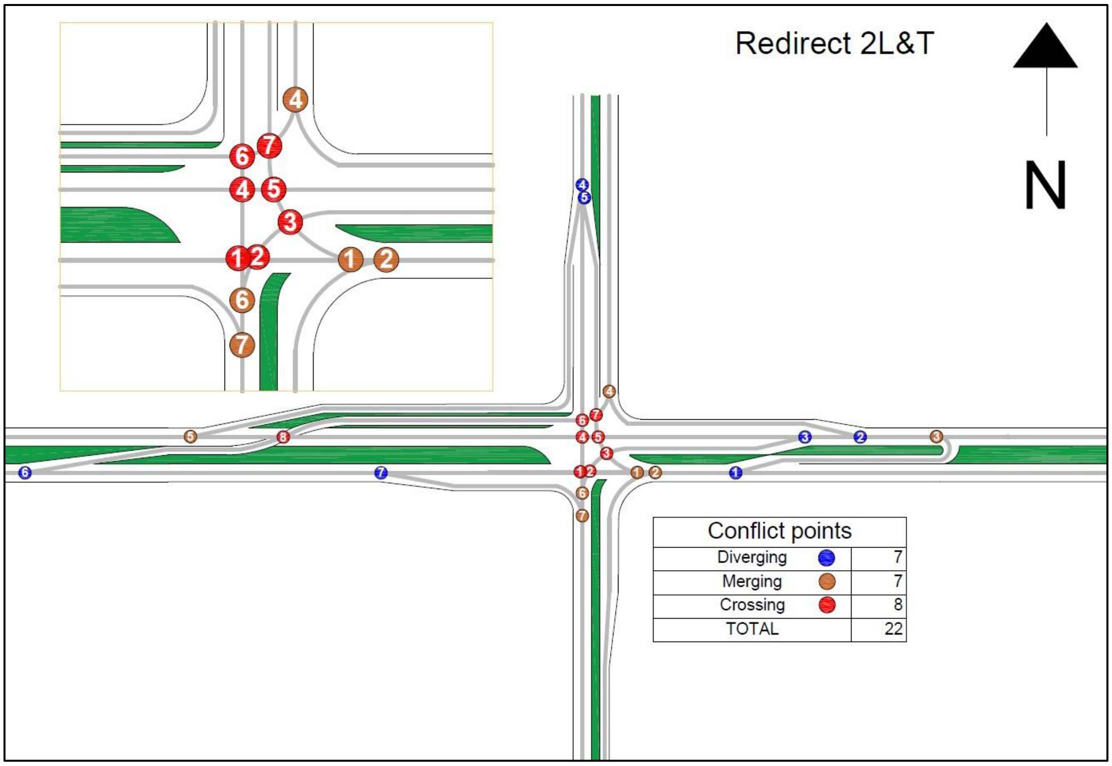

Figure 3.10 Redirect 2L&T Conflict Point Diagram

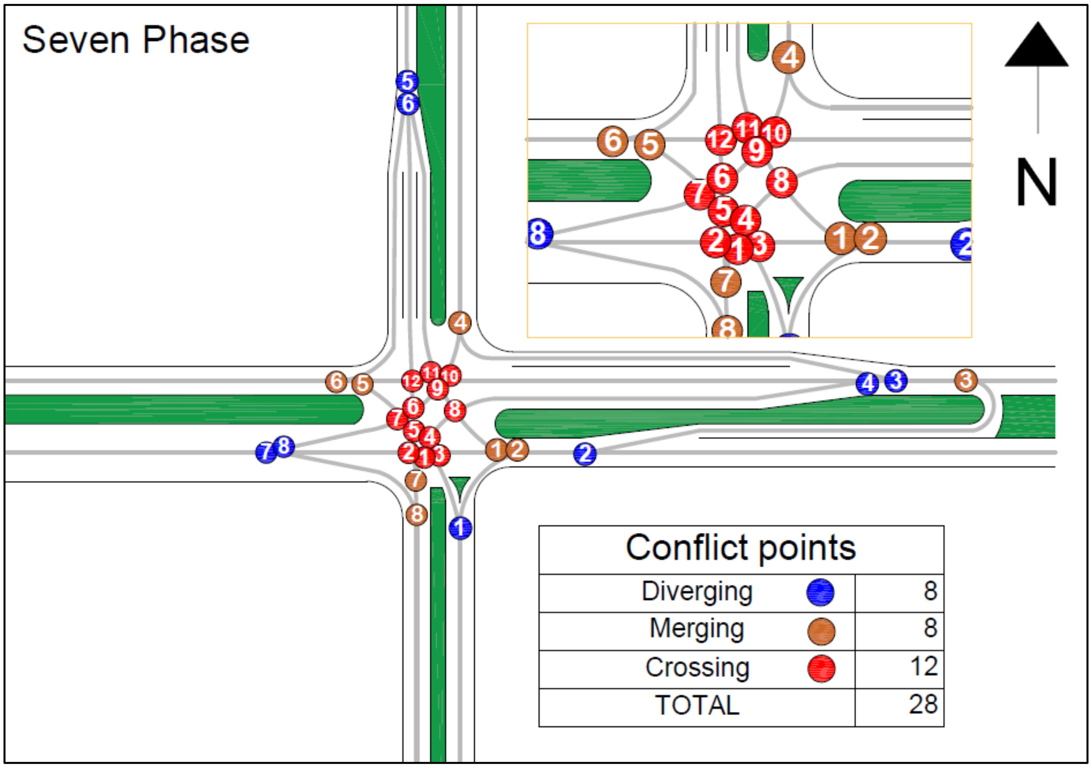

Figure 3.11 Seven-Phase Conflict Point Diagram

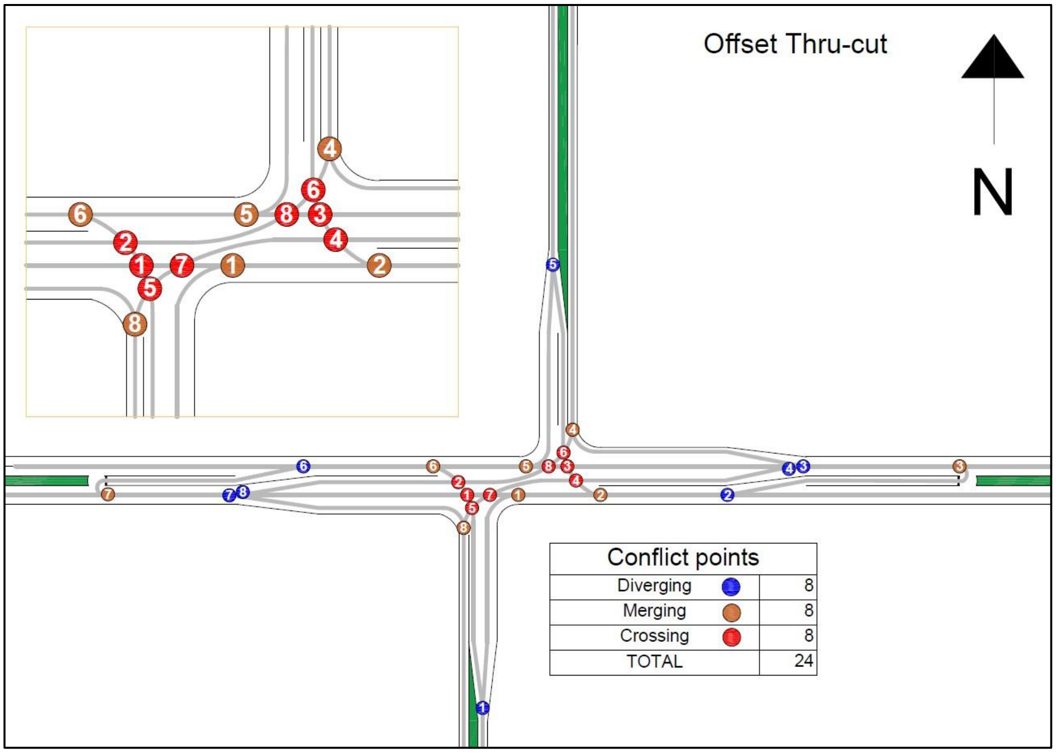

Figure 3.12 Offset Thru-Cut Conflict Point Diagram

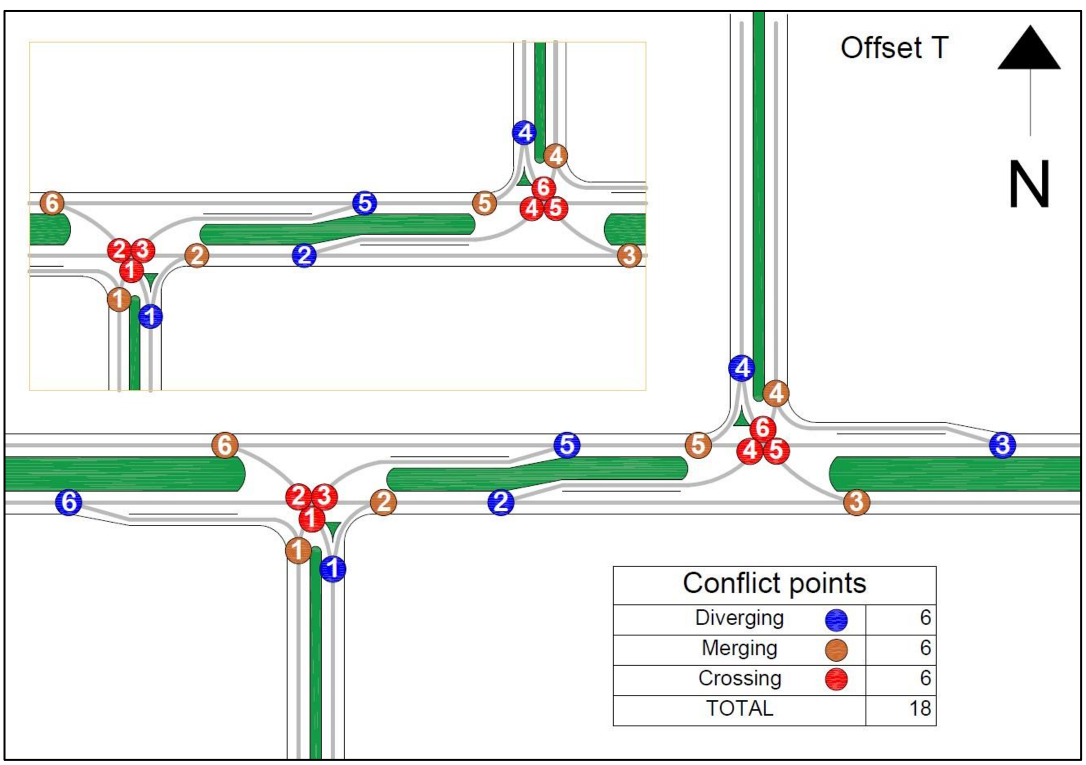

Figure 3.13 Offset T Conflict Point Diagram

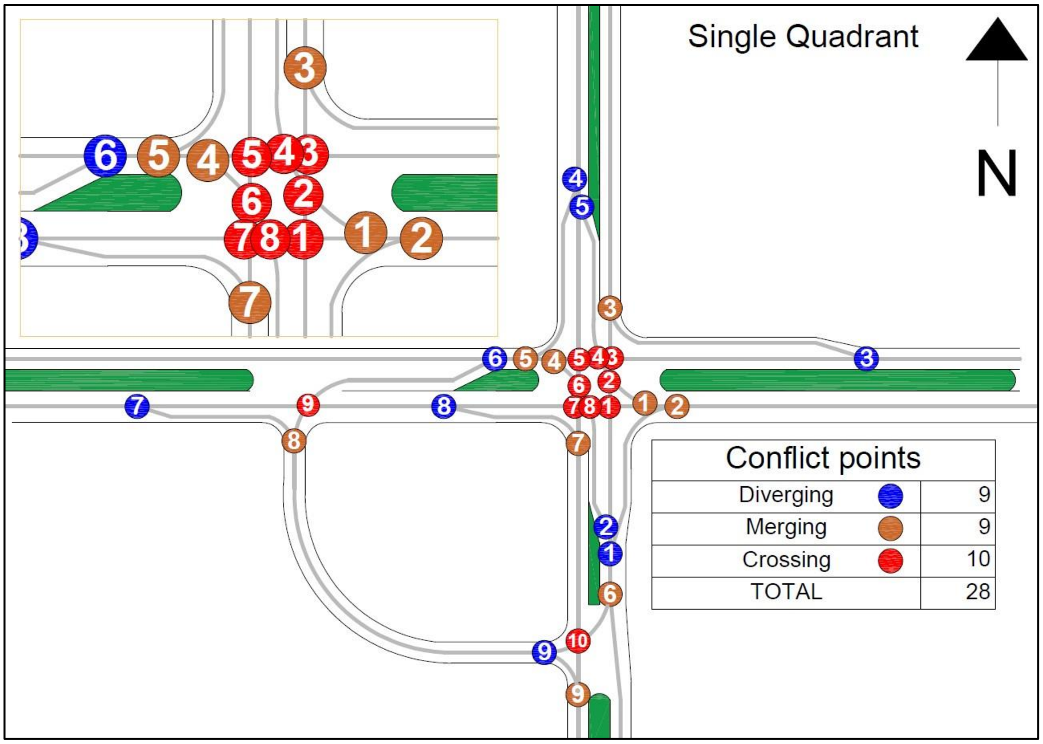

Figure 3.14 Single Quadrant Conflict Point Diagram

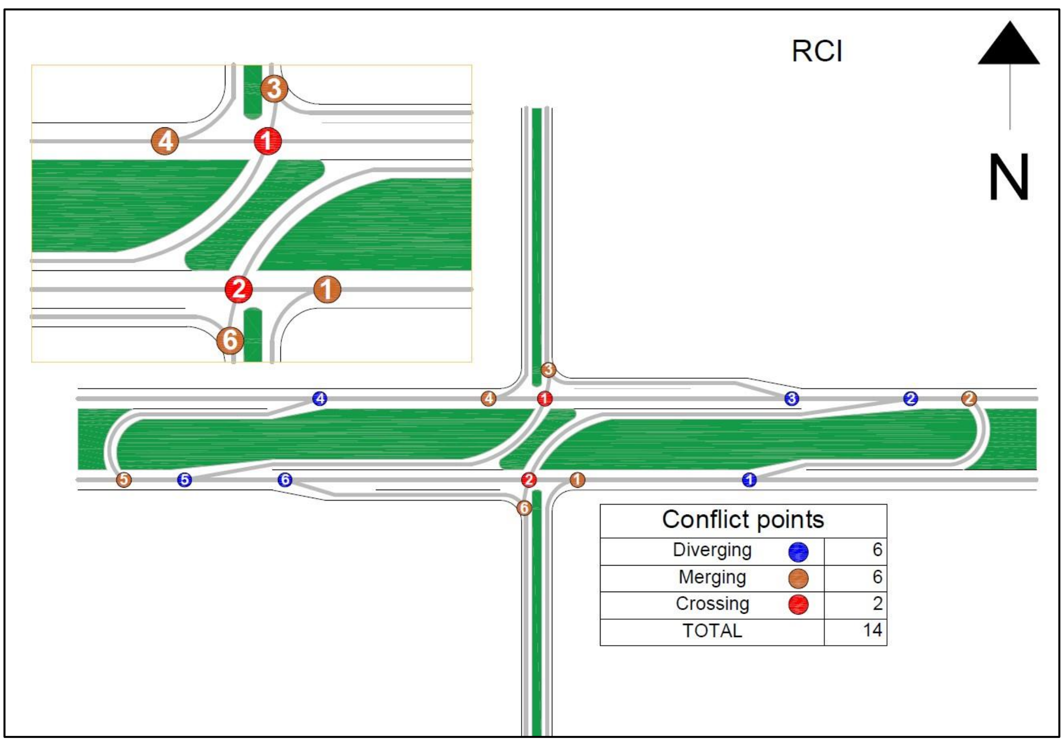

Figure 3.15 RCI Conflict Point Diagram

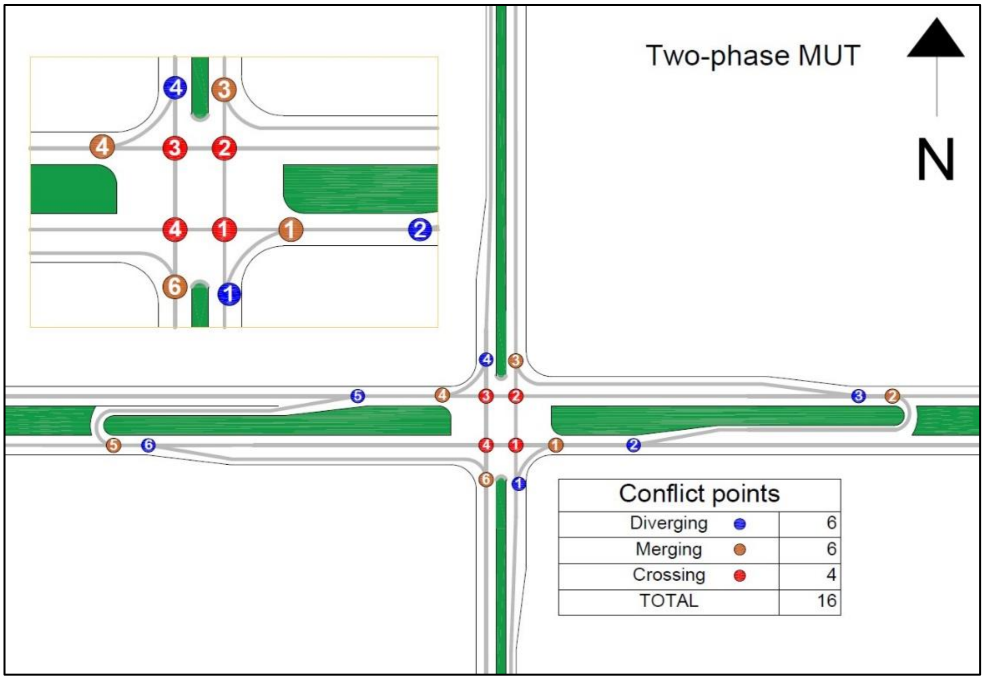

Figure 3.16 Two-Phase MUT Conflict Point Diagram

3.3.4 Flag Method for Pedestrians and Bicycles

The NCHRP Report 948 (2021) developed the evaluation technique known as the "20 Design Flags" to analyze intersection design elements regarding pedestrian and bicyclist safety. This approach allows designers to improve intersection safety for pedestrians and bicyclists during project development. By utilizing yellow and red flag thresholds, which consider various factors, and evaluating the percentage of flags, this method enables comparison between different intersection designs. Yellow flags represent a concern related to users' comfort, while red flags represent a safety concern for pedestrians and bicyclists.

This section presents the methodology for evaluating sixteen alternative intersection models using the 20 Design Flags. Out of the 20 flags outlined in the NCHRP 948 report, thirteen were used for the pedestrian safety assessment, while sixteen were utilized for the bicyclists' safety assessment. This resulted in fifty-two (52) and sixty-four (64) possible design flags, respectively, considering all four pedestrian and bicyclist movements for each design flag. Several assumptions were made during the completion of this 20 Design Flags assessment:

1. **Vehicle Turning Speed:** For flag 1 (motor vehicle right turns) and flag 10 (motor vehicle left turns), the vehicle turning speed was assumed to be less than 20 mph for all the intersections assessed. Although a speed of more than 20 mph might be expected for free-flow right-turn movements with larger curb radii, most drivers should have speeds below 20 mph on right turns at the eight intersections selected.
2. **Assessment of Flag 9 (Undefined Crossing at Intersections):** The conditions of the existing crossings for the conventional intersections were maintained for all the proposed alternative intersections at each assessed site.

3. **Bicyclist Safety Assessment:** It was assumed that bicyclists shared the use of paths with pedestrians at crossings and had a separate bike lane. In the analysis, bicycle through movements from each approach was only considered resulting in 64 flags (16x4).

3.4 Public Acceptance at Alternative Intersections

3.4.1 Factors Impacting Public Acceptance

The Public Acceptance Scoring System (PASS) at Alternative Intersections aims to assist decision-makers and designers in comparing alternatives based on expected public acceptance. In order to better understand how to address relevant issues regarding the public acceptance of alternative intersections, PASS includes a list of variables collected mostly from the current literature on public acceptance of alternative designs. These variables were categorized into three groups: driver confusion/wrong way potential, business impacts and resident discomfort, and pedestrian and cyclist discomfort. Using these categories as a baseline, the research team highlighted factors that impact these categories, and what those specific impacts were. This process was a crucial first step in developing the PASS system as it allowed us to focus on the main concerns the public has about alternative intersections.

3.4.2 Focus Group Meetings

In developing the PASS, the research team had four (4) focus group meetings with experts from different units of NCDOT to receive feedback on the selection of the appropriate variables from the list, rank the variables based on their significance to the public and assign appropriate weightage to each. The NCDOT members included the following experts, who were grouped into four (4) teams based on their respective units and area of expertise, along with the dates when the meetings were held (in parenthesis):

Group 1 – (**April 4th, 2024)**

- Dr. Joe Hummer, Traffic Management Unit.
- Mr. Clarence B. Bunting, Congestion Management Unit.
- Mr. Nicholas C. Lineberger, Congestion Management Unit.
- Mr. Michael P. Reese, Congestion Management Unit.

Group 2 – **(April 12th, 2024)**

- Ms. Michelle H. Gaddy, Construction Unit.
- Mr. David Olson, Congestion Unit.
- Ms. Renee B. Roach, Signing and Delineation Unit.

Group 3 – (**April 15th, 2024)**

- Mrs. Tatia L. White, State Roadway Design Engineer.
- Mr. Mike Lindgren, Roadway Design Unit.
- Mr. David Clodgo, Roadway Design Unit.
- Mr. Jordan Woodard, Design Development & Support Group Lead.

Group 4 – (**April 17th, 2024)**

- Mr. Jamille Robbins, Public Involvement, Community Studies & Visualization Unit.
- Ms. Diane Wilson, Public Involvement, Community Studies & Visualization Unit.

Eight questions were asked to the NCDOT experts during these meetings. These questions prompted the experts to identify from a list of variables that could impact wrong-way potential, user comfort, and businesses. Additionally, experts were asked to suggest the removal or inclusion of variables deemed unnecessary or important additions to the list. Moreover, experts were asked to assign weights to the listed variables, with each designated a color (red, brown, and yellow) to signify their importance.

3.4.3 Public Acceptance Scoring System (PASS) for Alternative Intersections

Using the factors discussed with the experts from NCDOT, the research team developed a spreadsheet that compares and ranks alternative designs based on estimated public acceptance. Drawing from past studies and literature reviews, this spreadsheet outlines 16 variables influencing public acceptance, categorized into measurable and binary variables, each assigned a color (Red, Brown, and Yellow) to denote differences. Measurable variables are quantifiable, while binary variables rely on engineering judgement. PASS focuses on user perceptions of new alternatives rather than safety and operational performance, highlighting its significance in understanding public sentiment towards these intersection designs. This spreadsheet is available as Appendix 4.

3.5 Benefit over Cost (B/C) Analysis

The research team met with Dr. Hummer on June 27, 2024 to discuss the best approach for estimating ROW costs. During this conversation, it was agreed upon that the NCDOT standard value of $12.75 per hour of travel time reduction was an acceptable value to use for this analysis. The research team was also provided with contact information for the NCDOT ROW unit. Based on discussion with NCDOT ROW unit, it was stated that ROW costs are extremely site specific and difficult to assess without a professional appraiser. Ultimately, a simple solution of using recent real estate sales near the case study sites was recommended by the NCDOT ROW unit.

Using the guidance provided by NCDOT ROW unit, the research team analyzed the values of adjacent properties using the real estate website Zillow. Five adjacent properties were selected for each case study intersection and the average cost per acre was calculated. This value was then compared to the estimated amount of cost savings from the travel time reductions of every alternative design that was simulated at each case study site. These results are shown in Section 4.5 of this report.

Of note, for the cost portion of this analysis, only ROW and travel time savings were considered. The following cost consideration were not considered in this analysis:

- Construction costs
  - Pavement
  - Striping
  - Temporary increase in travel times due to closed lanes
  - Business impacts
  - Project delays
- Installation of signals, signs, and barriers as shown in the condition diagrams

3.6 Framework for Selecting Alternative Intersections

Ultimately, based on the results of the study, the research team prepared a framework to guide state DOTs, including NCDOT, in implementation of new alternative intersections in future intersection improvement projects. This framework combines all of the elements of this report into a methodology for selecting the best alternative designs for a given intersection. The development of this framework was the ultimate objective of this research project.

Chapter 4 Results and Discussion

This chapter elaborates on the results of the study and proposes a framework (guideline) for the future implementation of alternative intersections with three-critical-phase traffic signals.

4.1 Traffic Operational Analysis

As the first part of chapter 4, traffic operational analysis conducted on hypothetical scenarios and case study sites is presented in the following sections.

4.1.1 Hypothetical Simulation Scenarios

4.1.1.1 Traffic Signal Optimization

Table 4.1 displays the average cycle length estimated from signal optimization. Note that single quadrant and offset T intersections were not included in the simulation modeling as there are available reports regarding their traffic operations (Reid and Hummer, 2020; Cunningham et al. 2021). The signal optimization analysis results (Table 4.1) indicated that the seven-phase intersection design had the longest average cycle length. This is primarily due to the presence of all four left-turn movements at the middle intersection and the minimal redirection of traffic (only one minor through movement is redirected from the middle intersection). Moreover, the redirected through movement (NB through in our study) now turns right at the middle intersection, which decreases saturation flow since turning movements have lower saturation flow rates than through movements. Therefore, due to the strong relationship between cycle length and saturation flow, a longer cycle length is expected for the seven-phase design compared to a conventional design.

Table 4.1 The Average Cycle Length (sec) on the Networks for Various Turning Cases

Intersection Type	Turning Cases			
	All	High	Moderate	Low
Conventional	98	98	94	103
Redirect L&T	94	90	92	102
Seven-Phase	133	125	135	140
Reverse RCI	84	83	85	85
Offset Thru-cut	76	75	73	80
Thru-cut	73	70	70	78
MUT #1	82	90	78	78
MUT #2	97	88	95	108
Redirect 2L&T	90	80	90	100
CFI/MUT Combo	60	60	60	60
Partial CFI	60	60	60	60
RCI	73	73	73	73
Two-Phase MUT	66	65	65	68

As expected, the conventional intersection also resulted in a long average cycle length among all intersection designs. The CFI/MUT and partial CFI intersections demonstrated the shortest average cycle lengths, a result attributed to their higher capacity. The redirect 2L&T design had relatively one of the longest cycle lengths among all three-phase designs. This can be explained three possible ways: 1) it has a conventional left-turn route on the major road, 2) each minor leg has its own signal phase serving all three traffic (left, through, and right) demands in one phase, and 3) one of the minor through movements is converted to a right turn at the middle intersection, which reduces the saturation flow on that minor leg. Despite the longer cycle lengths, the impact

on traffic operations on the major road at redirect 2L&T should be minimal, as two of the major critical movements receive green indications during two phases.
The two-phase MUT design had the shortest average cycle length among all the intersections studied other than the CFIs, as it has two phases with no left-turn movements at the middle intersection. In contrast, MUT #2 had the longest cycle length among the three-phase alternative intersections. This is likely because its third signal phase is accommodating all traffic demands (left turns, right turns, and through movements) from the minor road. Consequently, the green time needed for this signal phase was relatively longer than other three-phase designs.

Table 4.2 presents the average green over cycle length (g/cl) ratios for each node based on all tests included. Note that the yellow intervals are included in the green intervals. The partial MUT and RCI designs exhibited the highest g/cl ratios for through traffic on the major road, which is expected since both designs have two signal phases at the middle intersection. In contrast, the other alternative designs and the conventional design have three and four signal phases, respectively, at the middle traffic signal.

Table 4.2 The average green over cycle length (g/cl) ratios of traffic signals based on Synchro

Intersection Type	Western Crossover [c]		Middle Intersection						Eastern Crossover	
	Thru Traffic	Cross-over	Major Road (EB/WB)			Minor Road (NB/SB)			Thru Traffic	Cross-over
			Left	Thru	Right	Left	Thru	Right		
Conventional	-	-	0.14	0.43	0.43	0.10	0.24	0.24	-	-
Redirect L&T	-	-	0.24	0.51	0.62	0.23 [a]	0.23 [a]	0.30	0.63	0.33
Seven-Phase	-	-	0.17	0.42	0.50	0.25	0.21 [a]	0.27	0.65	0.28
Reverse RCI	0.52	0.44	NA [b]	0.55	FF [e]	0.12	NA	0.25	0.60	0.36
Offset Thru-cut	0.59	0.34	0.24	0.53	0.53	0.13	NA	0.24	0.64	0.29
Thru-cut	0.57	0.36	0.30	0.50	0.62	0.13	NA	0.30	0.63	0.30
MUT #1	0.66	0.29	NA	0.40	0.65	0.26	0.28	0.28	0.74	0.20
MUT #2	0.76	0.20	0.23	0.47	0.47	NA	0.25	0.48	0.80	0.16
Redirect 2L&T	0.71	0.24	0.58	0.45	0.35	0.25	0.25	0.25 [g]	0.53	0.42
CFI/MUT Combo	0.58 [f]	0.30	NA	0.39 [d]	0.28	0.16	0.36	0.36 [g]	0.62 [f]	0.35
Partial CFI	0.58	0.30	NA	0.39 [d]	0.16	0.16	0.36	FF	0.56	0.37
RCI	0.54	0.41	0.40	0.54	0.54	NA	NA	0.40	0.58	0.37
Two-Phase MUT	0.59	0.35	NA	0.59	0.59	NA	0.35	0.35	0.68	0.26

The g/cl ratios (yellow interval is also included in green) are based on all the 18 scenarios included (with all turning cases)
[a] The ratios are based on only one minor street (the same movements have been redirected on the other side)
[b] Not Applicable (the traffic movement has been redirected)
[c] Crossover will be the traffic on the U-turn or the CFI crossover
[d] The g/cl ratio for the redirected left-turn demand on the major road will also be equal to 0.39
[e] FF = Free-flow Traffic Movement
[f] The CFI and MUT crossovers were considered as western and eastern crossovers of the CFI/MUT combo
[g] Only on one side of the road (right turns have free-flow movement on the other side of the road)

The offset thru-cut design also had one of the highest g/cl ratios for through traffic on the major road at the middle intersection. This is expected, as through traffic movements on the major road receive a green signal in two phases in the offset thru-cut design. Additionally, Table 4.2 reveals that some three-phase designs, such as MUT redirected major (MUT #1) and MUT redirected minor (MUT #2), offer a longer g/cl ratio for through traffic at the U-turn crossovers compared to the two-phase designs, as they redirect less traffic than the two-phase designs to the U-turn crossovers.

When comparing the partial CFI and CFI/MUT combo, both designs showed similar g/cl ratios at the western DLT crossover and the middle intersection. However, the CFI/MUT combo achieved higher g/cl ratios for through traffic on the eastern crossover, possibly due to the reduced traffic demands compared to a partial CFI. Specifically, while the CFI/MUT only involves one major through and one major left turn at its U-turn crossover, the partial CFI accommodates these demands in addition to one minor right (from NB in our study) and one minor left (from SB) at its eastern DLT crossover. Moreover, the g/cl ratio for the right-turn lanes on the major road at the CFI/MUT combo is higher than that of the partial CFI design. This is because there is no conflict between right-turn vehicles and the oncoming left-turn traffic on one side of the major road at the middle intersection. On the other hand, the partial CFI provides free-flow movement for both minor right-turn demands.

4.1.1.2 Traffic Operations Analysis

Table 4.3 presents average vehicle travel times (sec), maximum queue lengths (feet), and average number of vehicle stops derived from the simulation model. It should be mentioned that all designs could complete their simulation tests with similar traffic output as their traffic input. Tables 4.4 and 4.5 also display the results of the ANOVA and the mean travel time differences among all intersections included in the study.

Table 4.3 Travel Times, Vehicle Stops and Queue Lengths

Turning Cases	High Turning			Moderate Turning			Low Turning			Overall		
Intersection Type	Ave Travel Time	Max Queue	Ave Stops	Ave Travel Time	Max Queue	Ave Stops	Ave Travel Time	Max Queue	Ave Stops	Ave Travel Time	Max Queue	Ave Stops
Conventional	220	1,367	1.18	168	945	1.00	153	968	0.78	181	1,094	0.98
Redirect L&T	174	604	1.45	171	624	0.97	175	861	1.61	**173**	696	1.42
Seven-Phase	198	1,525	1.77	193	1,542	1.78	212	1,556	2.23	201	1,541	1.92
Reverse RCI	166	531	0.60	161	371	0.40	**155**	405	0.41	161	436	0.47
Offset Thru-cut	161	360	0.72	154	393	0.60	**155**	391	0.59	156	381	0.63
Thru-cut	159	607	0.62	157	517	0.64	157	552	0.66	158	558	0.64
MUT #1	163	652	0.63	156	538	0.61	149	377	0.62	156	522	0.62
MUT #2	186	908	1.46	174	898	1.19	172	817	0.94	**177**	874	1.20
Redirect 2L&T	161	1,426	1.36	159	1,296	1.37	161	1,334	1.28	160	1,335	1.33
CFI/MUT Combo	159	938	0.83	142	459	0.64	145	965	0.76	149	787	0.74
CFI	162	1,127	0.96	141	665	0.80	156	1,419	1.01	153	1,070	0.92
RCI	162	783	0.91	156	544	0.73	152	329	0.64	156	549	0.72
Two-Phase MUT	174	865	1.30	160	675	0.98	150	499	0.78	162	680	1.02

Bold represents the insignificant travel time differences in comparison with the conventional design at the 0.05 level

According to Tables 4.3, 4.4, and 4.5, overall, all alternative designs resulted in shorter travel times than the conventional intersection, except for the seven-phase design. Mean travel time differences were also found to be insignificant for MUT #2 and redirect L&T compared to the conventional intersection. However, both these designs resulted in shorter travel times than the conventional design in high turning traffic conditions. In other words, while the performance of the conventional intersection was found to be similar to alternative designs (and better than a few of them) in low-turning conditions, it is not a promising intersection design in traffic conditions with higher turning ratios. Regarding the average number of stops, some alternative designs resulted in a higher number of stops than the conventional intersection, possibly due to having one or two additional traffic signals compared to the conventional design.

Table 4.4 Travel Time Differences and the Results of ANOVA for Conventional, Reverse RCI, Offset Thru-Cut, Thru-cut, and MUT Redirect Major (Partial MUT#1)

Intersection Type	Compares with…	Mean Difference (sec/veh)	F	P Value
Conventional	Redirect L&T	7.2	0.853	**0.358**
	Seven-Phase	-20.7	8.927	0.003
	Reverse RCI	19.6	8.126	0.005
	Offset Thru-cut	24.3	11.52	0.001
	Thru-cut	22.7	10.098	0.002
	MUT #1	24.6	11.817	< 0.001
	MUT #2	3.1	0.095	**0.758**
	Redirect 2L&T	19.4	8.006	0.006
	CFI/MUT Combo	31.7	20.397	< 0.001
	CFI	27.6	13.798	< 0.001
	RCI	24.1	11.309	0.001
	Two-Phase MUT	18.9	7.316	0.008
Reverse RCI	Offset Thru-cut	4.7	11.201	0.001
	Thru-cut	3	4.078	0.047
	MUT #1	5.1	9.204	0.003
	MUT #2	-16.6	113.903	< 0.001
	Redirect 2L&T	-0.2	0.039	**0.842**
	CFI/MUT Combo	12	41.395	< 0.001
	CFI	8	8.229	0.005
	RCI	4.5	8.429	0.004
	Two-Phase MUT	-0.7	0.127	**3.977**

Intersection Type	Compares with…	Mean Difference (sec/veh)	F	P Value
Offset Thru-Cut	Thru-cut	-1.6	2.196	**0.142**
	MUT #1	0.4	0.165	**0.685**
	MUT #2	-21.2	207.089	< 0.001
	Redirect 2L&T	-4.9	19.197	< 0.001
	CFI/MUT Combo	7.4	23.978	< 0.001
	CFI	3.3	4.015	0.048
	RCI	-0.2	0.025	**0.873**
	Two-Phase MUT	-5.3	6.267	0.014
Thru-cut	MUT #1	2	3.204	**0.077**
	MUT #2	-19.6	184.679	< 0.001
	Redirect 2L&T	-3.2	7.844	0.006
	CFI/MUT Combo	9	34.02	< 0.001
	CFI	5	4.518	0.037
	RCI	1.4	2.226	**0.14**
	Two-Phase MUT	-3.7	2.709	**0.104**
MUT #1	MUT #2	-21.6	166.951	< 0.001
	Redirect 2L&T	-5.2	13.166	< 0.001
	CFI/MUT Combo	7	17.682	< 0.001
	CFI	3	1.495	**0.225**
	RCI	-0.6	0.243	**0.623**
	Two-Phase MUT	-5.7	6.308	0.014

Bold represents the insignificant travel time differences in comparison with the conventional design at the 0.05 level
Travel time reductions (compared to the other designs) are highlighted in gray

Table 4.5 Travel Time Differences and the Results of ANOVA for Seven-Phase, Redirect L&T, Redirect 2L&T, CFI/MUT Combo, Partial MUT#2, CFI, and RCI

Intersection Type	Compares with…	Mean Difference (sec/veh)	F	P Value	Intersection Type	Compares with…	Mean Difference (sec/veh)	F	P Value
Seven-Phase	Reverse RCI	40.3	245.366	< 0.001	Redirect 2L&T	CFI/MUT Combo	12.2	48.434	< 0.001
	Offset Thru-cut	45	314.3	< 0.001		CFI	8.2	9.363	0.003
	Thru-cut	43.3	296.896	< 0.001		RCI	4.7	13.282	< 0.001
	MUT #1	45.3	291.933	< 0.001		Two-Phase MUT	-0.5	0.062	**0.802**
	MUT #2	23.7	71.496	< 0.001	CFI/MUT Combination	CFI	-4	3.041	**0.085**
	Redirect 2L&T	40.1	257.333	< 0.001		RCI	-0.76	22.874	< 0.001
	CFI/MUT Combo	52.3	324.79	< 0.001		Two-Phase MUT	-12.7	30.754	< 0.001
	CFI	48.3	250.246	< 0.001	CFI	RCI	-3.5	2.285	**0.135**
	RCI	44.8	300.22	< 0.001		Two-Phase MUT	-8.7	7.662	0.007
	Two-Phase MUT	39.6	189.786	< 0.001	RCI	Two-Phase MUT	-5.1	5.362	0.023
Redirect L&T	Seven-Phase	-27.9	121.322	< 0.001	MUT #2	Redirect 2L&T	16.3	130.181	< 0.001
	Reverse RCI	12.4	146.307	< 0.001		CFI/MUT Combo	28.6	194.027	< 0.001
	Offset Thru-cut	17.1	424.285	< 0.001		CFI	24.5	84.598	< 0.001
	Thru-cut	15.5	392.786	< 0.001		RCI	21	182.4	< 0.001
	MUT #1	17.4	230.744	< 0.001		Two-Phase MUT	15.9	63.805	< 0.001
	MUT #2	-4.1	7.9686	0.006					
	Redirect 2L&T	12.2	210.225	< 0.001					
	CFI/MUT Combo	24.5	212.701	< 0.001					
	CFI	20.4	73.405	< 0.001					
	RCI	16.9	302.015	< 0.001					
	Two-Phase MUT	11.7	53.964	< 0.001					

Bold represents the insignificant travel time differences in comparison with the conventional design at the 0.05 level
Travel time reductions (compared to the other designs) are highlighted in gray

Tables 4.3, 4.4, and 4.5 show that the CFI/MUT combo and partial CFI had the best travel time performance, resulting in significantly shorter average travel times than all other intersection designs at a 0.05 confidence level. Furthermore, the CFI/MUT combo performed slightly better than the partial CFI in terms of maximum queue lengths and the average number of stops. The superior performance of the partial CFI aligns with previous studies (Hummer and Molan, 2022; Steyn et al., 2014) which indicated that CFIs generally have one of the highest capacity levels among all existing intersection designs. For the CFI/MUT combo, several factors may contribute to its performance being on par with the partial CFI, including: 1) similar V/C (volume over capacity) ratios at nodes, 2) higher g/cl ratio for through traffic at one of CFI/MUT's node compared to partial CFI, 3) smoother flow at the diverging point between through and left-turn traffic on one side of the major road (WB in our study), and 4) the left-turn traffic on one side of the minor road (SB in our study) would have one signal fewer on their route compared to a partial CFI.

In addition to CFI/MUT combo and partial CFI, four other three-phase designs (MUT #1, offset thru-cut, thru-cut, and reverse RCI) not only performed similarly to the two-phase designs (RCI and the two-phase MUT) in low and moderate turning cases, but they also exhibited better travel time performance and shorter queues than the two-phase MUT in high-turning traffic conditions. The following paragraphs elaborate on the possible reasons behind the identified traffic performance results for three-phase intersection design.

Overall, CFI/MUT combo, partial CFI, offset thru-cut, thru-cut, MUT redirect major (MUT #1), and RCI demonstrated the best performance among all intersection designs considered. Following them, redirect 2L&T, reverse RCI and two-phase MUT resulted in the second-best traffic performance, but with (statistically significantly) longer travel times compared to the top performers. The initial hypothesis in this research assumed that three-phase designs would yield some of the benefits of two-phase designs. They did, but we did not anticipate that three-phase designs might deliver similar or even better benefits than the two-phase MUT. Hence, the potential of three-phase designs was found to be greater than expected. Next section will elaborate more on these possible reasons for the excellent performance of three-phase designs.

4.1.1.3 Possible Reasons for the Potential of Three-phase Designs

This section will elaborate on some possible reasons for the high potential of three-phase intersections. Since the geometric features and right-of-way (ROW) sizes of partial CFIs, CFI/MUT combinations are different from other alternative designs, the research team has divided the discussions into two groups in this section: 1) intersections with only U-turn crossovers, and 2) Partial CFI and CFI/MUT combination.

Group 1: Intersections with only U-turn crossovers

Possible reasons for the high potential of the first group (offset thru-cut, thru-cut, MUT #1) include:

a. U-turn crossovers are the critical nodes in two-phase designs. Thus, reducing U-turn demands can improve network performance.
b. At two-phase intersections, there is a trade-off between eliminating an additional signal phase and the increased travel distances for a larger portion of redirected traffic. Ultimately, both factors can yield similar network benefits in some traffic scenarios.

c. Previous studies (Hummer and Molan 2022) have also shown that two-phase designs (such as the two-phase MUT) may not perform well at locations with high turning traffic demands.
d. Traffic signal performance in some three-phase intersections, (such as thru-cut and offset thru-cut designs) were found to be similar to those in two-phase designs.

Further explanations of each of these possible reasons are provided in the following paragraphs:

a. U-turn crossovers are the critical nodes in two-phase designs; thus, reducing U-turn demands can improve network performance:

Table 4.6 shows V/C ratios estimated using the CLV method. Table 4.6 shows that while two-phase designs have relatively low V/C ratios at the middle signals, their critical node is the eastern U-turn crossover. For example, under high-turning conditions, the two-phase MUT had a V/C ratio of about 0.64, equivalent to a level of service (LOS) of A (Maji 2013); but its V/C ratio at the eastern U-turn crossover was 0.81 (LOS=D). In contrast, MUT #1 had V/C ratios of 0.69 (LOS=B) and 0.72 (LOS=C) at the middle and U-turn nodes.

Table 4.6 Volume to Capacity (V/C) Ratios at Different Signals for Various Turning Cases

Intersection Type	Turning Cases											
	High			Moderate			Low			Overall		
	West Signal	Main Signal	East Signal	West Signal	Main Signal	East Signal	West Signal	Main Signal	East Signal	West Signal	Main Signal	East Signal
Conventional	NA [a]	**0.90**	NA	NA	**0.90**	NA	NA	**0.90**	NA	NA	**0.90** [b]	NA
Redirect L&T	NA	0.61	**0.82**	NA	0.67	**0.79**	NA	0.74	**0.76**	NA	0.67	**0.79**
Seven-Phase	NA	**0.82**	0.74	NA	**0.81**	0.74	NA	**0.80**	0.74	NA	**0.81**	0.74
Reverse RCI	0.77	0.73	**0.88**	0.70	0.71	**0.82**	0.65	0.69	**0.78**	0.71	0.71	**0.83**
Offset Thru-cut	0.58	**0.78**	0.74	0.59	0.73	**0.74**	0.60	0.70	**0.74**	0.59	0.74	**0.74**
Thru-cut	0.58	**0.78**	0.74	0.59	0.73	**0.74**	0.60	0.70	**0.74**	0.59	0.74	**0.74**
MUT #1	0.61	0.69	**0.72**	0.51	**0.73**	0.63	0.45	**0.76**	0.57	0.52	**0.73**	0.64
MUT #2	0.50	0.73	**0.74**	0.45	**0.76**	0.64	0.42	**0.78**	0.58	0.46	**0.76**	0.66
Redirect 2L&T	0.80	**0.79**	0.75	0.68	**0.79**	0.69	0.60	**0.78**	0.65	0.69	**0.78**	0.69
CFI/MUT Combination [c]	0.65	**0.67**	0.54	0.59	**0.72**	0.47	0.56	**0.76**	0.43	0.60	**0.72**	0.48
CFI	0.65	**0.67**	0.59	0.59	**0.72**	0.50	0.56	**0.76**	0.44	0.60	**0.72**	0.51
RCI [d]	0.66	0.55 0.47	**0.82**	0.64	0.58 0.47	**0.79**	0.63	0.61 0.49	**0.76**	0.64	0.58 0.47	**0.79**
Two-Phase MUT	0.69	0.64	**0.80**	0.56	0.68	**0.68**	0.47	**0.72**	0.60	0.57	0.68	**0.69**

[a] Not Applicable (The design does not have the U-turn)
[b] Boldrepresents the maximum V/C ratio of the intersection designs for various turning cases
[c] The CFI crossover was considered as the West Signal, while the U-turn is the East Signal
[d] RCI has two traffic signals in the middle of its network (Overall, RCI has four traffic signals)

A similar trend can be seen in Table 4.2 for g/cl ratios: two-phase designs provide the highest g/cl ratios on the major road at the middle intersection, but most three-phase designs have higher g/cl ratios for through traffic at U-turn crossovers than two-phase designs. This indicates that two-phase designs might direct too much traffic to U-turns when it is not necessary to do so given the acceptable performance at their middle intersections. Conversely, three-phase designs like MUT redirect major (MUT #1) can reduce demand at U-turn crossovers, leading to a better balance of traffic distribution across the network. The higher portion of redirected traffic at two-phase MUT intersections could also be a possible reason for the higher number of stops compared to conventional and five of the alternative designs.

b. At two-phase designs, there is a trade-off between eliminating an additional signal phase and the increased travel distances for a larger portion of redirected traffic:

An analysis of travel times per traffic movement revealed a trade-off between the benefits of removing an additional phase (reducing from three phases to two) and the extra travel time (and distance) required for a larger portion of redirected traffic. To explore this further, Figure 4.1 compares the travel time performance of the two-phase MUT and MUT redirect major (MUT #1), while Figure 4.2 presents vehicle travel times per traffic movement on both major and minor roads at intersections studied.

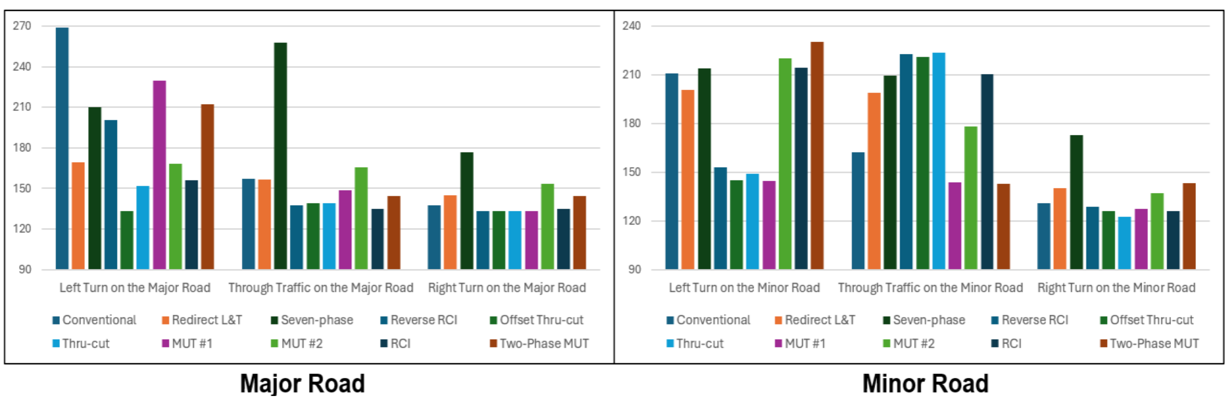

Figure 4.1 Vehicle Travel Times per Traffic Movement

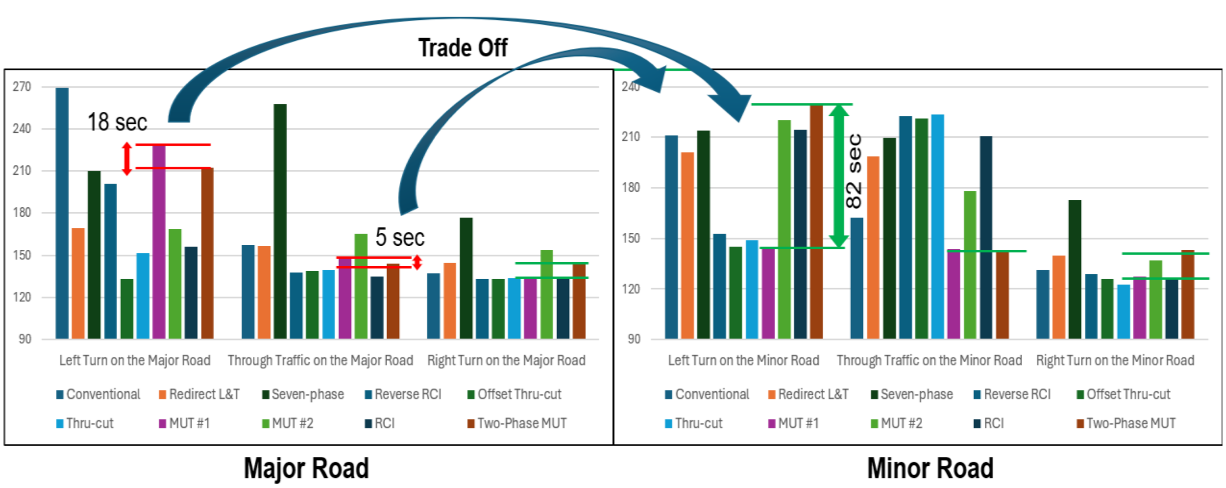

Figure 4.2 Travel Time Comparison Between Two-Phase MUT and Three-Phase MUT#1

c. Two-phase designs may not perform well at locations with high turning traffic demand

Regarding the third possible reason, previous studies have shown concerns for two-phase MUT intersections at locations with higher turning traffic demands (Howard et. al, 2023; Hummer and Molan, 2022; Bared and Kaisar, 2002). For example, Hummer and Molan (2022), found that a left-turn to through traffic (L/T) ratio of 0.5 was the threshold for satisfactory performance in a full MUT. At higher L/T ratios, they found similar travel times and V/C ratios to those of conventional intersections for full MUTs. Similar to the results shown in Table 4.3, Bared and Kaisar (2002) observed significant travel time savings at two-phase MUT intersections compared to conventional designs when left turns made up 10-20% of the entering traffic.

Thus, the longer travel times estimated for two-phase MUTs under high turning conditions in Table 4.3 should be expected. On the other hand, some three-phase intersections might have a higher threshold for the L/T ratio (due to less traffic redirected to U-turns), as they also resulted in lower V/C ratios in higher turning conditions based on Table 4.6.

d. Traffic signal performance in some three-phase intersections is similar to those in two-phase design

Based on Tables 4.1 and 4.2, some three-phase designs, such as thru-cut and offset thru-cut, showed similar cycle lengths and green-to-cycle length (g/cl) ratios to two-phase designs, with only minor differences. Therefore, eliminating an additional phase to convert a three-phase design to a two-phase design might not yield significant benefits. Additionally, the removal of one phase in two-phase designs might only offer minor progression improvements compared to thru-cut and offset thru-cut designs.

Group 2: Partial CFI and CFI/MUT Combination

The superior performance of the partial CFI aligns with previous studies (Hummer and Molan 2022; Steyn et al. 2014) which indicated that CFIs generally have one of the highest capacity levels among all existing intersection designs. At a partial CFI, note that none of the redirected traffic movements would experience longer travel distances compared to a conventional intersection. Possible reasons for the high potential of the CFI/MUT combinations include:

a. Similar V/C (volume over capacity) ratios at nodes,
b. Higher g/cl ratio for through traffic at one of the CFI/MUT nodes compared to partial CFI,
c. Smoother flow at the diverging point between through and left-turn traffic on one side of the major road (WB in our study), and
d. The left-turn traffic on one side of the minor road (SB in our study) would have one signal fewer on their route compared to a partial CFI.

The CFI/MUT combination exhibits similar V/C ratios to a partial CFI at two nodes, with slightly lower V/C ratios at another node (east signal). Due to geometric similarities between the intersection designs, both experience identical V/C ratios at the western and middle signals. However, the partial CFI accommodates higher traffic demands at its eastern traffic signal compared to the U-turn crossover of the CFI/MUT design. Therefore, the traffic signal at the CFI/MUT's U-turn could offer greater advantages for major traffic flows than the partial CFI's eastern traffic signal. This observation is also supported by Table 4.2, which indicates that major traffic experiences a higher g/cl ratio at the same node compared to the partial CFI configuration.

Another potential reason for the similar travel time performances between the CFI/MUT combo and partial CFI designs could be attributed to a trade-off related to left-turn traffic from one side of the major road (WB left in our study). At a partial CFI, the WB left-turn traffic might benefit from a shorter travel distance of approximately 1,200 ft compared to the WB left-turn at a CFI/MUT combo. This should be the primary advantage of partial CFIs compared to CFI/MUT combo designs. However, at the CFI/MUT combo design, the point where WB left-turn traffic diverges from through traffic occurs over a longer distance compared to a partial CFI. This divergence happens at the same location as the raised median at a partial CFI, as illustrated in Figure 4.3.

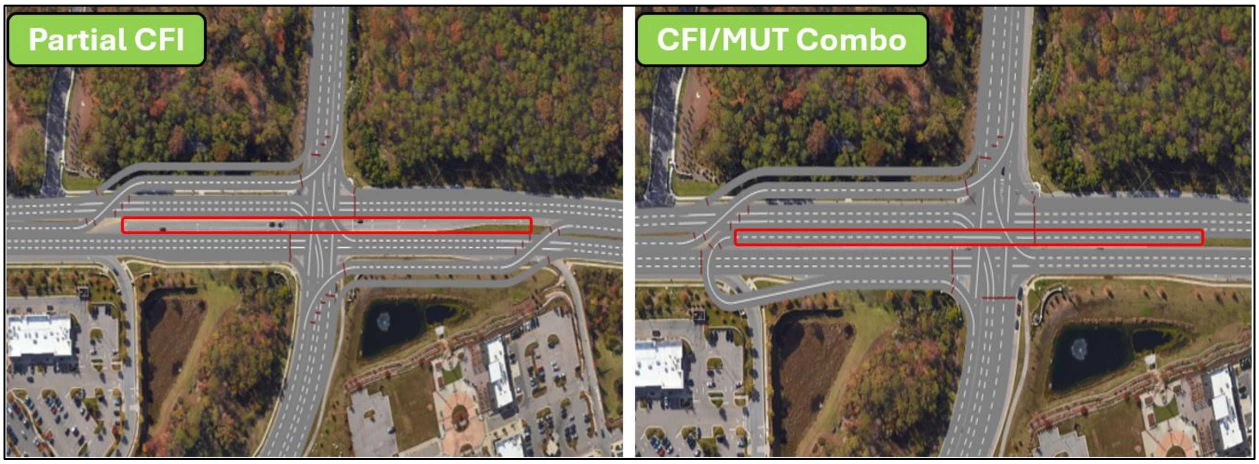

Figure 4.3 The Location of WB Left-Turn Storage Length of CFI/MUT

Figure 4.3 exemplifies this unique feature of CFI/MUT combo designs, where the WB left-turn traffic has approximately 400 ft of storage length before and 600 ft after the middle intersection, similar to several MUTs across the US. Therefore, the total storage length for WB left-turn traffic amounts to about 1,000 ft, which is 600 ft longer than the storage length at a partial CFI (400 ft). Consequently, smoother driving behaviors with fewer lane-change challenges could be expected at a CFI/MUT combo due to the longer distance available for the diverging point between WB left-turn and through traffic movements compared to a partial CFI.

Note that the unique feature of the CFI/MUT combo could provide benefits for WB through traffic, resulting in shorter average travel times compared to WB through traffic at a partial CFI, especially due to reducing the possibility of spillback of the left turn lanes. At a CFI/MUT combo, WB through traffic experiences smoother flow at the diverging point with WB left-turn traffic. Moreover, WB through traffic can reach the middle intersection without being impacted by any traffic signals on the right side of the network. In contrast, at a partial CFI, the eastern traffic signal can still affect WB through traffic vehicles before they reach the middle intersection, especially when WB left-turn queues exceed the 400-foot storage length and block one of the WB through traffic lanes.

As the last possible reason for the similar travel times of the CFI/MUT combo and partial CFI, the left-turn traffic on one of the minor legs (SB in our study) would encounter one fewer traffic signal on their route compared to a partial CFI. This should be added in favor of the CFI/MUT combo to the trade-off explained above.

4.1.1.4 Three-phase Intersection Designs with Some Potential

Compared to the intersections included in the previous section (offset thru-cut, thru-cut, MUT redirect major (MUT #1), partial CFI, and CFI/MUT combo), other three-phase designs (reverse RCI, redirect L&T, MUT #2, seven-phase, redirect 2L&T) showed fewer advantages. However, each of these designs could be advantageous in some traffic conditions. This section aims to show some potential of these intersection designs: reverse RCI, redirect L&T, MUT #2, seven-phase, redirect 2L&T.

According to Tables 4.3 and 4.5, the redirect 2L&T design emerged as a promising alternative for conventional intersections, demonstrating a similar overall travel time performance to partial MUT. However, it resulted in longer queues and a higher number of stops possibly due to its higher average cycle length as well as higher number of traffic signals on a few of its vehicle routes. For example, the redirected left-turn traffic from one minor leg (NB in our study) would face four traffic signals, which is the highest number of signals on a route among all designs included.

The redirect 2L&T's performance was not superior to other designs with DLT ramps (partial CFI and CFI/MUT combo). This finding could be attributed to the fact that most hypothetical simulation scenarios considered in our study had lower turning ratios than 25% (of the total through demand). Table 4.3 highlights that the travel time performance of the redirect 2L&T intersection is more positive under high-turning conditions. It ranked as one of the best in travel time performance for high-turning traffic in Table 4.3, while it showed one of the longest travel times among all designs in low-turning scenarios.

One reason for the redirect 2L&T's potential in high-turning conditions is its unique signal phasing diagram. The left-turn demand on one side of the major road (EB left in our study) receives a green indication during two out of three phases. In addition, both major left-turn movements do not experience any extra travel distance compared to a conventional intersection. Moreover, its average cycle length decreases as the turning traffic ratio increases, as shown in Table 4.1. Therefore, the redirect 2L&T design could possibly outperform all other intersection designs included in the study under even higher turning traffic ratios.

Furthermore, the unique signal phasing diagram of the redirect 2L&T allows one of the through demands (WB through in our study) and one of the left turns (EB in our study) on the major road to receive a green indication in two phases. This feature could be particularly advantageous during traffic conditions with significantly higher demands on one side of the major road. Also, the redirect 2L&T could provide significant signal progression benefits due to its feature on networks with adjacent signalized intersections. To explore this further, Table 4.7 presents average travel times estimated for each test, categorized into balanced and unbalanced traffic distribution on the major road. Based on Table 4.7, redirect 2L&T is the only intersection design which worked better during unbalanced traffic conditions compared to balanced traffic conditions, with shorter travel times than designs such as the partial CFI, as highlighted in gray.

Table 4.7 Average Vehicle Travel Time (sec)

Turning Ratios	Traffic Distributions		Redirect 2L&T	CFI/MUT Combo	Offset Thru-cut	Thru-cut	Seven-Phase	Reverse RCI	Redirect L&T	MUT #1	MUT #2	Partial CFI	RCI	Two-phase MUT	Conventional
	Major Rd	Minor Rd													
Low Turning Traffic	EB=WB	NB=SB	162	149	157	160	222	158	175	150	182	149	153	150	148
	EB=WB	NB=0.5SB	162	150	153	155	224	154	171	150	174	149	150	150	148
	EB=WB	0.5NB=SB	162	149	152	153	223	153	173	149	174	149	150	150	149
	EB=0.5WB	NB=SB	161	139	159	160	206	159	176	149	174	163	154	150	154
	EB=0.5WB	NB=0.5SB	159	139	155	156	200	153	173	150	171	164	152	149	155
	EB=0.5WB	0.5NB=SB	159	137	153	154	200	151	183	148	173	163	152	149	156
Moderate Turning Traffic	EB=WB	NB=SB	162	142	155	160	179	162	169	155	182	140	156	149	160
	EB=WB	NB=0.5SB	160	143	154	158	198	162	173	156	181	141	154	159	163
	EB=WB	0.5NB=SB	160	141	151	154	198	162	168	154	181	139	154	159	161
	EB=0.5WB	NB=SB	156	142	157	160	192	162	174	156	185	139	159	159	171
	EB=0.5WB	NB=0.5SB	156	142	156	158	196	158	174	157	180	143	158	160	174
	EB=0.5WB	0.5NB=SB	156	141	153	154	196	155	173	155	180	142	158	159	176
High Turning Traffic	EB=WB	NB=SB	169	150	162	161	181	163	170	160	183	146	159	159	174
	EB=WB	NB=0.5SB	165	150	161	163	182	167	168	162	185	147	160	173	178
	EB=WB	0.5NB=SB	165	147	157	157	182	164	172	159	185	144	160	174	179
	EB=0.5WB	NB=SB	157	160	162	161	211	174	176	165	203	180	163	174	244
	EB=0.5WB	NB=0.5SB	154	172	161	157	217	162	171	164	203	180	164	169	257
	EB=0.5WB	0.5NB=SB	154	168	156	161	217	159	179	167	202	176	164	173	288
Ave for Balanced Traffic (EB=WB)			**163**	**147**	**156**	**158**	**199**	**161**	**171**	**155**	**181**	**145**	**155**	**161**	173
Ave for Unbalanced Traffic (EB=0.5WB)			**157**	**149**	**157**	**158**	**204**	**159**	**175**	**157**	**186**	**161**	**158**	**161**	**161**

The performance of the seven-phase intersection was not great, likely due to longer cycle lengths compared to the conventional design. Specifically, the presence of all four left-turn traffic movements at the middle intersection prevented the complete removal of the fourth phase. Conversely, the seven-phase design (along with all alternative designs) could lead to significantly shorter travel times than the conventional design in scenarios with high turning volumes (and notably lower redirected through traffic on one of the legs). Therefore, from a traffic operations standpoint, it is advisable to consider the seven-phase design as an alternative at conventional intersections under conditions of: 1) high turning volumes, and 2) substantially lower through traffic on one of the minor legs.

Overall, MUT #2 (redirect minor Rd) and the redirect L&T designs could lead to slightly shorter travel times than the conventional design; however, significantly better travel time performance was observed compared to the conventional design only in high-turning conditions. This finding is reflected in the cycle lengths shown in Table 4.1, where MUT #2 and redirect L&T exhibited shorter cycle lengths than the conventional design specifically under high-turning traffic conditions. Therefore, signal performance advantages might not be significant compared to a conventional design in lower turning traffic conditions. For example, in a conventional design, through traffic demands on the major road would encounter red intervals spanning three phases at the middle intersection. However, two of these signal phases are relatively short when left turn demands receive a green indication during low and moderate turning traffic conditions. In contrast, at the middle intersection of MUT #2, through traffic demands would stop for a red light lasting two signal phases, approximately equivalent to the stop (red) time in the conventional design due to the high demand involved with its third phase.

It should be mentioned that MUT #2 should result in significantly shorter travel times than conventional and many of the three-phase designs at intersections with significantly higher demands for the left turns on the minor road compared to left turns on the major road. In fact, MUT redirect minor (MUT #2) would functionally perform similar to MUT redirect major (MUT #1) if the left turn demand is higher on the minor road compared to major road.

Results show that the redirect L&T could be highly advantageous in a network with adjacent signalized intersections and unbalanced traffic (higher traffic on one side) on the major road. Since our study did not include adjacent intersections, some benefits of redirect L&T could be overlooked, warranting further investigation in future research. For instance, at a redirect L&T, left-turn demand on one side of the major road can experience perfect progression (without needing to stop) at the middle intersection, along with through traffic. This is due to the unique phasing diagram of the redirect L&T, which allows for such a feature, as is illustrated in Figure 4.4. As shown in the green boxes in Figure 4.4, left-turn traffic on the westbound (WB) direction would receive a green indication in phase Ø5 as soon as they arrive at the middle intersection after a 20-second travel time between nodes 1 and 2.

Although the traffic operation benefits of these two somewhat promising designs, MUT #2 and redirect L&T, were found to be generally less than those of other alternative designs (MUT #1, thru-cut, offset thru-cut, and reverse RCI), they could still offer substantial advantages in terms of other measures of effectiveness (MOEs) including safety, pedestrian performance, public acceptance, and right-of-way (ROW) costs compared to other alternatives. For instance, the redirect L&T design includes 22 conflict points, fewer than most three-phase designs. Also, it requires extra ROW on only one side of the road, making it an excellent option for locations with ROW restrictions. Future studies by the authors will address the results concerning other MOEs. Furthermore, as mentioned above, some designs, such as redirect L&T, could show improved traffic performance in simulations involving adjacent traffic signals.

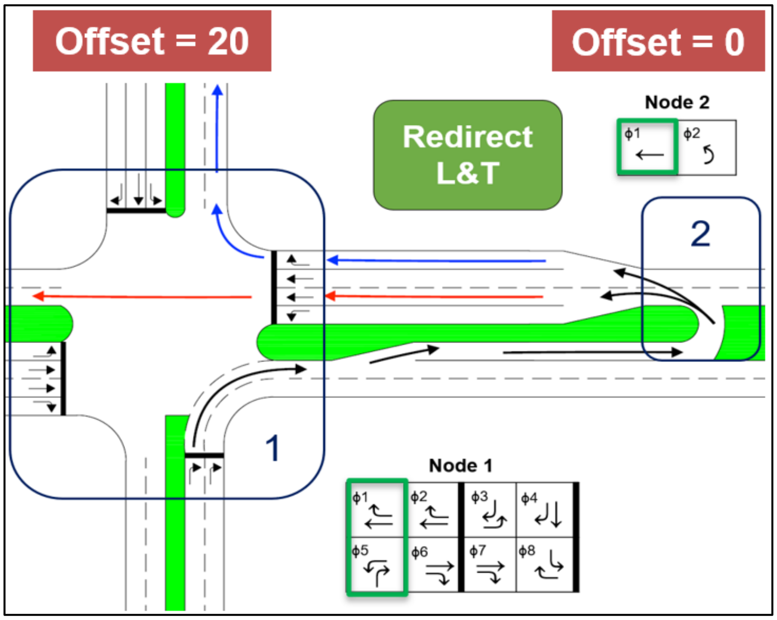

Figure 4.4 Perfect Progression for Left-turn Demand on One Side of the Major Road at Redirect L&T

4.1.2 TransModeler Analysis of Case Study Sites

This section elaborates on the results using TransModeler for simulation modeling of case study sites. It should be noted that no adjacent intersections were included in our simulation modeling because of the numerous assumptions needed about traffic distributions (to prepare realistic origin-destination tables that required significantly more traffic data collection). Therefore, the research team chose to model the case study sites and various alternative intersection designs with only the main intersection included (also includes crossovers and U-turns when necessary).

Travel time results from simulations are shown in Tables 4.8-4.14. It should be noted that discussions on the results are summarized in this section (TransModeler Analysis of Case Study Sites). The previous section (Hypothetical Tests) comprehensively elaborated on the performance of different intersection designs and possible reasons for travel time differences. Overall, most three-phase designs had lower travel times when compared to existing conditions. Notably, the seven-phase design was the only three-phase intersection in this study that had mixed results regarding travel times.

Of the eight alternative designs studied at site 1, the MUT redirect major (partial MUT #1) design had the lowest average travel time with an average reduction of 9% across all scenarios as shown in Table 4.8. The two-phase MUT was another design with considerable travel time reductions at site 1 with an average reduction of 8% across all scenarios. Seven-Phase increased travel times at site 1 by an average of 4% across all scenarios.

Of note, case study site 1 has some geometric features that are unlike the other case study sites. At the main intersection, both of the minor lefts have a shared through/left lane. This means that the left turn movements from the minor approach are permitted and do not take up an exclusive signal phase. Also, site #1 has the lowest traffic volume (relatively a low AADT) among all case study sites. This means that at this particular site, the existing conditions should perform very well when compared to alternative intersections than at other sites.

Table 4.8 Case Study Site 1 New Bern Ave and Peartree Ln
Weighted Average Travel Time (seconds)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM	Average
Existing	87	87	89	87	87	89	88
Seven-Phase	91	91	93	91	90	92	91
Full MUT	81	81	80	81	81	82	81
MUT #1	81	80	79	80	80	81	80
MUT #2	86	86	90	85	86	89	87
Redirect L&T	85	85	87	84	84	86	85
Reverse RCI	87	85	88	87	87	87	87
Thru-cut	84	85	87	85	85	88	86
RCI	81	81	83	82	82	84	82

As shown in Table 4.9, case study site 2 tested the seven-phase design and the redirect L&T. The Seven-Phase signal performed better at site 2 than site 1 and improved travel time performance in some instances. The redirect L&T reduced travel time by an average of 8% across all scenarios. Relatively low traffic demand on the minor road could be one of the possible reasons for the superior performance of both alternative designs compared to the conventional design at site 2.

Table 4.9 Case Study Site 2 Chapel Hill Rd and Trinity Rd
Weighted Average Travel Time (seconds)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM	Average
Existing	97	95	102	109	99	127	105
Seven-Phase	98	91	99	102	97	170	110
Redirect L&T	91	88	94	100	91	117	97

At case study site 4, six different alternative intersections were evaluated as shown in Table 4.10. Over all scenarios, the CFI/MUT combo design had the largest average reduction in travel time at 34%. The partial CFI had the second largest average travel time reduction at 31%. MUT redirect major (partial MUT #1) and full MUT also performed well at site 4 with average travel time reductions of 21% and 19% respectively. Of note, site 4 had one of the highest heavy vehicle percentages at 4.5% and one of the highest total traffic demands among all case study sites. Therefore, the superior performance of alternative designs such as partial CFI and CFI/MUT combo should be due to their higher capacity levels compared to conventional design, especially during the design year (2043).

Table 4.10 Case Study Site 4 Capital Blvd and Old Wake Forest Rd
Weighted Average Travel Time (seconds)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM	Average
Existing	116	110	115	327	230	320	203
CFI/MUT Combo	103	91	95	139	97	182	118
Full MUT	103	114	105	239	161	180	150
MUT #1	101	109	104	288	142	153	149
MUT #2	123	99	108	282	153	314	180
Partial CFI	100	91	101	115	103	240	125
Redirect 2LT	105	92	102	325	153	207	164

For case study site 5, MUT redirect major (partial MUT #1) and MUT redirect minor (partial MUT #2) were compared to the existing intersection as shown in Table 4.11. Unlike at site 4, partial MUT #2 reduced travel times further than partial MUT #1 at site 5 with an overall average reduction of 19% across all scenarios (compared to 12% for partial MUT #1). This is possibly due to the larger number of redirected left turns on the minor roads than major road. In other words, MUT #2 functionally performed similar to MUT #1 at intersections (such as site 5) with higher left-turn demands on the major road than minor road.

Table 4.11 Case Study Site 5 Capital Blvd and Trawick Rd
Weighted Average Travel Time (seconds)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM	Average
Existing	139	123	131	139	119	131	130
MUT #1	130	100	115	137	98	109	115
MUT #2	102	103	112	109	100	108	106

At case study site 7, the thru-cut reduced travel times by an average of 30% across all scenarios as shown in Table 4.12. The reduction in travel time was most significant in future scenarios where traffic volumes were at their highest. Of note, site 7 had the lowest heavy vehicle percentage at 1.5% and the through traffic demand on the minor road is significantly low. While through traffic demand on the minor road is less than 31 veh/hr during peak hours, right turn demand on the minor road averaged about 300 veh/hr. Therefore, the thru-cut intersection could be one of the best alternatives at this location.

Table 4.12 Case Study Site 7 Brier Creek Pkwy and Brier Leaf Ln
Weighted Average Travel Time (minutes)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM	Average
Existing	118	131	123	212	529	474	264
Thru-cut	115	126	126	114	193	149	137

At case study site 8, the Partial CFI reduced travel times by an average of 24% while the CFI/MUT Combo reduced travel times by an average of 21% as shown in Table 4.13. The reduction in travel time was most significant in the 2043 PM scenario in which the Partial CFI reduced travel times by 50%. This is possibly due to the large traffic volumes for this scenario, specifically for major road left turn movements which are allowed to turn simultaneously at the main intersection with the partial CFI design.

In a comparison between travel time performances of partial CFI and CFI/MUT combo at site 4 and 8, it was found that partial CFI outperformed CFI/MUT combo at site 8, while the CFI/MUT combo resulted in shorter travel times than partial CFI at site 4. There should be two reasons for this finding:

1) Site 8 has significantly lower traffic demand than site 4; therefore, extra travel distance for one movement at the CFI/MUT combo (compared to partial CFI with no extra travel distances) could increase the overall travel time, and
2) Site 4 had significantly high SB through traffic demand (about 2,700 veh/hr during PM peak hour); therefore, the CFI/MUT combo could be more advantageous than the partial CFI because of the smoother flow at the diverging point between through and left-turn traffic on SB at this site (similar to Figure 4.3).

Table 4.13 Case Study Site 8 NC-55 and O'Kelly Chapel Rd Weighted Average Travel Time (seconds)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM	Average
Existing	103	101	112	143	127	507	182
CFI/MUT Combo	88	90	97	96	103	333	135
Partial CFI	89	91	93	97	98	254	120

The average percent reductions in weighted average travel time for each design across all case study intersections are shown in Table 4.14. According to this table, three-phase designs with a CFI element (partial CFI and CFI/MUT combo) reduce travel time the most, followed by redirect 2L&T and Partial MUT #1. Of all the three-phase designs tested, the seven-phase signal is the only alternative that did not perform well in terms of weighted average travel time.

Table 4.14 Average Percent Reduction in Travel Time by Three-Phase Design

Intersection Type	Average Percent Reduction in Travel Time Compared to Existing Conditions
Partial CFI	28%
CFI/MUT Combo	27%
Redirect 2L&T	18%
MUT #1	17%
Thru-Cut	16%
MUT #2	14%
Full MUT	14%
RCI	6%
Redirect L&T	5%
Seven-Phase	-4%

4.2 Traffic Safety

The following sections elaborate on the results of surrogate safety assessments conducted in this study. Note that SSAM and CPA results solely focused on hypothetical scenarios, while the SSI analysis was conducted both for hypothetical scenarios and case study sites.

4.2.1 SSAM

Table 4.15 provides a summary of the average simulated conflicts identified by SSAM for hypothetical scenarios. Table 4.16 also shows average time-to-collision (TTC), average post-encroachment time (PET), and maximum speed at conflicts per run under various turning cases based on SSAM. Note that SSAM analysis was conducted only on hypothetical scenarios.

Table 4.15 Average classified conflicts per run under various turning cases using SSAM

Turning Cases	High Turning			Moderate Turning			Low Turning			Overall		
Simulated Conflicts	Cross -ing	Rear-end	Lane Change	Cross -ing	Rear-end	Lane Change	Cross -ing	Rear-end	Lane Change	Cross -ing	Rear-end	Lane Change
Conventional	2	1,023	147	1	285	57	0	104	13	1	471	72
Redirect L&T	0	336	42	0	289	27	0	326	37	0	317	35
Seven-Phase	0	382	48	0	282	32	0	381	37	0	348	39
Reverse RCI	3	324	66	2	265	39	2	272	36	2	287	47
Offset Thru-cut	1	631	96	1	473	72	2	427	56	1	505	74
Thru-cut	2	518	39	2	406	43	1	414	33	2	446	38
MUT #1	1	459	68	1	393	47	1	215	38	1	362	51
MUT #2	0	309	47	0	220	31	0	240	22	0	256	33
Redirect 2L&T	0	404	38	0	262	36	0	262	37	0	309	37
CFI/MUT Combo	5	585	116	2	392	71	0	322	53	2	443	80
Partial CFI	10	343	28	4	163	11	2	267	22	5	258	21
RCI	2	488	55	1	469	49	0	397	34	1	451	46
Two-Phase MUT	0	440	45	0	277	30	0	219	26	0	312	33

Table 4.16 Average TTC (sec), Average PET (sec), and Maximum Speed (mph) per Run under Various Turning Cases based on SSAM

Turning Cases	High Turning			Moderate Turning			Low Turning			Overall		
Simulated Conflicts	Ave TTC*	Ave PET**	Max Speed	Ave TTC	Ave PET	Max Speed	Ave TTC	Ave PET	Max Speed	Ave TTC	Ave PET	Max Speed
Conventional	1.13	1.76	6.89	1.11	1.54	7.88	1.22	1.51	9.37	1.15	1.60	8.04
Redirect L&T	1.21	1.91	7.58	1.24	1.88	7.80	1.22	1.83	8.12	1.22	1.87	7.84
Seven-Phase	1.20	1.75	8.32	1.20	1.69	8.60	1.22	1.69	8.80	1.20	1.71	8.57
Reverse RCI	1.18	1.73	7.53	1.23	1.63	7.94	1.25	1.68	7.78	1.22	1.68	7.75
Offset Thru-cut	1.20	1.87	7.31	1.16	1.80	7.60	1.10	1.72	7.42	1.16	1.80	7.44
Thru-cut	1.30	1.86	7.71	1.30	1.86	7.74	1.32	1.95	7.84	1.31	1.89	7.76
MUT #1	1.21	1.67	7.99	1.20	1.53	8.09	1.12	1.34	8.15	1.18	1.51	8.07
MUT #2	1.18	1.60	8.04	1.22	1.60	8.33	1.24	1.56	8.76	1.21	1.58	8.38
Redirect 2L&T	1.24	1.85	7.75	1.17	1.61	8.03	1.13	1.62	8.26	1.18	1.69	8.01
CFI/MUT Combo	1.08	1.54	7.78	1.07	1.30	8.56	1.10	1.29	8.63	1.08	1.37	8.35
Partial CFI	1.22	1.61	7.84	1.23	1.56	8.12	1.24	1.55	8.98	1.23	1.58	8.31
RCI	1.20	1.84	7.60	1.22	1.86	7.64	1.26	1.99	7.72	1.23	1.90	7.65
Two-Phase MUT	1.21	1.78	7.60	1.23	1.61	7.89	1.23	1.52	8.13	1.22	1.64	7.78

* Time to collision
** Post-encroachment time

According to the results in Tables 4.15 and 4.16, all intersection designs had similar or better performance than the conventional design in terms of total number of conflicts and average values of time-to-collision (TTC), post-encroachment time (PET), and speed at conflicts. However, the partial CFI and the CFI/MUT combo resulted in more crossing conflicts compared to the conventional design and other designs. When comparing these two designs, the CFI/MUT combo showed fewer crossing conflicts possibly because it has three crossing conflicts fewer than partial CFI (based on conflict point diagrams shown in Chapter 3). Redirect 2L&T, redirect L&T, seven-phase, MUT #2, and two-phase MUT did not result in any simulated crossing conflicts in all turning conditions.

4.2.2 Conflict Point Analysis (CPA)

As a part of the safety analysis, the research team developed a spreadsheet-based tool to conduct conflict point analysis (CPA) at intersections. When calculating based on total traffic conflict volume in each conflict point for all turning movements and categorizing them into diverging, merging and crossing conflicts, the following was observed. While the full results are presented in Appendix 6, the following paragraphs provide a summary of some results from applying conflict point analysis (CPA) to hypothetical scenarios.

Table 4.17 shows the total traffic volume conflicting at each conflict point at the intersections, based on the average traffic volume from Table 3.8. From Table 4.17, the total conflict volume for conventional intersection is 29,377 veh/hr. All the alternative intersections exhibited lower conflict volumes than the conventional intersection. The reverse RCI showed the lowest conflicting volume at its conflict points. It should be noted that thru-cut and offset thru-cut had lower crossing conflicts than the two-phase MUT. This shows the potential of thru-cut and offset thru-cut designs in reducing crash severity.

Table 4.17 Traffic Conflict Volume Based on Total Volume in Each Conflict Point

Rank	Name/Type	Diverging	Merging	Crossing	Total
1	Reverse RCI	8,542	10,563	2,917	22,022
2	RCI	10,831	8,562	2,917	22,310
3	Offset T	7,474	7,474	7,666	22,614
4	Two-Phase MUT	7,682	8,026	7,018	22,726
5	Redirect 2L&T	8,675	8,098	8,423	25,196
5	Redirect L&T	8,675	8,098	8,423	25,196
7	Thru-cut	10,649	11,403	6,320	28,372
7	Offset Thru-cut	10,649	11,403	6,320	28,372
9	MUT #2	9,951	8,294	10,203	28,448
10	Seven-Phase	8,880	9,419	10,153	28,452
11	CFI/MUT Combo	7,752	8,541	12,225	28,518
12	Single Quadrant	8,234	8,284	12,141	28,659
13	Partial CFI	7,484	7,484	13,712	28,680
14	MUT #1	8,112	10,619	10,365	29,096
15	Conventional	7,484	7,484	14,409	29,377

Table 4.18 shows the traffic conflict volume in proportion to conventional intersections. From Table 4.18, the total conflict volume in the reverse RCI was 0.75 times of the conventional i.e., a

25 % reduction in overall conflict volume. Also, the number of crossing conflicts at the reverse RCI was 0.2 times to the conventional, which shows a significant improvement. To create a better view regarding this finding, Figure 4.5 displays the percentage reduction in crossing conflict volume for each alternative intersection as compared to the conventional intersection.

Table 4.18 Traffic Conflict Volume in Proportion to Conventional Intersections

Rank	Name/Type	Diverging	Merging	Crossing	Total
1	Reverse RCI	1.14	1.41	0.20	0.75
2	RCI	1.45	1.14	0.20	0.76
3	Offset T	1.00	1.00	0.53	0.77
4	Two-Phase MUT	1.03	1.07	0.49	0.77
5	Redirect 2L&T	1.16	1.08	0.58	0.86
5	Redirect L&T	1.16	1.08	0.58	0.86
7	Thru-cut	1.42	1.52	0.44	0.97
7	Offset Thru-cut	1.42	1.52	0.44	0.97
9	MUT #2	1.33	1.11	0.71	0.97
10	Seven-Phase	1.19	1.26	0.70	0.97
11	CFI/MUT Combo	1.04	1.14	0.85	0.97
12	Single Quadrant	1.10	1.11	0.84	0.98
13	Partial CFI	1.00	1.00	0.95	0.98
14	MUT #1	1.08	1.42	0.72	0.99
15	Conventional	1.00	1.00	1.00	1.00

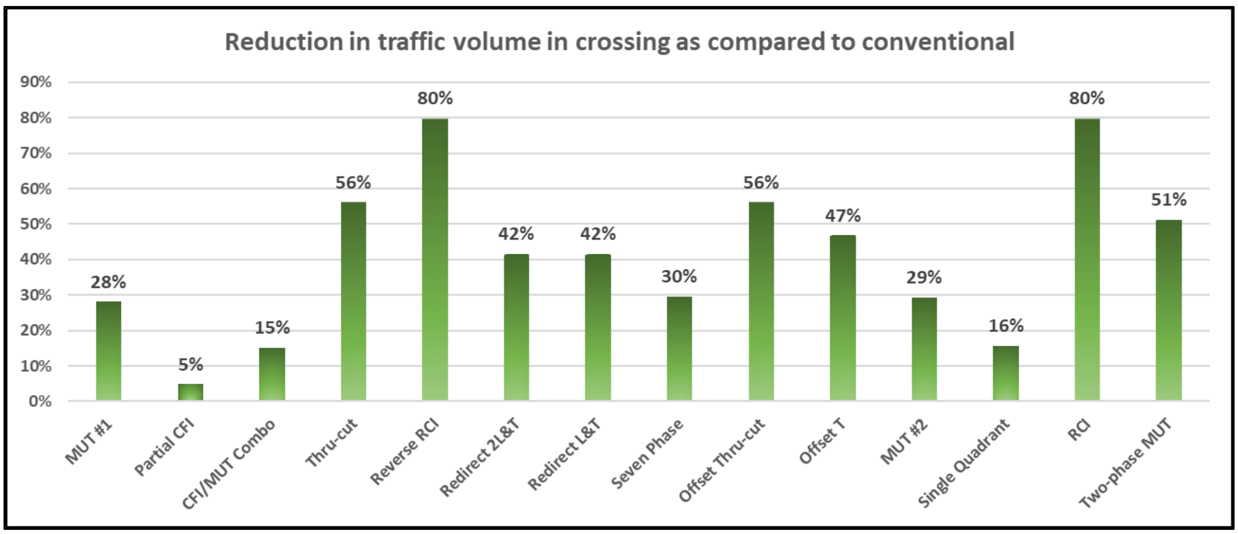

Figure 4.5 Crossing Conflict Reduction % in Comparison to Conventional Intersection

4.2.3 SSI

The SSI analysis was conducted in two parts: 1) SSI analysis of case study sites, and 2) SSI analysis based on hypothetical scenarios.

4.2.3.1 SSI at Case Study Sites

Table 4.19 shows the ranking of the intersections based on the average SSI score (0-100) for all the case study sites. Note that all traffic volume data for each case study site is provided in

Appendix 1. Thirteen of the assessed alternative intersections showed an improved average SSI score compared to the existing conventional intersection, all except for the partial CFI. This safety improvement at most alternatives (compared to the conventional design) can be attributed mainly to fewer number of crossing conflicts and minimizing the level of exposure created by the crossing conflicts. The reverse RCI recorded the highest average SSI score of 62 followed closely by the two-phase MUT and the RCI intersection type, with a score of 62 and 61, respectively.

Table 4.19 Average SSI Score at Case Study Sites*

Intersection Type	Rank	Site 1	Site 2	Site 4	Site 5	Site 7	Site 8	Average SSI Score
Reverse RCI	1	100	76	9	86	89	13	62
Two-phase MUT	2	100	80	3	90	93	5	62
RCI	3	98	71	5	94	83	12	61
Thru-cut	4	98	65	3	84	80	10	57
Offset Thru-cut	4	98	65	3	84	80	10	57
MUT #1	6	99	70	1	79	86	2	56
Redirect 2L&T	7	98	61	1	86	80	3	55
Redirect L&T	8	98	61	1	86	79	3	55
CFI/MUT Combo	9	99	60	1	77	84	1	54
MUT #2	10	97	63	0	87	77	2	54
Seven-Phase	11	98	60	1	79	78	4	53
Offset T	12	98	61	0	80	75	2	53
Single Quadrant	13	98	62	0	77	75	2	52
Conventional	14	97	56	0	76	73	1	51
Partial CFI	15	97	56	0	75	72	1	50

*The designs with the minimum score for each site are shaded.

It must be noted that the two-phase MUT outperformed both the RCI and the reverse RCI at sites with relatively lower traffic volumes such as sites 1, 2 and 7. This may be attributed to the reduced exposure levels associated with two-phase intersections at these sites, particularly for crossing conflicts resulting from the lower traffic volumes on the minor roads. Additionally, conflict severity, which is influenced by the speeds of the conflicting traffic, could be a contributing factor.

For the two-phase MUT, all crossing conflicts occur between through traffic from the minor road, characterized by lower speeds due to the application of signal control near and signal control far speeds, and through traffic from the major road, which operates at higher speeds. Signal control near-side refers to the speed at conflict points near the signal, while signal control far-side refers to the speed at points farther from the signal, where vehicles have more distance to accelerate at signalized intersections. Conversely, in the case of the RCI, the conflicts involve traffic only from major roads, specifically eastbound left and westbound through movements, and vice versa. According to the assumptions in the FHWA report, for a signalized intersection, the speed limits for the major roads should be utilized in calculating conflict severity, while the signal control near or signal control far speeds should be assumed for conflicts originating from the minor roads, based on the conflict point location. Therefore, this could be another reason that two-phase MUT outperformed RCI and reverse RCI designs in a few of the case study sites.

It is pertinent to note that the offset thru-cut and thru-cut designs exhibited comparable SSI scores. This similarity can likely be ascribed to the similar number of conflict points presented by these two intersection types. It is also important to highlight that a zero SSI score was recorded for some intersections at sites with relatively higher traffic volumes (AADT) such as site 4. This implies that these designs do not adhere well to the principles of the safe system due to the combination of high exposure levels and conflict point severity resulting from high user volumes and speeds.

Appendix 8 presents more information regarding the SSI results at case study sites including the intersection attributes, rankings of the analyzed intersections, and detailed SSI scores of each individual site and intersection type. Tables in Appendix 8 also provide detailed insights into the SSI results, focusing on the average severity, exposure levels and complexity adjustments of each conflict type. Overall, most alternatives showed a good score, particularly for crossing conflicts.

4.2.3.2 SSI Results for Hypothetical Scenarios

Table 4.20 presents the SSI scores for all intersections based on hypothetical scenario. Similar to the SSI results of the case study sites, all alternative intersections demonstrated higher scores than the conventional intersection with the exception of the partial CFI. The scores for the selected alternatives are generally high with the reverse RCI being the highest performer, scoring 92%. The combination of reduced exposure and fewer crossing conflicts contribute to a relatively lower average severity and complexity levels experienced at the reverse RCI. These are highlighted in Appendix 8 which presents a graph of the relative exposures, average severity and average complexity adjustments for each conflict type of all the assessed intersections. A similar reason applies to the RCI which came in second in the ranking.

4.2.3.3 Validation

As mentioned earlier, the SSI for new alternatives tool is a spreadsheet that was developed based on the processes, formulas, and steps provided in the FHWA's "A Safe System-Based Framework and Analytical Methodology for Assessing Intersections" (Report No. FHWA-SA-21-008). A validation was also done by the research team based on the examples (scenarios) provided in the FHWA's SSI report (Porter et al. 2021) for four of the intersections that were relevant to our research. The examples utilized for the validation focused on the signalized intersections. As a result of this, validation was done for examples (scenarios) 1 and 3 of the FHWA's SSI report (2021) because FHWA's scenario 2 includes unsignalized intersections. It is important to note that, in the calculations of the average complexity adjustment, the examples in the report focused on a permissive/protected left turn signal. In contrast, the spreadsheet-based tool developed in our study only includes intersections with a protected left turn phase only based on the scope of our study. Also, the validation did not take non-motorized traffic into consideration. Overall, based on the validation conducted, similar results were identified in the comparison between the spreadsheet-based tool developed in our study and scenarios included in the FHWA's SSI report (2021). The validation results are available as Appendices 9-11.

Table 4.20 shows the ranking of intersections based on SSI score for hypothetical scenarios. The values in each cell represent the average across all the hypothetical scenarios. The SSI score for intersection is calculated using the equations in Section 3.7 of the FHWA's Safe System-Based Framework and Analytical Methodology for Assessing Intersections (2021). Further details could be found in the SSI tool included in Appendix 5.

Table 4.20 Ranking of Intersections Based on SSI Score for Hypothetical Scenarios*

Rank	Intersection Type	Intersection Score	Conflict Type SSI Scores			
			Non-motorized	Diverging	Merging	Crossing
1	Reverse RCI	92	na	95	92	89
2	RCI	89	na	97	93	79
3	Thru-cut	87	na	97	93	72
3	Offset Thru-cut	87	na	97	93	72
5	Redirect L&T	80	na	98	96	55
6	Two-phase MUT	80	na	98	96	55
7	Redirect 2L&T	80	na	98	96	54
8	Seven-Phase	79	na	98	95	53
9	MUT #1	79	na	98	96	52
10	Offset T	74	na	98	96	43
11	CFI/MUT Combo	74	na	99	97	42
12	MUT #2	74	na	99	98	42
13	Single Quadrant	74	na	99	98	42
14	Conventional	71	na	99	98	36
15	Partial CFI	70	na	99	98	35

4.3 Pedestrian and Bicycle Performance

The following paragraphs elaborate on the results of pedestrian and bicycle performance conducting NCHRP Report's 948 flag method (2021) and simulation modeling. It should be noted that no simulation modeling was considered for case study sites as TransModeler is not able to model pedestrians. Therefore, pedestrian simulation modeling was only conducted based on hypothetical scenarios.

4.3.1 Flag Method

This section presents the results of the evaluation of twenty (20) intersection models utilizing the 20-flag method. Among the twenty (20) models, four intersections have different crosswalk variations. These include the thru-cut standard crosswalk, which has a similar crosswalk orientation to the conventional intersection; the thru-cut Barnes dance crosswalk Type I, which does not include a middle island on the minor road approach; and the thru-cut Barnes dance crosswalk Type II, which includes middle islands on the minor approach. In this study, the same signal phasing was applied to both the Barnes Dance crosswalk and the standard crosswalk. However, it is important to note that pedestrian signal phasing considerations should be addressed for all crosswalk types during implementation.

There are also the redirect L&T one-less crosswalk (redirect L&T Type II) and the seven-phase one-less crosswalk (seven-phase Type II), which do not have crosswalks on the east leg of the intersection. The redirect L&T standard crosswalk (redirect L&T Type I) and the seven-phase standard crosswalk (seven-phase Type I) have crosswalks like those in a conventional intersection. Finally, there are two types for the offset thru-cut: 1) offset thru-cut without middle island (offset thru-cut Type I), and 2) offset thru-cut with middle island (offset thru-cut Type II), with the main difference being the presence of middle islands on the offset thru-cut Type II minor road approaches. All the pedestrian path configurations of the analyzed intersections have been presented in Figure 4.6.

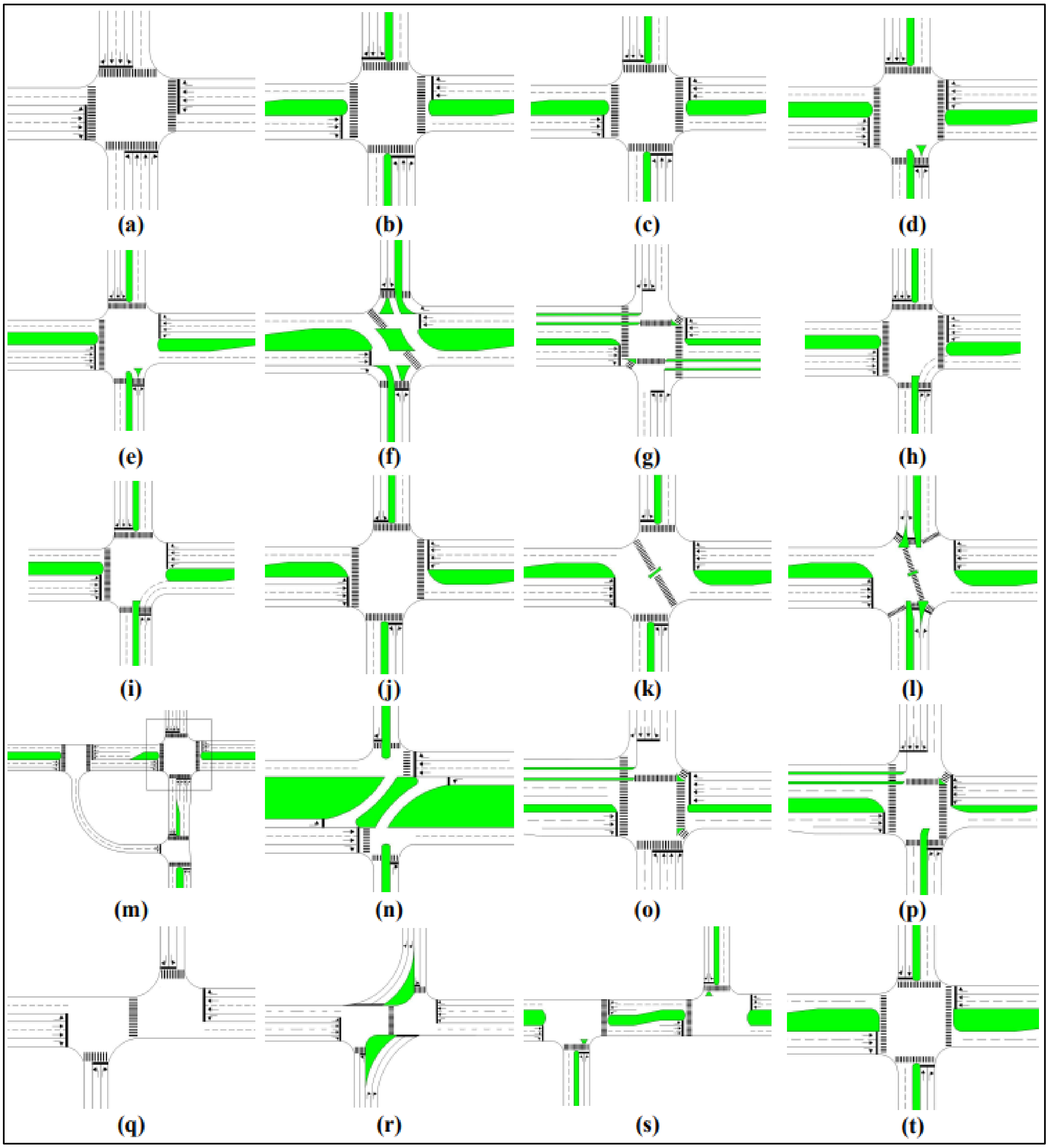

Figure 4.6 Pedestrian Paths of All Assessed Intersections

(a) Conventional; (b) MUT Redirect Major (MUT #1); (c) MUT Redirect Minor (MUT #2); (d) Seven-Phase Standard Crosswalk (Type I); (e) Seven-Phase One-Less Crosswalk (Type II); (f) Reverse RCI; (g) Partial CFI; (h) Redirect L&T Standard Crosswalk (Type I); (i) Redirect L&T One-Less Crosswalk (Type II); (j) Thru-cut (Standard crosswalk); (k) Thru-cut (Barnes dance Type I); (l)Thru-cut (Barnes Dance Type II); (m) Single Quadrant; (n) RCI; (o) CFI/MUT Combo; (p) Redirect 2L&T; (q) Offset Thru-cut Without Middle Island (Type I); (r) Offset Thru-cut With Middle Island (Type II); (s) Offset T; (t) Two-phase MUT

Thirteen design flags out of the 20 flags outlined in the NCHRP 948 report were used for the pedestrian safety assessment whereas sixteen design flags out of the twenty flags were utilized for the bicyclists' safety assessment. This resulted in fifty-two (52) and sixty-four (64) possible design flags, respectively, taking into consideration all four pedestrian and bicyclist movements for each of the design flags.

4.3.1.1 Flag Method for Hypothetical Scenarios

Table 4.21 presents the results of the pedestrian and bicyclist assessment of the alternative intersections, and the conventional intersection assessed based on the NCHRP report 948's 20-flag analysis.

Table 4.21 Pedestrian and Bicyclist Flag Assessment of Alternative Intersections using 20-Flag Analysis

Intersection Type	Pedestrian Flag Assessment			Bicyclist Flag Assessment		
	Yellow Flags	Red Flags	Flagged	Yellow Flags	Red Flags	Flagged
Conventional	4%	15%	19%	21%	24%	44%
Partial CFI	4%	23%	27%	15%	32%	47%
CFI/MUT Combo	4%	15%	19%	19%	21%	40%
Redirect 2L&T	4%	15%	19%	21%	19%	40%
RCI	15%	8%	23%	21%	18%	38%
Reverse RCI	15%	15%	31%	18%	24%	41%
Offset T	8%	27%	35%	24%	50%	74%
Quadrant	8%	8%	15%	8%	8%	35%
MUT #1	8%	8%	15%	24%	18%	41%
MUT #2	4%	12%	15%	18%	18%	35%
Two-phase MUT	8%	8%	15%	24%	18%	41%
Redirect L&T (Type I)	2%	13%	15%	22%	18%	40%
Redirect L&T (Type II)	2%	12%	13%	16%	15%	31%
Thru-cut (standard crosswalk)	4%	12%	15%	21%	18%	38%
Thru-cut (Barnes dance Type I)	8%	12%	19%	24%	18%	41%
Thru-cut (Barnes dance Type II)	8%	19%	19%	21%	18%	38%
Seven-Phase (Type I)	4%	19%	23%	26%	21%	47%
Seven-Phase (Type II)	4%	15%	19%	21%	16%	37%
Offset thru-cut (Type I)	4%	12%	15%	15%	24%	38%
Offset thru-cut (Type II)	4%	12%	15%	15%	24%	38%

Overall, the offset T exhibited the highest percentage of flags at 35% with 27% being red flags in the pedestrian assessment. This increase may be attributed to the two separate legs of the offset T, with each leg having a crosswalk in each direction of the intersection. This was followed closely by the reverse RCI with overall percentage flags of 31%. However, reverse RCI had a relatively lower number of red flags of 15% compared to the offset T and the partial CFI. The partial CFI had the second-highest red flags at 23%. This may be attributed to the two free-flow northbound and southbound right turns which resulted in the non-intuitive motor vehicle movement (flag #3) and crossing yield or uncontrolled vehicle paths (flag #4). The MUT #1, two-phase MUT, thru-cut Barnes dance Type II, and the RCI all recorded a lower percentage of red flags at 8% with the quadrant recording the lowest overall percentage flagged at 15%.

The offset T in the assessment of the bicyclists also showed the highest percentage flagged, with 50% being red flags, the highest among all the intersections assessed. Following closely is the partial CFI having 47% flagged with 32% red flags. Similar to the pedestrian assessment, this may be attributed to the two free-flow northbound and southbound right turns, resulting in the crossing yield or uncontrolled vehicle paths flag (flag #4). The redirect L&T (Type II) recorded the lowest number of flags at 31% with one of the lowest percentages of red flags at 15%. Appendix 12 offers a comprehensive overview of each design's computed percentages of red and yellow flags based on hypothetical scenarios and evaluation of case study sites.

4.3.1.2 Flag Method for Case Study Sites

Table 4.22 presents the ranking of the pedestrian and bicyclist assessment of the alternative intersections at case study sites included in this study.

Table 4.22 Ranking of Pedestrian and Bicycle Flag Assessment of Proposed Alternative Intersections for Each Site

Ranking of Pedestrian Flag Assessment						
Rank	Site 1	Site 2	Site 4	Site 5 and 6	Site 7	Site 8
1	Two-Phase MUT	Conventional	MUT #1	MUT #2	Thru-cut (Barnes I)	Conventional
2	MUT #1 (Redirect Major)	Redirect L&T	MUT #2	MUT #1	Conventional	CFI/MUT Combo
3	MUT #2 (Redirect Minor)	Seven-Phase	Two Phase MUT	Conventional		CFI
4	Seven-Phase		Redirect 2L&T			
5	Thru-Cut (Barnes Dance I)		Conventional			
6	Conventional		CFI/MUT Combo			
7	Thru-cut (Standard)		Partial CFI			
8	Redirect L&T					
9	Reverse RCI					
Ranking of Bicyclists Flag Assessment						
Rank	Site 1	Site 2	Site 4	Site 5 and 6	Site 7	Site 8
1	Two-Phase MUT	Conventional	MUT #1	MUT #1	Thru-cut (Barnes I)	Conventional
2	MUT #1	Redirect L&T	MUT #2	MUT #2	Conventional	CFI/MUT Combo
3	MUT #2	Seven-Phase	Two Phase MUT	Conventional		CFI
4	Seven-Phase		Redirect 2L&T			
5	Thru-cut (Barnes Dance I)		Conventional			
6	Conventional		CFI/MUT Combo			
7	Reverse RCI		Partial CFI			
8	Redirect L&T					
9	Thru-cut (Standard)					

Based on Table 4.22, the MUT designs (two-phase MUT, MUT #1, and MUT #2) emerge as potentially safer options based on the Pedestrian Flag Assessment criteria. Thru-cut designs with the Barnes dance crosswalk generally showed better rankings compared with the conventional intersection and the thru-cut with the standard crosswalk design. For example, among the two types of thru-cut pedestrian walkways assessed for site 1, the Barnes dance thru-cut performed better than the standard thru-cut, resulting in a 4% reduction in the percentage of red flags. The relatively shorter red times experienced by pedestrians using the Barnes dance crosswalk thru-cut may be one reason for its better performance. The other intersections designs including redirect L&T, seven-phase, redirect 2L&T, CFI/MUT Combo, partial CFI, and reverse RCI showed mixed results across sites. A comprehensive analysis has been provided as Appendix 12.

4.3.2 Simulation Modeling

This section provides a detailed analysis of the pedestrian performance across twelve (12) three-phase alternative intersections and a conventional intersection. To assess the pedestrian performance of the proposed alternative intersection designs in comparison to a conventional design, an extensive series of simulation scenarios was conducted to obtain pedestrian travel times. Given that many of these alternative intersections have not yet been implemented in practice, simulation modeling provided a robust method for thoroughly evaluating each concept. PTV VISSIM (version 2024) was used to conduct pedestrian analysis, focusing on travel times and the number of stops. This analysis was facilitated by importing signal data from Synchro. It should be noted that pedestrian simulation modeling was conducted only on tests 1 (high turning condition with balanced traffic distribution on the major road), 4 (high turning condition with unbalanced distribution on the major road), 7 (moderate turning condition with balanced distribution on the major road), 10 (moderate turning condition with unbalanced distribution on the major road), 13 (low turning condition with balanced distribution on the major road), and 16 (low turning condition with unbalanced distribution on the major road) of Table 3.8

Among the twelve models analyzed, the thru-cut design had three variations based on crosswalk orientation: thru-cut with a standard crosswalk, thru-cut with Barnes dance crosswalk Type I, and thru-cut with Barnes dance crosswalk Type II. The thru-cut Barnes dance crosswalk Type I has no middle island on the minor road approach whereas the thru-cut Barnes dance Type II has the minor crosswalks connected through the middle islands on the minor approach. Figure 4.6 showed all the configurations of the assessed intersections with their pedestrian paths.

Pedestrians were given the right of way in all simulation models at all (signalized and unsignalized) conflicts with vehicles. Each intersection quadrant was allocated 90 pedestrians per hour, who were evenly distributed along pedestrian paths from their origin to their destination within the quadrant. For pedestrians needing to cross diagonally to reach their destination, their movement was evenly split between two routes, using the adjacent quadrant as a midway point to streamline routing decisions. The pedestrian walking speeds were based on a range between 3.5 ft/sec and 9 ft/sec, as reported in an NCDOT project (Hummer 2014). Specifically, for a selected percentage of pedestrian composition moving at a desired speed, the distribution was set at 20%, 20%, 30%, 20%, and 10% for walking speeds of 3.5 fps, 4 fps, 5 fps, 6 fps, and 9 fps, respectively.

Table 4.23 presents the average pedestrian travel times. The two-phase MUT, MUT redirect major (MUT #1), conventional, RCI, and thru-cut (standard crosswalk) designs exhibited relatively shorter travel times compared to the other intersections, with the two-phase MUT performing the best. The outstanding performance of the two-phase MUT may be attributed to the reduced number of phases compared to other alternative intersections and the conventional intersection.

This reduction decreases the number of red intervals that a pedestrian has to experience, as compared to the three-phase intersections and the four-phase conventional intersection.

Among the three variations analyzed for the thru-cut intersection, the standard crosswalk orientation within the thru-cut design emerged as the most effective in terms of pedestrian travel time. This superior performance may be due to the fact that, in the other variations, pedestrians must traverse longer distances, particularly when using diagonal crosswalks. These diagonal crosswalks often span a greater length compared to the traditional crosswalks positioned along the east and west legs of the standard thru-cut intersection. The results also reveal that the thru-cut Barnes dance crosswalk Type I configuration performed better than the thru-cut Barnes dance crosswalk Type II configuration. Reviewing simulation animations, it was found that pedestrians can access the diagonal crosswalk more easily than Type II to cross the major road in the presence of middle islands on minor approaches. Also, it is worth noting that the offset thru-cut design resulted in shorter travel times for pedestrians than thru-cut designs with Barnes dance crosswalks. As a possible reason for this finding, the offset thru-cut's signal phasing diagram increases green interval for pedestrians crossing minor roads. It should be noted that thru-cut designs could also utilize the same signal phasing as offset thru-cuts. However, for the purpose of comparison in this study, the research team considered a different signal phasing diagram for the thru-cut designs. Also, pedestrians crossing the major road will experience a slightly shorter travel distance at the offset thru-cut intersection than thru-cut designs with diagonal crosswalks.

Table 4.23 Ranking of Assessed Intersections Based on Average Travel Time

Rank	Intersection Type	Average Travel Time (sec)
1	Two-phase MUT	43
2	MUT #1 (Redirect Major Rd)	56
3	Conventional	58
4	RCI	60
5	Redirect L&T (Type I)	62
6	Thru-cut (standard crosswalk)	66
7	Redirect L&T (Type II)	68
7	Reverse RCI	68
8	CFI/MUT combo	70
8	MUT #2 (Redirect Minor Rd)	70
8	Offset Thru-cut	70
9	Redirect 2L&T	73
10	Partial CFI	81
11	Thru-cut (Barnes Dance-Type I)[a]	82
12	Seven-phase (Type II)	88
13	Thru-cut (Barnes Dance-Type II)[b]	94

[a] This type of Barnes dance crosswalk has no middle island on the minor road approach
[b] This type of Barnes dance crosswalk has middle islands on the minor approach

The relatively poor performance of the seven-phase intersection may be attributed to the longer cycle lengths and increased travel distances for pedestrians on the eastern side of the intersection. In other words, at the seven-phase intersection, the absence of a crosswalk on the east leg results in longer travel distances for some pedestrians. Based on Table 4.23, it was also found that shorter pedestrian travel times (about 14%) could be expected for CMF/CFI combo compared to partial CFI as pedestrians on one side of the intersection would experience shorter crosswalks and fewer traffic signals than a partial CFI.

Table 4.24 provides an overview of intersections that feature free-flow crossings and the associated conflicting traffic volumes at these crossings. Out of all the intersections examined, only four are distinguished by their inclusion of free-flow crossings: the reverse RCI, partial CFI, redirect 2L&T, and the CFI/MUT combo.

It is noteworthy that, despite both the reverse RCI and partial CFI incorporating two free-flow crossings, their impact on pedestrian comfort and safety varies. The reverse RCI presents challenges for pedestrians at those free-flow crossings due to the higher volume of conflicting traffic from major right turns.

Table 4.24 Free–flow Crossings for Pedestrians in each Intersection

Intersection Type	Free-Flow Crossing		
	N*	L*	C*
Conventional	0	0	0
Partial CFI	2	2	160
CFI/MUT Combo	1	1	80
RCI	0	0	0
MUT #1	0	0	0
MUT #2	0	0	0
Seven-Phase	0	0	0
Redirect 2L&T	1	1	80
Redirect L&T	0	0	0
Two-phase MUT	0	0	0
Offset Thru-cut	0	0	0
Thru-cut (standard crosswalk)	0	0	0
Thru-cut (Barnes Dance-Type I)	0	0	0
Thru-cut (Barnes Dance-Type II)	0	0	0
Reverse RCI	2	2	322

*N=Number of crossings, *L=Number of lanes crossed, *C=Average conflicting traffic volume (veh/hr)

4.4 Public Acceptance Scoring System (PASS) Analysis

The research team developed the public acceptance scoring system (PASS tool) to analyze the anticipated public acceptance of the three-phase designs included in this research project. In the first phase of the development of the new tool, several variables impacting public acceptance were identified. In the next step, throughout a series of meetings, NCDOT experts engaged in comprehensive discussions regarding variables influencing driver confusion (and wrong-way potential), user comfort, and business impacts. In summary, the NCDOT experts highlighted the importance of the variables within these categories and suggested modifications to better address public concerns. Table 4.25 provides the final list of ten measurable variables and scores included in PASS to evaluate public acceptance at alternative intersections. In Table 4.25, variables impacting driver confusion, pedestrian and bicyclists' discomfort, and business and driver discomfort are highlighted in red, brown, and yellow, respectively. The weight assigned to each variable ranges from 1 to 3, based on its significance. Each variable is independently scored on a scale from 1 to 5 for each design, with higher scores indicating better public acceptance. The individual scores are then multiplied by their respective weights to calculate the weighted scores. Finally, the weighted scores are summed across all 10 categories for each design, with a maximum possible overall score of 100.

Table 4.25 Measurable Variables Listed in PASS Tool*

No	Category	Variables	Measure of Effectiveness	Weight (1-3)	Seven-Phase	MUT #2	Redirect L&T	MUT #1	Offset Thru-cut	Thru-cut	CFI/MUT Combo	Two-Phase MUT	RCI	Redirect 2L&T	Reverse RCI	Partial CFI
1	Driver Confusion	Early Left-Turn	Whether a left turn lane is developed early (prior to the middle intersection)	**2**	5	5	5	5	5	5	4	5	5	4	5	3
2	Driver Confusion	Multiple Route Choices for Redirected Traffic	Whether drivers can violate to reach their destination using a direct route (instead of following the redirected pattern)	**1**	5	5	5	4	5	5	4	3	5	4	5	4
3	Driver Confusion	Unusual Maneuvers	Whether there are any unconventional traffic movements	**1**	4	3	3	3	3	3	3	1	1	2	1	3
4	Driver Confusion	Acute Intersection Angle (and Scissors Channelization)	Whether the redirected traffic intersects with opposite traffic movement at an acute angle (70 degrees)	**3**	5	5	5	5	5	5	4	5	5	4	5	3
5	Driver Confusion	Wrong-Way Entry	Whether there are any ""parallel lanes"" for wrong-way entry	**3**	5	5	5	5	5	5	4	5	5	4	5	3
6	Pedestrians and Bicyclists Discomfort	Extra Pedestrian Travel Distance	Whether pedestrians and bicyclists would experience a longer travel distance	**2**	5	5	5	5	4	4	4	5	4	4	3	3
7	Pedestrians and Bicyclists Discomfort	Indirect and Confusing Paths	Whether pedestrians and bicyclists should use an indirect (and confusing) path with possibilities for safety concerns	**2**	5	5	5	5	5	3	4	5	3	4	3	3
8	Business Impact and Driver Discomfort	Number of Additional Traffic Signals	Whether the redirected traffic demands on the major and minor roads should cross more than one traffic signal on their routes	**2**	4	3	4	3	3	3	4	1	3	3	1	5
9	Business Impact and Driver Discomfort	Redirected Access to Some Business Properties	Whether a percentage of traffic movements does not have direct access to business properties located at one or more corner(s) of the intersection	**3**	4	5	4	4	3	3	4	3	2	3	1	3
10	Business Impact and Driver Discomfort	Extra Lane Changes	The number of additional lane changes needed for redirected traffic to reach their destination.	**1**	3	3	3	5	3	3	5	3	3	3	3	3
Overall score					**92**	**92**	**91**	**90**	**84**	**80**	**80**	**78**	**75**	**72**	**66**	**65**

*The lowest scores for each variable type are shaded in grey.

Table 4.26 shows a summary of the PASS results based on hypothetical scenarios. The PASS results show that the seven-phase signal and partial MUT#2 will likely be the most accepted three-phase designs followed by Redirect L&T and partial MUT#1. This is expected as both seven-phase and MUT #2 redirect only about 7% and 4% of the total traffic (based on hypothetical scenarios), respectively. Partial CFI scored the lowest overall with reverse RCI scoring second lowest. Reverse RCI redirects about 23% of the total traffic. The partial CFI did not perform well mostly because of the driver confusion concerns such as early left-turn and acute intersection angle

All MUT designs (two-phase MUT, MUT #1, and MUT #2) will be among the most accepted designs for pedestrians and bicyclists. Reverse RCI and partial CFI scored lowest in this regard. Regarding business impact and driver discomfort, partial CFI and CFI/MUT combo resulted in the highest score mainly due to minimizing extra travel distances and lane changes.

Overall, based on Table 4.26, seven of the alternative designs with three-phase signals (seven-phase, redirect L&T, MUT #1 (Redirect Major Rd), MUT #2 (Redirect Minor Rd), offset thru-cut, thru-cut, and CMF/MUT combo) should perform better than two-phase designs. This confirms the initial hypothesis of our study regarding higher public acceptance of three-phase designs compared to RCI and two-phase MUT. More information regarding the PASS results is attached as Appendix 7.

Table 4.26 PASS Analysis of Three-Phase Intersections

Rank	Intersections	Red	User Discomfort (Yellow + Brown)	Overall
1	Seven-Phase	49	43	92
1	MUT #2	48	44	92
3	Redirect L&T	48	43	91
4	MUT #1	47	43	90
5	Offset Thru-cut	48	36	84
6	Thru-cut	48	32	80
6	CFI/MUT Combo	39	41	80
8	Two-Phase MUT	44	34	78
9	RCI	46	29	75
10	Redirect 2L&T	38	34	72
11	Reverse RCI	46	20	66
12	Partial CFI	31	37	65

4.5 Benefit over Cost (B/C) Analysis

The benefit/cost (B/C) analysis was conducted based on estimated ROW costs and travel time savings during peak hours due to shorter travel times by implementation of alternative designs.

4.5.1 Cost Estimations and ROW Considerations

The research team found the following values for cost/acre and cost/sqft using the methods described earlier in section 3.5. As shown in Table 4.27, the total average cost between all case study sites was found to be $21 per sqft. This value will be used later in the report when discussing ROW considerations.

Table 4.27 Average Cost of Land at Case Study Sites

Site #	Intersection	Average Cost ($/acre)	Average Cost ($/sqft)
1	Peachtree Ln @ New Bern Ave	$1,06,000	$24.4
2	Chapel Hill Rd @ Trinity Rd	$944,000	$21.7
4	Capital Blvd @ Old Wake Forest Rd	$1,018,000	$27.1
5	Capital Blvd @ Trawick Huntleigh	$488,000	$11.2
7	Briar Creek @ Briar Leaf Ln	$764,000	$17.5
8	NC 55 @ O'Kelly Chapel Rd	$ 1,010,000	$23.3

4.5.2 Travel Time Savings during Peak Hours

In order to find the travel time savings during peak hours, the average travel times of the tested alternative designs were compared to existing travel times for each case study site. The difference in average travel time when compared to existing conditions was then divided by 60 to find the average travel time per hour. This value was multiplied by the average number of vehicles per peak hour shown in the third column of Table 4.28. This number represents the average total travel time savings per hour. This value was then multiplied by four (peak hours per day) and then multiplied again by 260 (weekdays per year), resulting in the average travel time (in hours) saved per year as shown in column four of Table 4.28.

4.5.3 B/C Analysis

Using the average travel time savings per year from Table 4.28 and the NCDOT-approved value of $12.75 per hour of travel time saved, it is possible to estimate the monetary savings provided by three-phase designs as shown in Table 4.29. To estimate the cost of each design, the ROW values from Table 4.27 were multiplied with the assessed ROW required for each design. Comparing the yearly benefits of travel time savings to ROW costs shows that for most cases (with the exception of case study sites 1 and 2), three-phase designs have the potential to "break even" with ROW costs after only one year. As previously mentioned, it is important to note that this analysis does not consider many cost estimates from construction or benefit savings from crash reductions since both of these would require too many assumptions.

Table 4.28 Travel Time Savings at Case Study Sites

Intersection Type	Average Travel Time (Minutes)	Average Traffic (Vehicles/Hour)	Average Travel Time Saved (Hours/Year)
Case Study Site 1 New Bern Ave and Peartree Ln			
Existing	1.46	1,670	
Seven-Phase	1.52	1,670	0
Full MUT	1.35	1,520	2,960
MUT #1	1.34	1,530	3,350
MUT #2	1.45	1,570	256
RLT	1.42	1,670	1,270
Reverse RCI	1.45	1,480	396
Thru-cut	1.43	1,670	984
RCI	1.37	1,510	2,450
Case Study Site 2 Chapel Hill Rd and Trinity Rd			
Intersection Type	Average Travel Time (Minutes)	Average Traffic (Vehicles/Hour)	Average Travel Time Saved (Hours/Year)
Existing	1.74	3,200	
Seven-Phase	1.83	3,170	0
Redirect L&T	1.61	3,170	7,360
Case Study Site 4 Capital Blvd and Old Wake Forest Rd			
Intersection Type	Average Travel Time (Minutes)	Average Traffic (Vehicles/Hour)	Average Travel Time Saved (Hours/Year)
Existing	3.38	7,400	
CFI/MUT Combo	1.96	7,350	180,000
Full MUT	2.50	5,690	86,400
MUT #1	2.49	6,300	97,500
MUT #2	3.00	6,920	45,400
Partial CFI	2.08	7,770	174,000
Redirect 2L&T	2.74	7,190	80,200
Case Study Site 5 US-1 Capital Blvd and Trawick Rd			
Intersection Type	Average Travel Time (Minutes)	Average Traffic (Vehicles/Hour)	Average Travel Time Saved (Hours/Year)
Existing	2.17	5,540	
MUT #1	1.91	5,580	25,300
MUT #2	1.76	5,290	37,900
Case Study Site 7 Brier Creek Pkwy and Brier Leaf Ln			
Intersection Type	Average Travel Time (Minutes)	Average Traffic (Vehicles/Hour)	Average Travel Time Saved (Hours/Year)
Existing	4.41	2,770	
Thru-cut	2.29	2,510	91,900
Case Study Site 8 NC-55 and O'Kelly Chapel Rd			
Intersection Type	Average Travel Time (Minutes)	Average Traffic (Vehicles/Hour)	Average Travel Time Saved (Hours/Year)
Existing	3.04	4,460	
CFI/MUT Combo	2.24	4,460	61,100
Partial CFI	2.01	4,870	86,900

Table 4.29 B/C Analysis at Case Study Sites*

Case Study Site 1 New Bern Ave and Peartree Ln					
Intersection Type	Average Travel Time Saved (Hours/Year)	Average Travel Time Savings ($/Year)	ROW Cost Cost ($)	Annualized ROW Cost ($/Year)	B/C Ratio (per Year)
Seven-Phase	0	0	$405,000	$32,498	0.00
Full MUT	2,960	$37,800	$809,000	$64,916	0.58
MUT #1	3,350	$2,710	$809,000	$64,916	0.04
MUT #2	256	$3,270	$809,000	$64,916	0.05
Redirect L&T	1,270	$16,200	$405,000	$32,498	0.50
Reverse RCI	396	$5,050	$809,000	$64,916	0.08
Thru-cut	984	$12,600	$809,000	$64,916	0.19
RCI	2,450	$31,200	$809,000	$64,916	0.48
Case Study Site 2 Chapel Hill Rd and Trinity Rd					
Intersection Type	Average Travel Time Saved (Hours/Year)	Average Travel Time Savings ($/Year)	ROW Cost ($)	ROW Cost ($/Year)	B/C Ratio (per Year)
Seven-Phase	0	0	$360,000	$28,887	0.00
Redirect L&T	7,360	$93,800	$360,000	$28,887	3.25
Case Study Site 4 Capital Blvd and Old Wake Forest Rd					
Intersection Type	Average Travel Time Saved (Hours/Year)	Average Travel Time Savings ($/Year)	ROW Cost ($)	ROW Cost ($/Year)	B/C Ratio (per Year)
CFI MUT Combo	180,000	$2,300,000	$840,000	$67,404	34.12
Full MUT	86,000	$1,100,000	$900,000	$72,218	15.23
MUT #1	97,600	$1,240,000	$900,000	$72,218	17.17
MUT #2	45,400	$579,000	$900,000	$72,218	8.02
Partial CFI	174,000	$2,220,000	$1,520,000	$121,969	18.20
Redirect 2L&T	80,000	$1,023,000	$1,210,000	$97,094	10.54
Case Study Site 5 US-1 Capital Blvd and Trawick Rd					
Intersection Type	Average Travel Time Saved (Hours/Year)	Average Travel Time Savings ($/Year)	ROW Cost ($)	ROW Cost ($/Year)	B/C Ratio (per Year)
MUT #1	25,300	$323,000	$372,000	$29,850	10.82
MUT #2	37,900	$483,000	$372,000	$29,850	16.18
Case Study Site 7 Brier Creek Pkwy and Brier Leaf Ln					
Intersection Type	Average Travel Time Saved (Hours/Year)	Average Travel Time Savings ($/Year)	ROW Cost ($)	ROW Cost ($/Year)	B/C Ratio (per Year)
Thru-cut	92,000	$1,170,000	$582,000	$46,701	25.05
Case Study Site 8 NC-55 and O'Kelly Chapel Rd					
Intersection Type	Average Travel Time Saved (Hours/Year)	Average Travel Time Savings ($/Year)	ROW Cost ($)	ROW Cost ($/Year)	B/C Ratio (per Year)
CFI/MUT Combo	61,100	$779,000	$722,000	$57,935	13.45
Partial CFI	86,900	$1,110,000	$1,300,000	$104,315	10.64

*An interest rate of 5% and a design period of 20 years were used for the annual cost calculations. The formula for the calculation of annualized right of way (ROW) costs is as follows: $A = P \times \frac{i(1+i)^n}{i(1+i)^n - 1}$

4.6 Traffic Control Devices (TCD)

The research team completed condition diagrams of ten existing three-phase designs showing the signage and pavement markings at each of the sites. The condition diagrams were prepared regarding information and guidance needed in terms of traffic control devices (TCDs) at three-phase intersections. An example condition diagram showing existing signage for the partial MUT #1 depicted in Figure 2.3 is shown below in Figure 4.7. The remaining nine condition diagrams are attached as Appendix 13. Of note, the condition diagram for the CFI/MUT combo in Fairbanks, Alaska does not include all traffic signs because an updated Google Street view is not yet available for that location. However, the research team contacted Alaska DOT and received the full package of design plots (including signage information).

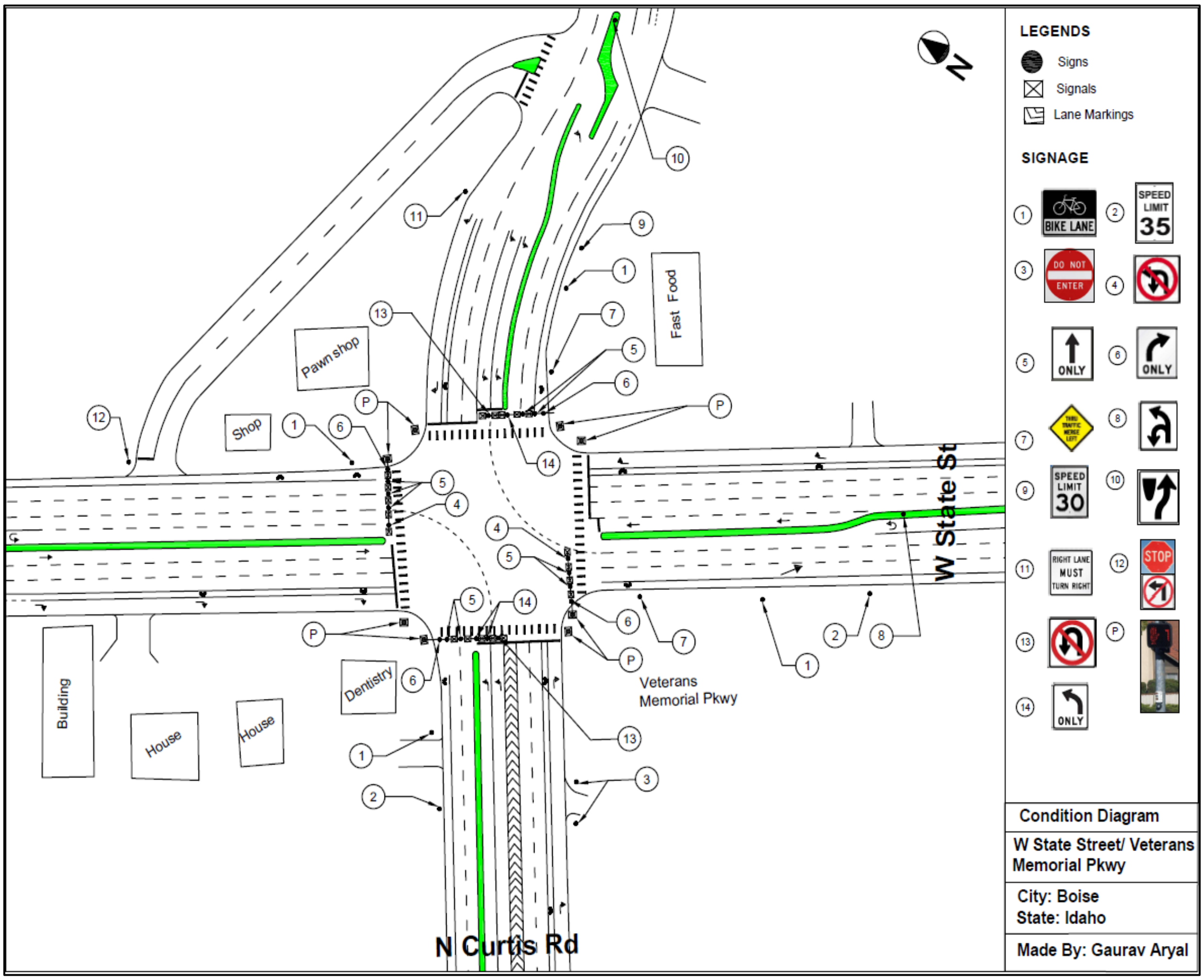

Figure 4.7 Condition Diagram for Partial MUT #1 in Boise, ID

4.7 Framework Recommended for Selecting Alternative Intersections

This section describes the framework developed to answer the central question this proposal seeks to address: where are the suitable locations for three-phase designs? To answer this question, a framework for intersections with three-phase signals (FITS) was developed in this project. The

FITS includes five measures of effectiveness (MOEs) to identify locations where three-phase alternatives could be the most suitable. The MOEs included are:

- Right-of-way Considerations
- Traffic Operations
- Traffic Safety
- Pedestrian and Bicycle Safety, and
- Public Acceptance

4.7.1 Right-of-way (ROW) Considerations

ROW considerations at alternative intersections were reviewed based on the primary goal of fitting those intersections within the existing ROW or with the minimum additional ROW needed compared to the existing intersection. Figure 4.8 shows the flowchart recommended based on this primary goal. It should be noted that the flowchart shown in Figure 4.8 has two parts to separate three-phase designs with DLT (displaced left-turn) ramps on the right side from the rest of the intersection designs on the left side, as they require different ROW considerations (typically larger ROW sizes). Also, single quadrant and offset T intersections were excluded from Figure 4.8 as they have specific ROW requirements compared to the other alternative designs listed. As a reminder, full (two-phase) versions of CFI, MUT, and CFI/MUT were not included in the ROW consideration either based on the scope of the study.

Regarding the distance to adjacent signalized intersections, a longer distance (more than 1,000 ft) is recommended to consider if there might be concerns regarding possible spillback due to high demands at U-turn or DLT crossovers. Additionally, further evaluations (including simulation modeling) are recommended to estimate maximum queue lengths. The 1,000-ft distance was recommended based on the maximum queue lengths recorded in hypothetical simulation tests as well as MUTCD's (2023) threshold considered for signal warrant #6 (signal coordination warrant). Moreover, it should be noted that the negative impacts of short intersection spacings on signal coordination and the risk of spillback would be less at DLT and U-turn crossovers because of their half-signals. A signal is called a half-signal when it stops only one of the through traffic movements on the major road (similar to DLT and U-turn crossovers); however, a full signal would stop both through traffic movements on the major road (similar to a conventional intersection) (Molan and Hummer 2018). Table 4.30 also includes more information regarding the other criteria listed in Figure 4.8 (in the diamonds).

According to Figure 4.8, thru-cut, offset thru-cut, and seven-phase designs have the least ROW restrictions among all alternatives with three-phase signals. These three designs could be implemented more easily than others without needing to add U-turn crossovers if adjacent streets and/or intersections are available to redirect through traffic demands from the minor roads to existing adjacent streets and/or intersections. Figure 4.9 shows an example from Holly Springs, NC, for this relative advantage of thru-cut, offset thru-cut, and seven-phase intersections.

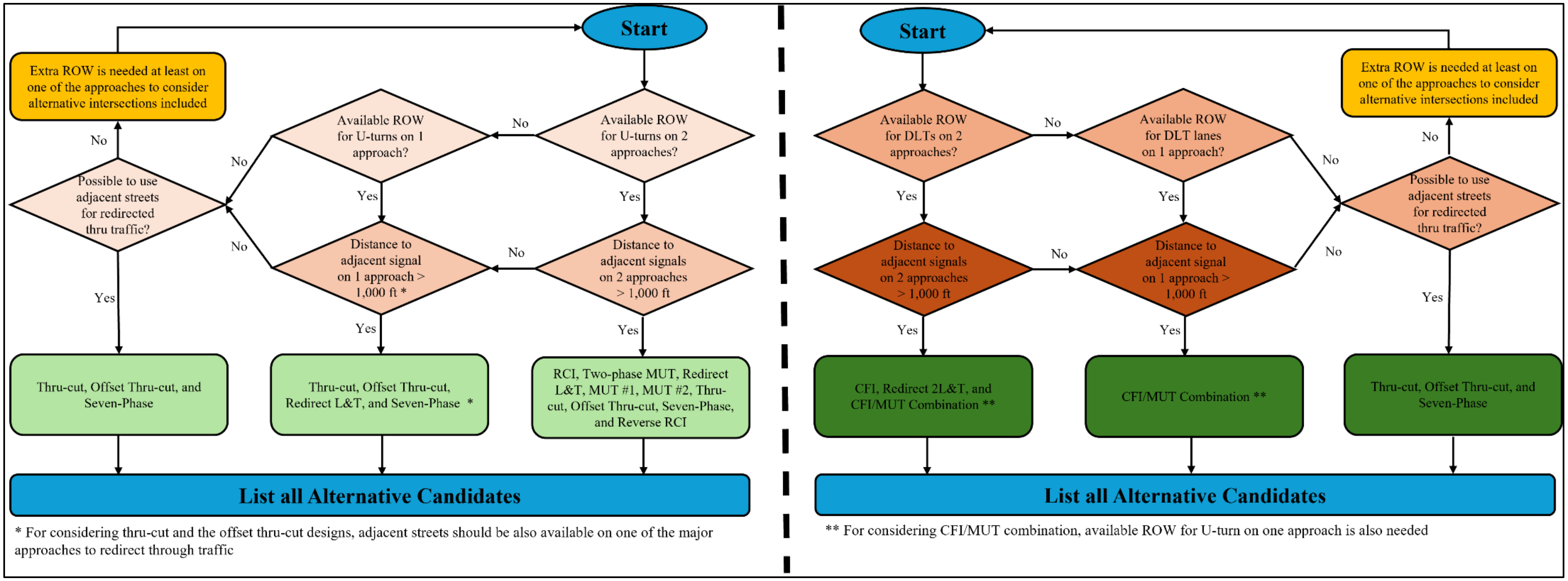

Figure 4.8 Flowchart Recommended for Right-of-Way (ROW) Considerations of Alternative Intersections

Figure 4.9 An Example of a Thru-cut Intersection without U-turn Crossovers in S Main St and Village Walk Dr in Holly Springs, NC

Table 4.30 Supplemental Information Needed to Use Figure 4.8 (ROW Flowchart)

Available ROW Needed for U-turns	Available ROW Needed for DLTs	Conditions Needed to use Adjacent Streets and/or Intersections
Minimum U-turn spacing of 400 ft (600-800 ft if possible) to the middle intersection	Minimum distance of 400 ft from the DLT crossover to the middle intersection (500-600 ft if possible)	Consider only for alternatives with redirected through traffic movements from minor legs: thru-cut, offset thru-cut, and seven-phase
Available space for building bulb-outs with a minimum U-turn radius of 30 feet (45 feet at intersections with more trucks)	Available extra space for building DLT ramps with parallel right-turn lanes	Relatively low through traffic demand on minor roads compared to total intersection traffic. A maximum ratio of 10% for redirected through traffic over total traffic (RT/TT = 0.1) is recommended. At higher ratios, further investigations (including simulation modeling) are necessary
No operational and safety concerns regarding possible access points (from adjacent businesses) within the distance between the middle intersection and the U-turn crossovers	No sight distance concerns based on ISD (intersection sight distance) considerations of AASHTO Green Book (2018) [3]	Presence of adjacent streets and/or intersections with relatively insignificant distance (less than 800 ft) from the middle intersection
No sight distance concerns based on ISD (intersection sight distance) considerations of AASHTO Green Book (2018) [3]		Maximum AADT on the minor road < 25,000 veh/day

Redirect L&T and CFI/MUT combination intersections could be the next designs in the ranking of alternatives with the least ROW restrictions, as their ROW requirements only affect one approach, with no extra ROW needed on the other three approaches.

As another consideration regarding the ROW of alternative intersections, ROW costs for converting a conventional intersection to the 12 alternative designs listed in Figure 4.8 were estimated based on the geometric features included in the hypothetical simulation models. Table 4.31 ranks the alternative intersections based on ROW cost estimations and the findings identified in Figure 4.8.

Table 4.31 Alternative Intersections' Ranks Based on ROW Considerations

Intersection Design	Extra ROW Needed (sq ft)	ROW Costs (Million $) *	Number of Approaches Impacted	Rank
Seven-Phase	0 to 16,600	0 to 1.71	0 or 1	1
Thru-cut	0 to 33,200	0 to 3.42	0 or 2	2
Offset Thru-cut	0 to 34,200	0 to 3.52	0 or 2	3
Redirect L&T	16,600	1.71	1	4
CFI/MUT Combination	31,000	3.20	1	5
Reverse RCI	33,200	3.42	2	6
RCI	33,200	3.42	2	6
MUT #1	33,200	3.42	2	6
MUT #2	33,200	3.42	2	6
Two-Phase MUT	33,200	3.42	2	6
Redirect 2L&T	44,600	4.60	2	11
Partial CFI	56,000	5.77	2	12

*$21 per sq ft near case study sites based on unit costs from Zillow's website for NC (www.zillow.com)

It should be noted that the cost estimations shown in Table 4.31 might vary significantly depending on the specific circumstances of different intersection improvement projects, particularly due to variations in property values across different districts in urban, suburban, and rural areas. However, the ranking provided in Table 4.31 should offer a fair comparison among the alternative intersections based on their ROW characteristics.

According to Table 4.31, the partial CFI was identified as the most expensive alternative, with higher ROW considerations needed compared to other intersection designs. Conversely, the CFI/MUT combination could reduce ROW requirements and costs significantly, as it only needs extra ROW on one approach. Specifically, the ROW costs of a CFI/MUT combination could be about 55% (about $2.5 million) cheaper than a partial CFI.

Seven-phase, thru-cut, and offset thru-cut were found to be the top three intersections in terms of minimal ROW requirements. As previously explained, no extra ROW (for implementing U-turn crossovers) might be needed for these three designs if adjacent streets and/or intersections are available. Note that the ROW costs for an offset thru-cut were estimated to be slightly higher than for a thru-cut due to the 50-ft offset between its two minor legs. Redirect L&T was found to be another alternative with one of the lowest ROW cost estimates, as it only requires extra ROW on one approach.

All alternatives with two U-turn crossovers were estimated to have similar ROW costs and requirements since they share a similar ROW size, but with different traffic movement routes.

Overall, based on Table 4.31, alternative intersections with three-phase signals have fewer ROW restrictions, as the top five ranks belong to those designs in Table 4.31. Moreover, in terms of ROW costs, only partial CFI and redirect 2L&T are more expensive than the two-phase alternatives (MUT and RCI).

4.7.2 Traffic Operations

Traffic operations is the second MOE included in the FITS. Table 4.32 presents the alternative designs recommended for traffic operation improvements at intersections. The recommendations in Table 4.32 are mainly based on the simulation results identified from case study sites and hypothetical tests in the current study, and the results presented in a recent study by Luo et al. (2024), using a similar methodology and simulation modeling approach.

Table 4.32 Recommended Alternatives for Traffic Operation Improvements

Capacity Levels	Traffic Distributions	Turning Traffic Conditions		
		High Turning	Moderate Turning	Low Turning
Near Capacity (v/c=0.9)	Unbalanced Traffic on the Major Road	1. Redirect 2L&T, 2. Offset thru-cut, and Thru-cut 3. RCI, MUT #1, and Reverse RCI	1. CFI/MUT Combo, and Partial CFI, 2. Offset thru-cut, MUT #1, and Redirect 2L&T 3. Thru-cut	1. CFI/MUT Combo, 2. MUT #1, and Two-phase MUT, 3. RCI and Reverse RCI
	Balanced Traffic on the Major Road	1. Partial CFI, 2. CFI/MUT Combo, 3. Offset Thru-cut, Thru-cut, MUT #1 and RCI	1. CFI/MUT Combo, and Partial CFI, 2. Offset Thru-cut, 3. MUT #1, and RCI	1. CFI/MUT Combo, and Partial CFI 2. MUT #1, and Two-phase MUT, 3. RCI and Conventional
At Capacity (v/c=1.0)	Overall	1. CFI/MUT Combo, and Partial CFI, 2. MUT #1	1. CFI/MUT Combo, and Partial CFI, 2. MUT #1, RCI, and Two-phase MUT	NA*

*No simulation tests were conducted in low turning conditions in the research by Luo et al. (2024)

According to Table 4.32, the CFI/MUT combination design performs best across various capacity levels, turning traffic conditions, and traffic distributions, except in high turning traffic conditions with unbalanced traffic on the major road. In this case, the redirect 2L&T design demonstrated superior traffic operations compared to other alternatives.

The partial CFI design should perform similarly to the CFI/MUT combination but does not rank among the top designs during low turning ratios with unbalanced traffic on the major road.

The offset thru-cut and thru-cut designs were listed among the top-ranked designs in all categories except for low turning traffic and at-capacity scenarios in Table 4.32. Reverse RCI was also found to be a promising design for intersections with near-capacity levels and unbalanced traffic conditions.

The RCI design appears promising in most traffic conditions included in Table 4.31. In contrast, the two-phase MUT design only appeared as a top-ranked design in three conditions: both low turning traffic ratios at near-capacity levels, and moderate turning conditions at at-capacity levels.

Conventional intersections are expected to be effective in sites with low turning and balanced traffic conditions but do not perform well under other traffic conditions.

All intersection designs were mentioned at least once in Table 4.32, except for the seven-phase, redirect L&T, and MUT redirected minor (MUT #2) designs. Despite their absence from Table 4.33, these designs may also show potential in specific contexts. For instance, based on the results from case study site #5 (the intersection of Capital Blvd and Trawick Rd in Raleigh, NC), MUT #2 could significantly outperform MUT #1 and conventional intersection designs. At site #5, traffic counts revealed an average of 35 left-turns per hour on the major road and 127 left-turns from minor roads. MUT #2 could perform better than MUT redirected major (MUT #1) due to its ability to handle high left-turn demands from minor roads by redirecting them to U-turn crossovers, thus reducing delays on the major road. This shift in functionality at site #5, where left-turn demand was higher on minor roads, indicates that MUT #2 might be more effective in similar scenarios. However, this finding requires further investigation in future studies.

Note that Table 4.32 might not fully capture the expected performance on corridors with several signalized intersections spaced closely together. The results could differ based on the potential for signal progression in those designs. The research team did not present a specific table to assess the impact of signal progression, as it varies significantly across different corridors depending on traffic characteristics such as intersection spacing and corridor speed. However, five alternatives—RCI, two-phase MUT, offset thru-cut, thru-cut, and redirect 2L&T—could show improved performance on corridors with multiple signalized intersections.

The following AADT thresholds are also recommended to consider based on AADT data collection from the existing three-phase intersections listed in Table 2.13:

- Similar to the FHWA guide for RCIs (Hummer et al. 2014), a maximum AADT of 25,000 veh/day is recommended on the minor road for thru-cut, reverse RCI, redirect L&T, MUT #1, MUT #2, and partial CFI/MUT combination.
- Thresholds of 40,000 and 65,000 veh/day are recommended for the maximum AADTs on four-lane and six-lane roads, respectively, for consideration of any of the three-phase intersections mentioned above in the previous bullet point (and listed in Table 2.13).
- For the full CFI/MUT combination design, the AADT thresholds of 40,000 and 65,000 veh/day could be considered on both intersecting roads.

4.7.3 Traffic Safety

One of the main factors affecting intersection safety is the number of conflict points where vehicles navigating the intersection could potentially collide. For the safety analysis of the FITS (framework for intersections with three-phase signals), the research team created two spreadsheet-based tools to guide NCDOT in selection of safe alternatives: 1) Conflict Point Analysis (CPA), and a specific version of the FHWA's SSI (Safe System Intersections) for three-phase designs.

4.7.3.1 Conflict Point Analysis

The CPA tool provides a quick analysis of the safety performance of three-phase designs compared to two-phase MUT, RCI, and conventional designs at a given intersection. The CPA tool was essential for safety analysis in our study as the current FHWA's SSI (Porter et al., 2021) does not include any alternative designs with three-phase traffic signals. This tool is available in Appendix 6.

Utilizing the CPA tool, the research team assessed the safety performance of three-phase designs. Table 4.33 presents alternative designs recommended for traffic safety improvements at different segments and the whole network.

Table 4.33 Recommended Alternatives for Traffic Safety Improvements Based on CPA

Location	Reducing FI Crashes*	Reducing Total Crashes
At the Middle Intersection	1. Reverse RCI and RCI 2. Offset T 3. Thru-cut, Offset Thru-cut, and Redirect 2L&T	1. Offset T 2. Reverse RCI and RCI 3. Two-Phase MUT 4. MUT #1
Near DLT and U-turn Crossovers	All designs except Offset T, CFI, CFI/MUT Combo, Single Quadrant, and Redirect 2L&T	1. Redirect L&T, and Seven-Phase 2. Single Quadrant 3. CFI/MUT Combo 4. MUT #2
The Whole Network	1. Reverse RCI and RCI 2. Thru-cut, and Offset Thru-cut 3. Offset T 4. Two-Phase MUT	1. Reverse RCI 2. RCI, and Offset T 3. Two-Phase MUT 4. Redirect 2L&T

*Fatal and injury crashes

Based on Table 4.33, the Reverse RCI and RCI are the safest alternative intersections. This is an expected finding, as these designs have significantly fewer conflict points compared to other intersections included in the analysis. Also, the RCI is well-known as one of the safest intersection designs, according to past studies. Thru-cut and offset thru-cut were ranked second in their potential for reducing FI (Fatal and Injury) crashes. Offset T and two-phase MUT were also identified as some of the safest designs for reducing both FI and total crashes. Among alternatives featuring a DLT ramp, the redirect 2L&T design was the only one listed among the top designs for reducing total crashes.

4.7.3.2 FHWA's SSI for Three-Phase Alternative Intersections

The research team followed the instructions given in the FHWA's SSI manual (Porter et al. 2021) to create a spreadsheet version of the manual with a specific focus on three-phase alternatives compared to conventional, RCI, and two-phase MUT. Therefore, similar to the CPA tool, users will be able to run a quick analysis of the safety performance of three-phase designs at a given intersection. However, unlike the FHWA's SSI manual, the SSI tool developed in our research includes only protected signal controls, and it does not conduct any evaluation regarding non-motorized users. The SSI tool developed is available in Appendix 5.

Using the SSI tool developed, Table 4.34 presents the alternative designs recommended for traffic safety improvements based on the SSI analysis conducted on hypothetical simulation tests.

Table 4.34 Recommended Alternatives for Traffic Safety Improvements Based on SSI Analysis

Rank	Intersection Type	Intersection Score	Conflict Type SSI Scores			
			Nonmotorized	Diverging	Merging	Crossing
1	Reverse RCI	92	NA*	95	92	89
2	RCI	89	NA	97	93	79
3	Thru-cut	87	NA	97	93	72
3	Offset Thru-cut	87	NA	97	93	72
5	Redirect L&T	80	NA	98	96	55
6	Two-Phase MUT	80	NA	98	96	55
7	Redirect 2L&T	80	NA	98	96	54
8	Seven-Phase	79	NA	98	95	53
9	MUT #1	79	NA	98	96	52
10	Offset T	74	NA	98	96	43
11	CFI/MUT Combo	74	NA	99	97	42
12	MUT #2	74	NA	99	98	42
13	Single Quadrant	74	NA	99	98	42
14	Conventional	71	NA	99	98	36
15	Partial CFI	70	NA	99	98	35

*Not applicable (analysis was not conducted for non-motorized users)

According to Table 4.34, the top four safest designs identified through the SSI analysis are similar to those found in the CPA analysis (Table 4.33), with only one difference: the offset T received a lower rank in the SSI analysis. This discrepancy arises from differences in the assumptions regarding exposure estimation between the two tools. While the differences between Table 4.33 and Table 4.34 are minor, it is recommended to apply both analyses to achieve a comprehensive safety assessment in intersection improvement projects.

Note that no evaluations were conducted regarding driver confusion and the potential of wrong-way movements in this part because factors impacting driver confusion have been evaluated in the next section (titled "public acceptance scoring system for alternative intersections"). Therefore, to avoid an overlap with those results, the research team did not analyze driver confusion in this section.

4.7.4 Pedestrian and Bicycle Safety

Regarding pedestrian and bicycle safety, FITS utilizes the 20-flag method developed in the NCHRP Report 948 (2021). The 20-flag method evaluates the expected safety and comfort pedestrians and bicyclists will experience at a particular intersection by providing either no flag, a yellow flag (discomfort), or red flag (safety concern) for 20 different criteria. Table 4.35 shows the results of this analysis for 12 three-phase designs in a comparison with conventional, RCI, and two-phase MUT based on assumptions included in hypothetical simulation tests.

Note that the intersection designs were ranked based on the total number red flags, with ties resolved by considering the number of yellow flags, identified in Table 4.35. According to Table 4.35, the offset T was found to have the highest number of red flags among all the intersections included. The CFI/MUT combination was ranked eighth in Table 4.35; therefore, the CFI/MUT combination could be a safer alternative than the partial CFI at intersections with pedestrian and bicycle demands. The single quadrant, MUT #1, two-phase MUT, and thru-cut (Barnes Dance-Type II) were found to be the safest designs for pedestrians and bicyclists. These designs had only four red flags, which is four fewer than a conventional design. The offset T had the highest percentage of red flags at 27%, followed by partial CFI at 23%. Note that the offset thru-cut resulted in two more red flags compared to the thru-cut (Barnes Dance-Type II) because pedestrians face a longer multilane crossing when crossing the major street, as there is no central island (refuge) like in thru-cut designs.

Table 4.35 Recommended Alternatives for Pedestrian and Bicycle Safety Improvements Based on 20-Flag Analysis

Design/ Flags	Offset T	Partial CFI	Seven-phase (Type I)	Reverse RCI	Seven-phase (Type II)	Redirect 2L&T	CFI/MUT Combo	Conventional	Redirect L&T (Type I)	Thru-cut (Barnes Dance-Type I)	Offset Thru-cut (Type II)	Offset Thru-cut (Type I)	Thru-cut (Standard crosswalk)	MUT #2	Redirect L&T (Type II)	RCI	Thru-cut (Barnes Dance -Type II)	Two-phase MUT	MUT #1	Single Quadrant
Yellow Flags	4	2	2	8	2	2	2	2	1	4	2	2	2	2	1	8	6	4	4	4
Red Flags	14	12	10	8	8	8	8	8	7	6	6	6	6	6	6	4	4	4	4	4
% of Yellow	8%	4%	4%	15%	4%	4%	4%	4%	2%	8%	4%	4%	4%	4%	2%	15%	12%	8%	8%	8%
% of Red	27%	23%	19%	15%	15%	15%	15%	15%	13%	12%	12%	12%	12%	12%	12%	8%	8%	8%	8%	8%
% Flagged	35%	27%	23%	31%	19%	19%	19%	19%	15%	19%	15%	15%	15%	15%	13%	23%	19%	15%	15%	15%
Rank	20	19	18	17	13	13	13	13	12	11	7	7	7	7	6	5	4	1	1	1
Designs Rank	16	15	14	13	9	9	9	9	NA	NA	NA	7	NA	7	6	5	4	1	1	1

4.7.5 Public Acceptance

In the last step of the FITS, the Public Acceptance Scoring System (PASS) at Alternative Intersections was developed to provide insights regarding public acceptance potential of the three-phase alternatives. Particularly, the PASS aims to assist decision-makers and designers in comparing alternatives based on expected public acceptance. In developing the PASS, the research team identified and listed several variables impacting public acceptance at intersections reviewing literature. Those variables were categorized into three groups: 1) drivers wrong-way potential, 2) pedestrians and bicyclists' discomfort, and 3) business impact and driver discomfort.

To develop the PASS tool, the research team had four (4) focus group meetings with experts from different units of the North Carolina Department of Transportation (NCDOT) to receive feedback on the selection of the appropriate variables from the list, and rank the variables based on their significance to the public and give appropriate weightage to each. The PASS tool developed is available in Appendix 4.

Table 4.36 summarizes the results of the PASS analysis. According to Table 4.36, the seven-phase, MUT redirected minor (MUT #2), redirect L&T, and MUT redirected major (MUT #1) designs are the most recommended alternatives for improving public acceptance in future intersection projects. Overall, three-phase designs could perform better than two-phase designs, primarily because they redirect fewer traffic movements. Since MUT #1, thru-cut, and offset thru-cut also showed potential in all other MOEs discussed above, they could be considered promising alternatives where the implementation of two-phase designs might be challenging due to public acceptance concerns. In other words, while many three-phase designs performed similarly to two-phase designs (or even better in some MOEs), they would likely result in higher public acceptance.

On the other hand, partial CFI, reverse RCI and redirect 2L&T were ranked lower than two-phase MUT and RCI. Reverse RCI got a significantly lower score in the third group (business impact and driver discomfort) because it increases travel distance for a relatively high percentage of total traffic demand. Partial CFI and redirect 2L&T also showed some concerns regarding wrong-way potential as their scores were the lowest in this category. Regarding partial CFIs, similar results were found in a recent study (Adsit et al., 2022).

Table 4.36 Recommended Alternatives for Public Acceptance Improvements Based on PASS Analysis

Rank	Intersections	Drivers Wrong-way Potential	Pedestrians and Bicyclists' Discomfort	Business Impact and Driver Discomfort	Overall
1	Seven-Phase	49	20	23	92
1	MUT #2	48	20	24	92
3	Redirect L&T	48	20	23	91
4	MUT #1	47	20	23	90
5	Offset Thru-cut	48	18	18	84
6	Thru-cut	48	14	18	80
6	CFI/MUT Combo	39	16	25	80
8	Two-Phase MUT	44	20	14	78
9	RCI	46	14	15	75
10	Redirect 2L&T	38	16	18	72
11	Reverse RCI	46	12	8	66
12	Partial CFI	31	12	22	65

4.7.6 General Recommendations

Figure 4.10 shows the different components, tools, and methods recommended to follow the FITS (framework for intersections with three-phase signals) for identifying alternative designs with potential in future intersection implementation projects.

As shown in Figure 4.10, it is recommended to evaluate ROW considerations in the first step to list all possible alternatives based on existing ROW restrictions. In the next step, the other four MOEs of the design candidates should be reviewed to determine the most appropriate alternative for a given intersection site.

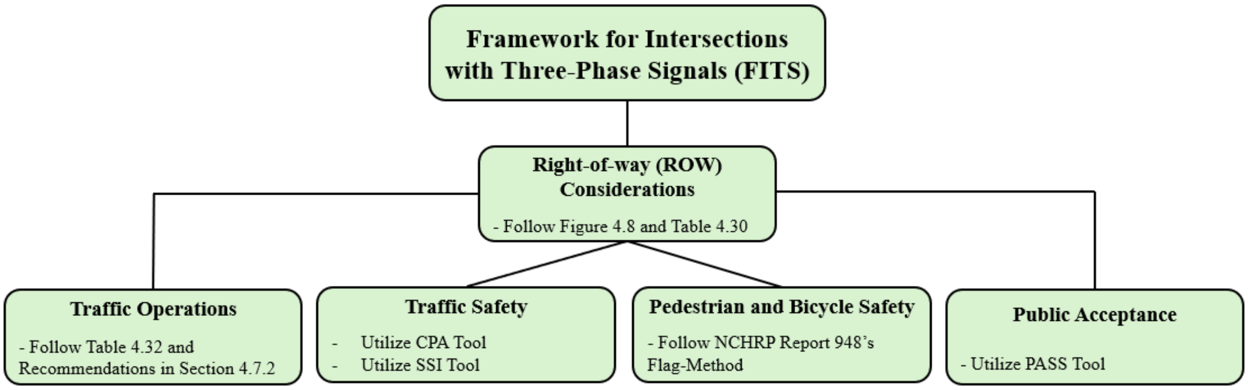

Figure 4.10 Recommended Framework for Selecting Appropriate Intersections with Three-Phase Signals

4.7.7 Examples for Framework's Application

As an example, to show framework's application, Table 4.37 was developed applying FITS for hypothetical scenarios included in this study (Table 3.8). According to FITS, Table 4.37 ranks all intersection designs based on five MOEs outlined in the framework.

Table 4.37 Alternative Intersections' Ranks Following FITS Based on Hypothetical Simulation Tests Included in this Study

Rank	Intersections	Sum	ROW Considerations	Traffic Operations	Traffic Safety *	Pedestrian and Bicycle Safety	Public Acceptance
1	Thru-cut	17	2	3	3	3	6
2	Offset Thru-cut	20	3	3	3	6	5
3	MUT #1	22	6	3	8	1	4
4	RCI	24	6	3	2	4	9
5	Two-Phase MUT	27	6	7	5	1	8
5	Redirect L&T	27	4	10	5	5	3
7	CFI/MUT Combo	30	5	1	10	8	6
8	Seven-Phase	33	1	12	8	11	1
9	MUT #2	34	6	11	10	6	1
10	Reverse RCI	35	6	7	1	10	11
11	Redirect 2L&T	41	11	7	5	8	10
12	Partial CFI	49	12	1	12	12	12

*Only SSI results were considered in this table

In Table 4.37, thru-cut and offset thru-cut emerged as the best alternative designs, showcasing strong performance across all five MOEs. These designs consistently ranked within the top six for each MOE. In contrast, other alternatives exhibited varying levels of effectiveness across different MOEs. For instance, while the partial CFI was rated the best for traffic operations, it received one of the lowest rankings in the remaining four MOEs. MUT #1 (Redirect Major Rd) secured the third rank with an insignificant difference compared to RCI (the fourth rank). Both RCI design and the two-phase MUT were ranked lower than three of the three-phase intersection designs: offset thru-cut, MUT #1, and thru-cut. Redirect L&T also performed the same as a two-phase MUT. The CFI/MUT design ranked seventh, outperforming the partial CFI in four MOEs and matching it in traffic operations. As a result, the CFI/MUT could be a promising alternative where there are concerns about implementing a partial CFI.

Despite the explanations given above, two important notes should also be taken into account: 1) the ranking provided in Table 4.37 is not weighted, and it could be significantly changed by considering different weights based on various priorities in projects, and 2) while some of the designs did not receive a high rank, they might still have potential in specific conditions. For example, although redirect 2L&T was ranked as the seventh design in traffic operations based on Table 4.37 from a general comparison among different designs, it will be the best design in terms of traffic operations during unbalanced traffic conditions with high turning traffic ratios, as shown in Table 4.33.

4.7.8 Where are the Suitable Locations for Three-Phase Intersections?

The researchers believe that following the framework (titled FITS) presented in this report will help traffic engineers make informed decisions about where three-phase intersections could perform well. However, the question of "where the suitable locations are for three-phase intersections" does not have a unique answer in all intersection sites. As illustrated by the framework presented in the previous section of this report, the answer might vary in different intersection improvement projects based on differences in terms of several factors such as stakeholders' priorities, traffic conditions, ROW restrictions, available budget, presence of adjacent business properties and residential districts.

Chapter 5 Conclusions

5.1 Summary of Results

This study identified some of the benefits and drawbacks of 12 new alternative intersection designs with three phases, comparing them to conventional, two-phase MUT (median U-turn), and RCI (reduced conflict intersection) designs. To the best of the authors' knowledge, many of these designs have not been studied previously, making this research the first to evaluate them. All intersections were evaluated considering various measures of effectiveness (MOEs) in terms of traffic operations, safety, pedestrians and bicyclists' performance, right-of-way (ROW), and public acceptance. Overall, three-phase intersections designs were found to have potential benefits in all MOEs. The following paragraphs summarize the most important findings of the research.

To address the central question of this proposal, "Where are the suitable locations for three-phase designs?" a framework for intersections with three-phase signals (FITS) was developed in this project. Including all five MOEs selected, FITS has several tables, flowcharts, and spreadsheet-based tools to assist transportation professionals in selecting suitable designs with three-phase or two-phase signals for different intersection sites. Excluding flag method developed in NCHRP Report 948 (2021), the rest of the spreadsheet-based methods were developed by the research team, including PASS (public acceptance scoring system), CPA (conflict point analysis), and SSI (safe system intersections) for new alternatives (following FHWA's SSI method, 2021).

Overall, based on FITS applied to hypothetical scenarios (Table 3.8) in this study, the thru-cut and offset thru-cut designs were identified as the most suitable options for future intersection improvement projects compared to other designs. RCI and MUT #1 (with a three-phase signal that redirects left turns from the major road) were ranked the second-best designs based on FITS. Other alternatives with three-phase signals also demonstrated potential suitability under certain conditions, as indicated in the current report.

According to the traffic operations analysis, six of the three-phase designs—offset thru-cut, thru-cut, reverse RCI, partial CFI, CFI/MUT combo, and MUT #1—could demonstrate similar or even superior performance to two-phase intersections (such as two-phase MUT and RCI) under certain traffic conditions. This suggests that three-phase designs can offer operational benefits not only compared to conventional designs but also over two-phase designs in specific scenarios, such as intersections with high turning traffic demands. This finding indicates that there may be no advantages to redirecting a portion of the traffic demand in two-phase designs such as the two-phase MUT. Additionally, redirecting this extra traffic could potentially have a negative impact on the overall network performance of two-phase alternatives.

Regarding traffic safety, reverse RCI and RCI should be the safest intersections designs, followed by thru-cut and offset thru-cut design as the second-best intersections based on surrogate safety assessments conducted in this study. Excluding the reverse RCI, all these intersections could also perform very well in terms of pedestrian and bicycle safety based on flag method assessments developed in NCHRP Report 948 (2021). Also, it should be noted that MUT designs (MUT #1, MUT #2, and two-phase MUT) could also show significant potential in improving safety for pedestrians and bicyclists.

Based on the results identified conducting the PASS analysis, seven of the alternative designs with three-phase signals (seven-phase, redirect L&T, MUT #1, MUT #2, offset thru-cut, thru-cut, and CMF/MUT combo) should result in better public acceptance than two-phase designs. This finding confirms the initial hypothesis presented in the study.

Thru-cut, offset thru-cut, and seven-phase designs have the least ROW restrictions among all alternatives. These three designs could even be implemented without needing to add U-turn crossovers if adjacent streets and/or intersections are available to redirect through traffic demands from the minor roads to existing adjacent streets and/or intersections. Also, based on the benefit/cost (B/C) analysis at case study sites with high traffic demands, three-phase intersection designs have the potential to "break even" with ROW costs after only one year due to their significant travel time savings compared to conventional intersections.

While both the partial CFI and CFI/MUT combo resulted in similar travel time performance, the CFI/MUT combo is likely to be a safer design than the partial CFI for both motorized and non-motorized users. Pedestrians should experience better service with the CFI/MUT combo due to one fewer free-flow conflict with vehicles and shorter crosswalks than a partial CFI on one approach. Additionally, the CFI/MUT combo would require a smaller ROW, needing extra space only on one approach. Therefore, ROW costs and construction restrictions should be less than those for the partial CFI. Moreover, public acceptance of CFI/MUT combo designs is expected to be higher than for the partial CFI, based on PASS analysis.

5.2 Recommendations for Future Studies

Even though the current research project provided some information regarding traffic control devices (TCDs) and geometric design of intersections with three-phase signals, it is recommended to develop a guideline with a primary focus on TCDs and geometric features. Also, after implementing more three-phase intersections, it is necessary to develop Crash Modification Factors (CMFs) to better understand their safety performance.

It is highly recommended to estimate the capacity and traffic operations of these new three-phase designs under various V/C (volume to capacity) ratios. The performance of alternative intersections can vary, sometimes significantly, on a case-by-case basis across different projects. Therefore, conducting additional evaluations under diverse traffic conditions could yield new insights. Furthermore, a network analysis that includes adjacent signalized intersections could provide further understanding of the performance of three-phase designs, particularly for the three-phase designs with high potential regarding signal progression such as redirect 2L&T and offset thru-cut designs. For example, the redirect 2L&T intersection offers a green signal during two phases (out of three phases) for one through and one left-turn movements on the major road. Therefore, its performance could be much more beneficial on a network with close distances to adjacent signalized intersections.

With the gradual rise of autonomous vehicles (AVs) on roadways, a potential idea for future research is to include AVs in the fleet of vehicles being simulated at intersection with three-phase signals. The spreadsheet-based tools developed in this study could be enhanced in future efforts. For instance, the SSI tool (for new alternatives) currently does not account for non-motorized users and was designed specifically for intersections with protected-only left-turn phase modes, as per the scope of the current study. Regarding another important topic on safety, it is highly recommended to conduct a study on the wrong-way potential and driver violations at three-phase intersections.

As a summary of recommendations for future studies, Table 5.1 presents the questions discussed in this study and past studies, and those requiring further investigation in the future.

Table 5.1 Overview of Focus Questions Covered in this Study and Past Studies

#	Question	Any Available Answers for These Questions?									
		Partial MUT	Partial CFI	Reverse RCI	CFI/MUT Combo	Thru-cut	Offset T	Seven-Phase	Quadrant	Redirect L&T	Redirect 2L&T
1	At what locations are three-phase designs most well suited?										
2	How much do they cost, especially compared with other intersections?										
3	What kind of traffic control devices (pavement markings, signs, and signals) are needed?										
4	What movement restrictions could cause motorist confusion and violations?										
5	How could we minimize drivers' violations?										
6	What are the considerations needed for pedestrian and bicyclist safety?										
7	What kind of geometric and right-of-way (ROW) limitations are faced during construction?										
8	What movements are less impactful for redirecting in different cases?										
9	What designs would be most readily accepted by the public?										

Relatively Good, *Limited knowledge*, *Almost No Knowledge*

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