ABSTRACT

EDWARDS, HAYDEN ROSS. Analysis and Comparison of Three-Phase vs Four-Phase Intersections (Under the direction of Dr. William Rasdorf).

At four-phase conventional intersections where traffic demand is near or above capacity, alternative intersections may perform better in terms of safety and capacity. Designs with two-phase traffic signals such as reduced conflict intersections (RCI, also called RCUT and superstreet) result in shorter travel times, fewer crashes, and better pedestrian service.

Despite their inherent benefits, two-phase signals may be impactful and unpopular with local communities. Higher minor street demand, 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 well at many intersections, planners might need additional options in order to choose the optimal designs for some projects. An alternate solution is intersections with three-phase signals, which might provide some of the advantages of two-phase designs while providing more direct movements and alleviating public concerns.

This thesis includes a state-of-the-art literature review as well as modeling of the operational performance of 11 different three-phase designs across six case study intersections in North Carolina using TransModeler. In total, 28 different models were tested with various traffic conditions. This includes existing 2023 conditions and traffic estimates for 2043 for AM, noon, and PM peak hours (total of 6 simulations per model). Measures of effectiveness for these simulations include travel times and delay.

Analysis and Comparison of Three-Phase vs Four-Phase Intersections

by
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DEDICATION

I would like to dedicate this thesis to all of the transportation professionals working every day to make it easier and safer for folks to get from one place to another. I am excited and humbled to join such a noble cadre of professionals.

I would also like to thank my wife for her patience and support.

BIOGRAPHY

Hayden Edwards is currently a graduate student of Civil Engineering at North Carolina State University. He received his B.S. in Naval Architecture from the United States Naval Academy in May 2015 and was then commissioned as an Ensign in the U.S. Navy. He graduated from multiple training commands in 2016-2017 including: Navy Nuclear Power School, Division Officer Leadership Course, Information Warfare Basic Course, and Naval Intelligence Officer Basic Course. His first duty station was the Office of Naval Intelligence in Suitland, MD where he served as an intelligence analyst and earned his Information Warfare Officer qualification. His second (and final) duty station was Naval Air Station Whidbey Island where he served as the squadron intelligence officer for VAQ-138.

Hayden was honorably discharged from the U.S. Navy in 2022 and began graduate school at North Carolina State shortly after. During his time at NC State, Hayden worked as a graduate research assistant on NCDOT Research Project 2023-20 (Evaluating the Benefits and Drawbacks of Intersections with Three Signal Phases), and as an engineering assistant in the Congestion Management Unit at the North Carolina Department of Transportation.

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Chapter 1: Literature Review

This literature review report includes a summary of studies related to traffic operation, safety, pedestrian performance, construction costs, and public and stakeholder acceptance of alternative (also known as innovative and unconventional) intersections with three-phase signals.

1.1 Introduction

With regards to safety, intersections are critical components of our national transportation infrastructure. Traffic signals cycle through a set pattern of green, yellow, all-red, and red lights with the transition from one color to the next defined as a traffic phase. Traffic signal design has resulted in multiphase control of intersections. A typical standard signalized intersection has four 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-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 et al. 2022; Luo et al. 2024).

At four-phase conventional intersections where traffic demand is near or above capacity, alternative intersections may perform better (Luo et al. 2022; Luo et al. 2024). Relatively new designs with two-phase traffic signals such as reduced conflict intersections (RCI, also called RCUT, J-Turn, and superstreet), median U-turn (MUT) and continuous flow intersections (CFIs, also called displaced left-turn, DLT) result in shorter travel times, better pedestrian service, and mixed safety benefits (Cunningham et al. 2022; Abdelrahman et al. 2020; Al-Omari et al. 2020; 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 (FHWA, 2020).

However, retrofits to designs with two-phase signals may be 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 select 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-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.

This literature report was developed 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 (pavement markings, traffic signs, and traffic signals) 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, and QR. There are also two other three-phase designs called "redirect left and through (redirect L&T or RLT)", and "redirect two left and one through (redirect 2L&T or R2LT, proposed by one of the committee members)"; however, the research team did not find any literature regarding these R2lT. The design geometry for each of these intersections is provided in section 3.1 of this literature review.

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 Departments of Transportation (DOTs).

1.1.1 Problem

Three-phase intersection design is a relatively new concept related to alternative designs that has not been comprehensively explored in past studies. Based on the best knowledge of the authors, the new concept was introduced for the first time in a presentation by Dr. Joseph Hummer at the 2021 Southern District ITE Meeting, Wilmington, NC, April 2021. Therefore, it is essential to identify gaps, challenges, concerns, and propose solutions to advance the implementation of three-phase intersections where appropriate. We begin with this review literature review.

1.1.2 Objective

The objective of this literature review report is to inform readers about the current state of the art related to alternative intersections with three-phase signals. This review identifies the most important concepts of alternative intersections with three-phase signals and presents responses to some of problems and questions listed above related to their performance (benefits and drawbacks), cost, and public acceptance.

1.2 Thesis Organization

This section lists the abbreviations utilized throughout this thesis, defines the most important terms related to this research, and explains the format of the literature view, results, and conclusion.

1.2.1 List of Abbreviations

The following abbreviations are utilized throughout the review/thesis:

- **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
- **DDI:** Diverging Diamond Interchange
- **DLT:** Displaced Left Turn
- **DOT:** Department of Transportation
- **FHWA:** Federal Highway Administration
- **LOS:** Level of Service
- **MOE:** Measure of Effectiveness
- **MUT:** Median U-Turn

- **NCDOT:** North Carolina Department of Transportation
- **NCHRP:** National Cooperative Highway Research Program
- **QR:** Quadrant Roadway Intersection
- **RCI:** Reduced Conflict Intersection
- **REDIRECT L&T:** Redirect Left and Thru
- **REDIRECT 2L&T:** Redirect Two Lefts and One Thru
- **ROW:** Right-of-Way
- **SaFID:** Safest Feasible Intersection Design
- **TRB:** Transportation Research Board
- **TRR:** Transportation Research Record
- **V/C:** Volume over Capacity

1.2.2 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.

1.3 Literature Review

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, identified by a numerical ID (publication #) is presented in the reference section at the end of this report.

This portion of the 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 1.

Table 1. Publication Category

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

1.3.1 Three-Phase Intersection Performance Overview

This section presents the literature related to the safety, pedestrian, and operational performance in three-phase intersection designs. Specific three-phase intersection designs discussed in this section are: partial MUT versions #1 and #2, partial CFI, reverse RCI, CFI/MUT combo, thru-cut, offset-T, seven-phase signal, QR, redirect left and thru (redirect L&T), and redirect two lefts and one through (redirect 2L&T). These three-phase designs were chosen to study because, in appropriate situations, they should provide greater capacity with fewer impacts and may be more palatable to stakeholders.

We found 15 works related to the performance of these three-phase intersections and studied them to find answers to the nine questions presented in the introduction of this report. Tables 2 and 3 provide a breakdown of the works we found by three-phase intersection design type, and the focus of the study, respectively. The main findings of these studies are highlighted in sections 3.1, 3.2, and 3.3 of this literature review. Additionally, section 4 provides a consolidated summary of these findings.

Table 2. Summary of Three-Phase Intersection 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

[*] The study included only unsignalized offset-T intersections

[**] With three-phases

Table 3. Summary of Three-Phase Design 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

1.3.1.1 Partial MUT #1 and #2

1.3.1.1.1 Design Description

There are two versions for the three-phase MUT. The partial MUT #1 redirects only the left-turn traffic from the major road, while 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 1 and 2 show the design geometry for both partial MUT configurations.

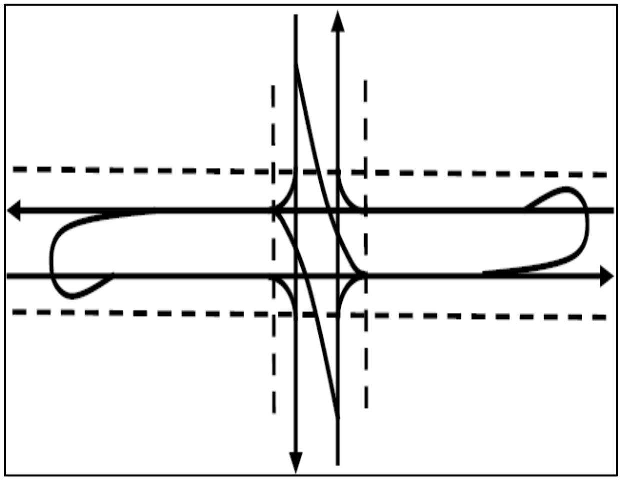

Figure 1. Partial MUT#1 Design Geometry

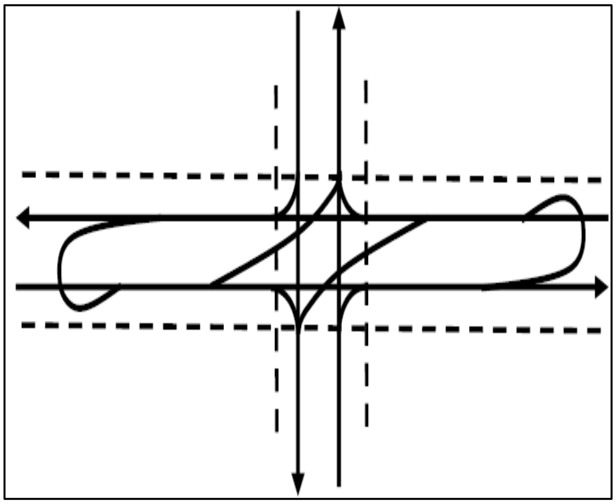

Figure 2. Partial MUT#2 Design Geometry

1.3.1.1.2 Performance

According to Luo et al. 2022; Luo et al. 2024, the partial MUT 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). It should be noted that the 20-flag method evaluates the expected safety and comfort pedestrians will experience at a particular intersection. In total, 20 criteria of an intersection are assessed, such as: sight distance, grade change, and motor vehicle right or left turns. A flag can be considered as a discrepancy with varying levels of severity. No flag is given when there are no noted discrepancies for a specific criterion, a yellow flag is given when a minor discrepancy could cause users discomfort at an intersection, and a red flag is given for discrepancies which represent a safety concern. Of the 20 total criteria, 13 are applicable to pedestrians, and 17 are relevant to bicycles. Additionally, each potential direction of flow through the intersection is analyzed. For example, a typical conventional intersection will have four pedestrian paths for navigation. With 13 pedestrian-related flags, there would be 52 (13 multiplied by 4) potential pedestrian flags at that intersection. Luo et al. (2022) found partial MUT 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 et al. (2022) also provided the information regarding vehicle and pedestrian travel times summarized in Tables 4 and 5, respectively. For both tables, an assumed volume/capacity ratio of 1.00 was used. Also, high turning conditions are 5,200 total vehicles per hour per lane (vphpl) with equal turning and through volumes, moderate turning conditions are 5,000 total vphpl with turning volumes set to 66% of through volumes, and low turning conditions are 4,800 total vphpl with turning volumes set to 50% of through volumes (Luo et al. 2022). According to Tables 4 and 5, the estimated pedestrian travel time for partial MUT is 70 seconds, and the average simulated vehicle travel time is 192 seconds (Luo et al. 2022). Additionally, partial MUTs have the lowest pedestrian travel times of the six intersections included in Table 4 and provide an improvement in vehicle travel time compared to conventional intersections as shown in Table 5 (Luo et al. 2022).

Table 4. Pedestrian Travel Times for Three-Phase Intersections (Luo et al. 2022)

Intersection Type	Overall		High Turning		Moderate Turning		Low Turning	
	Travel Time (sec)	Stops (no)	Travel Time (sec)	Stops (no)	Travel Time (sec)	Stops (no)	Travel Time (sec)	Stops (no)
Conventional	84	0.46	89	0.47	88	0.46	76	0.45
Partial MUT	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 5. Average Vehicle Travel Time for Alternative Intersections Based on VISSIM (Luo et al. 2022; Luo et al. 2024)

Intersection Type		Overall		High Turning		Moderate Turning		Low Turning	
		Travel Time	Completed Tests (%)	Travel Time	Completed Tests (%)	Travel Time	Completed Tests (%)	Travel Time	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	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

Idaho DOT constructed a partial MUT in Boise in November 2018 at State Street and Veterans Memorial Parkway (Figure 3) (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 6 and 7. The AADT values reveal that this is a busy intersection with possible capacity issues. 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.

Figure 3. Partial MUT at State Street/Veterans Memorial Parkway, Boise, Idaho

Table 6. Crash Data Summary for State Street/Veterans Memorial Parkway, Boise, Idaho

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

Table 7. AADT (veh/day) Data for State Street/Veterans Memorial Parkway, Boise, Idaho

Street Name	AADT (2021)
State Street (East)	27500
State Street (West)	33500
Veterans Memorial Pkwy (North)	9700
Veterans Memorial Pkwy (South)	21000

The 2014 FHWA MUT Informational Guide 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.

1.3.1.2 Partial CFI

1.3.1.2.1 Design Description

The partial CFI has left-turn crossovers only at the major street. 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. The design does not have a U-turn crossover. This feature allows it to have the same traffic flux at the main intersection as the conventional design.

There are multiple options for sidewalk placement at partial CFIs: traditional, midblock, and offset. Figure 4. shows a partial CFI with an offset sidewalk placement (Ahmed et al. 2021). The traditional design has sidewalks in a layout similar to conventional intersections. The midblock configuration has the main street pedestrian crossings located away from the main intersection closer to the left turn crossovers.

Figure 4. Partial CFI Design Geometry

1.3.1.2.2 Performance

Partial CFIs are not pedestrian-friendly because they create long walking distances, the concept might be confusing for pedestrians, and they have 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 were dropped due to lack of data or an unexpected situation. For each crash type, researchers found that the CMFs were all less than one with the range being 0.616-0.960. Of note, 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 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. For future studies, more research was recommended to make the data more comprehensive and representative of all CFIs due to many CFIs being too new to have AADT data or states being unresponsive. Secondly, crash data collection and collection systems sometimes vary state-by-state, making it more difficult to locate some crashes. Once these data collection issues are solved and the date is more representative of all CFIs, this data could be used for surrogate conflict-based methods.

According to Luo et al. (2022) (Tables 4 and 5), partial CFIs have an estimated pedestrian travel time for partial CFIs of 107 seconds, and an average simulated vehicle travel time is 176 seconds. Therefore, partial CFIs have the lowest vehicle trave time of the six intersections included in Luo et al. (2022) but it increases pedestrian travel time by 23 seconds compared to conventional intersections (see Table 5).

Rouphail et al. (2020) found that partial CFIs have a cycle length of 110 seconds for offset pedestrian crossings, and 140 seconds for traditional and midblock pedestrian crossings (compared to 135 seconds for a conventional intersection) using the modeling software PTV VISTRO. Of the three pedestrian crossing designs at partial CFIs, traditional 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 2014 FHWA DLT Intersection Informational Guide 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 than overhead signage.

1.3.1.3 Reverse RCI

1.3.1.3.1 Design Description

The reverse RCI redirects one through movement from each intersecting side using U-turn crossovers: the left turn traffic from the major street and through traffic from the minor street. Based on the best knowledge of the authors, there should be at least five reverse RCIs in North Carolina. Figure 5 shows the geometry of reverse RCI design.

Figure 5. Reverse RCI Design Geometry

1.3.1.3.2 Performance

According to Luo et al. 2022; 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 Tables 4 and 5, estimated pedestrian travel time for reverse RCIs is 75 seconds, and average vehicle travel time is 251 (Luo et al. 2022). While reverse RCI has the second-best pedestrian travel time and good pedestrian safety characteristics, it has the longest travel time of all three-phase intersections studied in Luo et al (2022).

1.3.1.4 CFI/MUT Combo

1.3.1.4.1 Design Description

The 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 is at least one CFI/MUT Combo in Virginia Beach, VA; however, the CFI left-turn ramp and the U-turn crossover are located on two separated approaches (while they are located on the same approach in Figure 6).

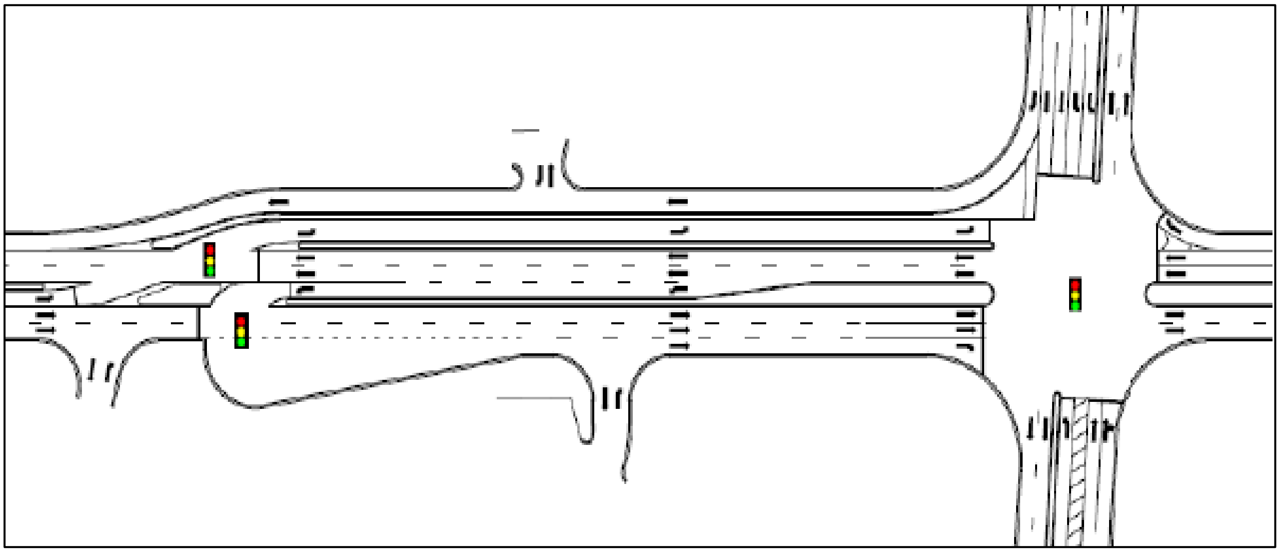

Figure 6. CFI/MUT Combo Design Geometry

1.3.1.4.2 Performance

Based on a recent presentation and an article published at Transportation Research Record (TRR) by Hummer (2020), the 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, respectively. Regarding pedestrian safety, this design has 4 yellow flags and 10 red flags.

The CFI/MUT combo has the longest pedestrian travel time of the three-phase designs included in Tables 4 and 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).

1.3.1.5 Thru-Cut

1.3.1.5.1 Design Description

Figure 7 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 8, there are at least two existing thru-cut intersections in North Carolina. Also, 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 very 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 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.

The offset thru-cut shown in Figure 9 is a recently proposed version of the thru-cut which enhances pedestrian performance due to the placement of a crosswalk between minor legs.

Figure 7. Thru-Cut Design Geometry

Figure 8. Thru-Cut Intersections at Village Walk Dr/S Main St, Holly Springs, NC (Left) and Arrowood Rd/Arrowpoint Blvd, Charlotte, NC (right)

1.3.1.5.2 Performance

Thru-cut intersections have fewer conflict points (24) than a conventional intersection (32). According to Luo et al. 2022; Luo et al. 2024, thru-cut intersections have one of the lowest average cycle lengths compared to other three-phase designs (106 seconds) 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). Regarding pedestrian performance, the simulations in Luo et al. (2022) showed the thru-cut intersection has an average pedestrian travel time of 81 seconds compared to a simulated conventional intersection with an average of 84 seconds. Additionally, thru-cut intersections have a score of 2 yellow flags and 14 red flags using the 20-flag method compared to 0 yellow flags and 14 red flags for a conventional intersection.

According to Luo et al. (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 either category.

As previously mentioned, VDOT is planning to construct seven thru-cut intersections in a corridor along US-220. Construction is not scheduled to begin until late 2023; however, our research team contacted VDOT about the intersection 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 8 and 9) 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.

For instance, at each of the seven thru-cut intersection along US-220 an average of 42 total crashes occurred. 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 8. 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 9. 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 initial evaluations done by NCDOT, the thru-cut intersection illustrated in Figure 8 (left) at SR 1114 (S Main St.) and Village Walk Dr. in North Carolina showed great safety potential with a 67% reduction in 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. There was an increase in left-turn crashes after the thru-cut implementation, but the study attributes this to the increase in volume along SR 1114. Additionally, given that thru-cuts force would-be thru movements to make U-turns downstream, the study analyzed U-turn crash rates for intersections along SR 1114. None of the downstream intersections experienced U-turn crashes during the after period of the study.

1.3.1.6 Offset T-Intersection

1.3.1.6.1 Design Description

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 is required.

Figure 9. Offset Design Geometry

1.3.1.6.2 Performance

Offset 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 significantly longer travel distances. Also, the offset intersection can be considered as a candidate only in specific geometry configurations with enough ROW.

Yang et al. (2023) found that offset intersection 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 half of crashes in comparison to the four-leg intersection because of the fewer number of conflict points. Also, almost in half of the simulation tests, offset intersections performed better in terms of reducing delay compared to conventional design. Fewer angle crashes were predicted at offset 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 t al. (2021) found a 35% increase in the number of crashes at rural, unsignalized offset-T intersections compared to conventional intersection 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.

1.3.1.7   Seven-Phase Signal

1.3.1.7.1   Design Description

As shown in Figure 10, 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 similar examples in Maryland (Figure 11) that could provide guidance in designing appropriate traffic control devices (TCDs) for the seven-phase signal design.

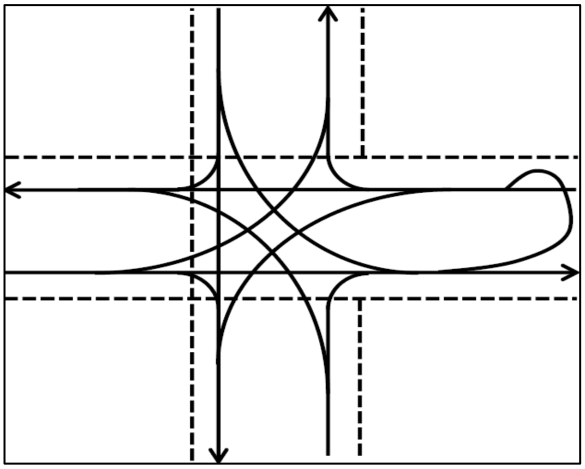

Figure 10. Seven-Phase Signal Design Geometry

Figure 11. Democracy Boulevard at Fernwood Road, Bethesda, Maryland

1.3.1.7.2 Performance

Possible benefits include higher capacity and shorter travel times 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.

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 east-west four-lane major street with 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 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 nearly150 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.

1.3.1.8 Quadrant Roadway

1.3.1.8.1 Design Description

This design, as shown in Figure 12, redirects all left turns at the main intersection. 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 through the main intersection and on to the additional roadway connecting a major leg to a minor leg.

The FHWA Quadrant Roadway Intersection Informational Guide provides guidance regarding signals and pavement markings (Reid and Hummer 2020). Specifically, they recommend providing adequate signage and pavement markings to ensure 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.

1.3.1.8.2 Performance

According to The FHWA Quadrant Roadway Intersection Informational Guide, the quadrant is appropriate for an intersection with two busy roads (Reid and Hummer 2020). 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.

Figure 12. Single QR Design Geometry

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 QRs could perform well at intersections with high through volumes and low to moderate left-turn volumes.

The FHWA guide highlights that QRs have a reduced number of conflict points, no left-turn conflicts, lower delays, and less travel distances compared to conventional intersections (Reid and Hummer 2020). For through movements, there is increased green time, shorter delays, smaller queues, and decreased potential for spill back. The authors note that unfamiliarity with the flow of travel through a QR, and higher right turn traffic demands could increase vehicle-pedestrian conflicts. Additionally, increased queues, delays, and travel time could result at QRs since left turns are not prioritized.

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.

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

1.3.1.9.1 Design Descriptions

This design is a derivation from 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.

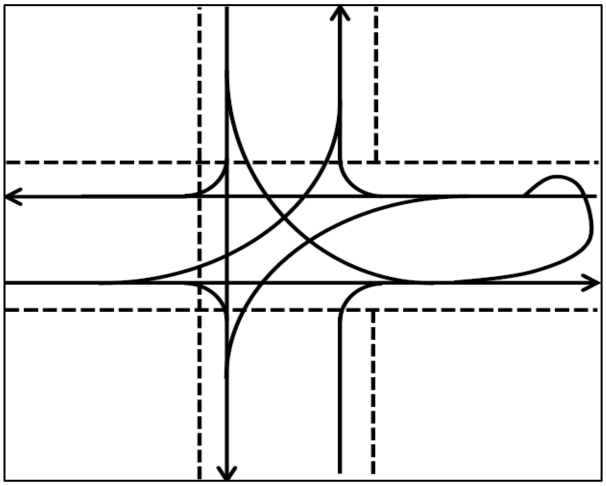

Figure 13. Redirect One Left and Thru Design Geometry

During the Deep South ITE fall meeting on September 28th, 2023, in Lafayette, LA, one of the research team members unexpectedly identified three redirect left and through from one minor leg (redirect L&T or RLT) intersections. Therefore, on October 10th, 2023, the research team had a meeting with Mr. Nick Fruge, Louisiana Department of Transportation and Development (LaDOTD) District 03 Traffic Operations Engineer, regarding the redirect L&T intersections found in Lafayette, Louisiana.

Based on the meeting with Mr. Fruge, the research team found that there are at least three redirect L&T intersections in Lafayette, Louisiana: 1) US 90 and University Ave/Surrey St, 2)

US 90 and E Verot School Rd, and 3) US 90 and Southpark Rd as shown in Figure 14. Mr. Fruge further provided the research team with documents and PowerPoint presentations highlighting the crash analysis performed in 2008 before an improvement project on the entire US 90 stretch in Lafayette where the three identified redirect intersections are located. These crashes were compared to data from 2013 after the improvements to US-90 (including the three RLT intersections) were implemented. Table 10 summarizes the crash data from this study.

Table 10. 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

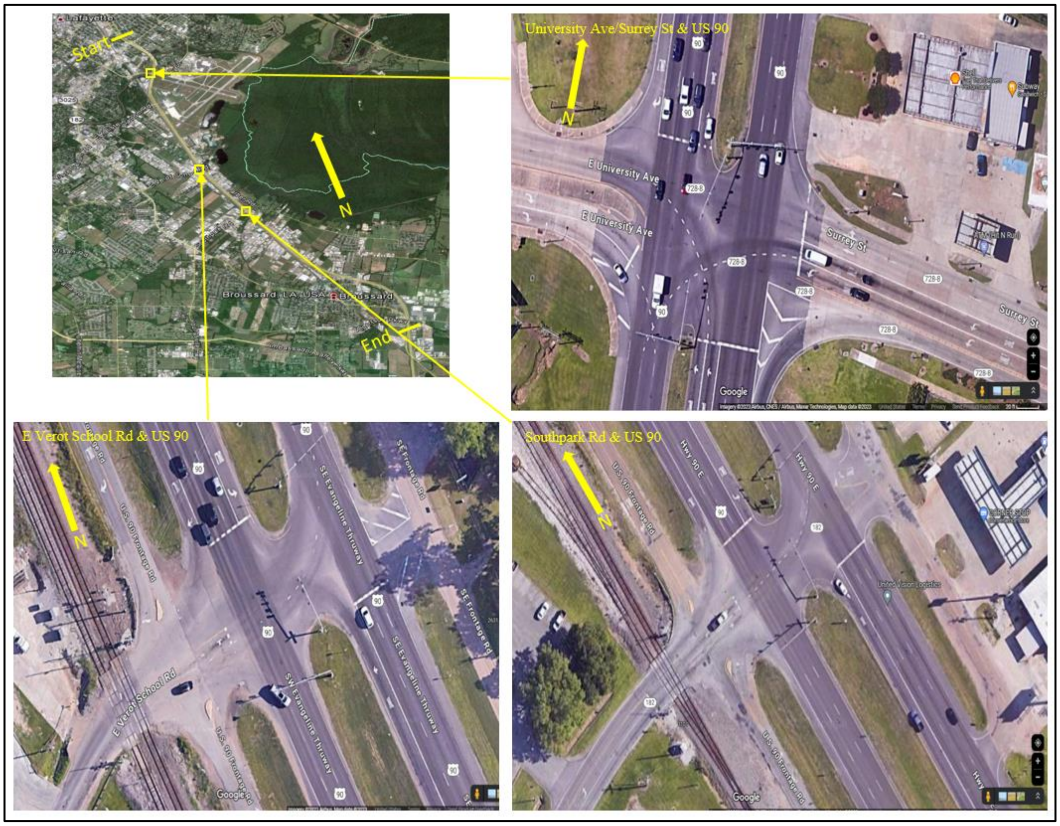

Figure 14. Redirect One Left and Thru Intersections in Lafayette, Louisiana

1.3.1.9.2 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 might negatively impact capacity and vehicle travel times due to the network's larger volume over capacity ratio.

1.3.1.10 Unpublished Designs

1.3.1.10.1 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 Amir Molan.

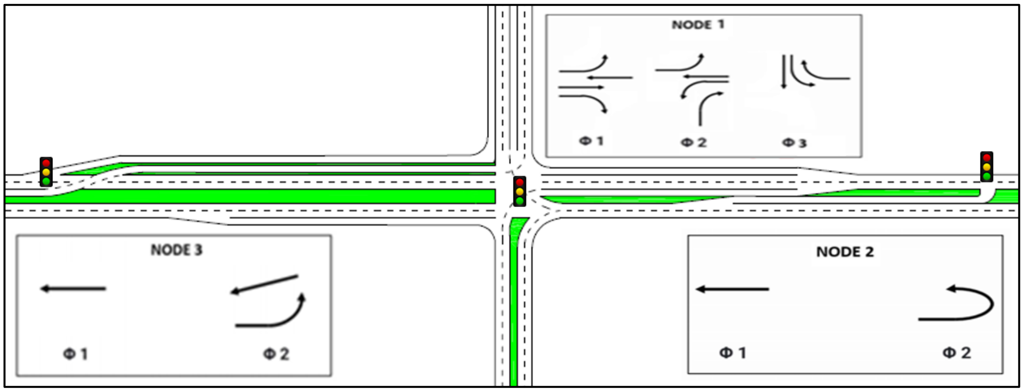

Figure 15. Redirect Two Lefts and One Thru Design Geometry

There are no past studies evaluating the performance of the redirect 2L&1T intersection. However, based on the proposed phasing diagram, one of the major street 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 new design has 19 conflict points. Among all the designs mentioned in this literature review, only the reverse RCI and the offset designs 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.

1.3.1.10.2 Offset Thru-Cut

The offset thru-cut has only recently been proposed Dr. Joe Hummer and has not been published. This design is a version of the thru-cut which enhances pedestrian performance due to the placement of a crosswalk between minor legs as shown in Figure 16. Compared to a standard thru-cut, this design will require more ROW, but the offset design should minimize the risk of a driver making an illegal thru movement.

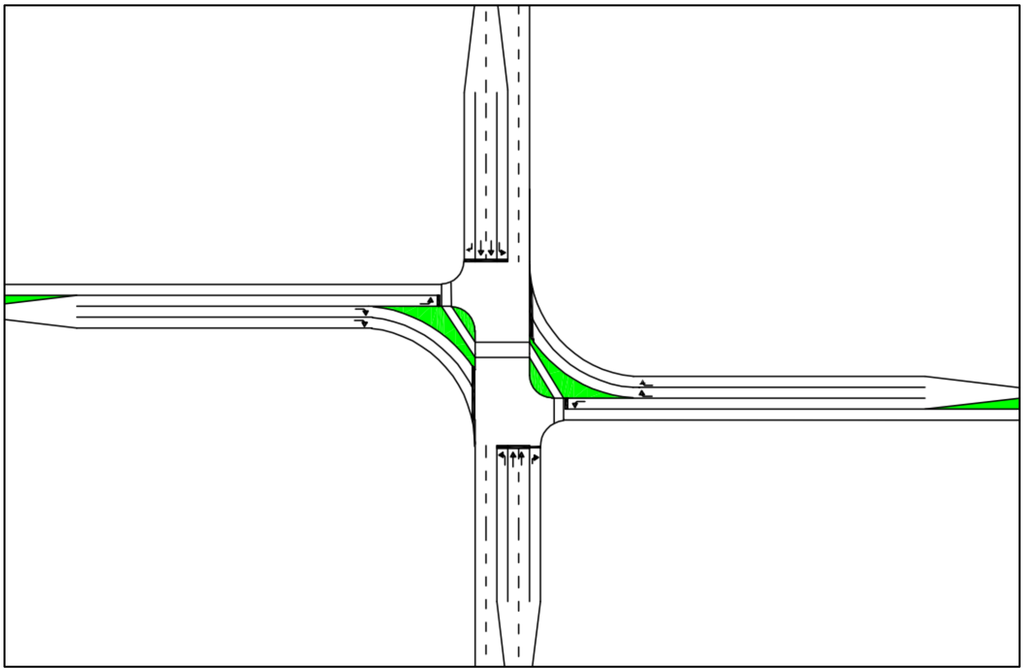

Figure 16. Offset Thru-Cut Design Geometry

This design has the same number of conflict points as a standard thru-cut at 24 total. This design incorporates channelized right turns which should improve operational performance but could inconvenience pedestrians who would not be able to cross the street at the channelized rights.

This design is expected to provide substantial improvement to travel times in scenarios with higher turning ratios due to the reduced impact of redirected through traffic movements from the minor road.

1.3.2 Public and Stakeholder Acceptance

Several past studies have assessed public acceptance of new intersection designs and roundabouts. Some of these studies are highlighted in Table 11. 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. Also, the literature collected in this part will help the research team in designing the public and stakeholder acceptance survey in Task 6 of the study.

Table 11. 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 and Myers (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

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.

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 that 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 noted that the general public's negative perception towards roundabouts hinders advanced implementation and that public education should be exerted to minimize oppositions (Pochowski and Myers 2010).

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 there was no proof that RCI 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.

1.3.3 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).

According to Luo et al. 2022; 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. Partial MUT, reverse RCI, and thru-cuts were estimated to cost the least to implement. CFI/MUT combo and partial CFI were found to be the most expensive.

Table 12. Estimated ROW Cost for Replacing a Conventional Intersection in California (Luo et al. 2022; Luo et al. 2024)

		ROW Cost ($)	
Intersection Type	**Extra ROW (sq ft)**	**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

VDOT is constructing a corridor of seven thru-cut intersections along US-220. The cost estimates for the project are highlighted in Table 13.

Table 13. Anticipated Project Costs for VDOT US-220 Thru-Cut Corridor

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

1.4 Summary of Results

This section aims to summarize possible answers found to the nine main questions proposed in the introduction (and listed in Table 14), as well as to highlight other findings of note.

Table 14. Summary of Focus Questions

		Answer Available for Given Intersection Geometry from Current Literature?									
#	Question	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?	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No
2	How much do they cost, especially compared with other intersections like RCIs?	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No
3	What kind of traffic control devices (pavement markings, signs, and signals) are needed?	Yes	Yes	No	No	No	No	Yes	Yes	No	No
4	What movement restrictions could cause motorist confusion and violations?	Yes	Yes	No	No	No	No	No	Yes	No	No
5	How could we minimize those violations?	Yes	Yes	No	No	No	No	No	Yes	No	No
6	What are the considerations needed for pedestrian and bicyclist safety?	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No
7	What kind of geometric and right-of-way (ROW) limitations are faced during construction?	No	No	No	No	No	No	No	Yes	No	No
8	What movements are less impactful for redirecting in different cases?	No	No	No	No	No	No	Yes	No	No	No
9	What designs would be most readily accepted by the public?	No	No	No	No	No	No	No	No	No	No

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 20-Flag method).

A few studies address what locations three-phase designs are best suited for. The 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. 2022; Luo et al. 2024, the partial MUT is advantageous in the case of low or moderate turning demand. The partial MUT might be also safer (in terms of vehicular traffic and pedestrian safety) than the partial CFI due to the fewer number of conflict points and fewer red flags based on the NCHRP 20-Flag method. Thru-cut design should be one of the best alternatives for corridors with shorter intersections 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.

Regarding construction costs, Luo et al. 2022; Luo et al. 2024, found 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. Several three-phase designs such as the CFI/MUT combo, redirect left and thru, and redirect two lefts and one thru have not yet been constructed and do not have cost estimates. Regarding geometric and ROW limitations, the FHWA Quadrant Roadway Informational Guide provides insight into the benefits (smaller main intersection) and drawbacks (additional ROW for redirecting loop) of constructing Quadrant Roadways.

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 et al. (2022) applied this 20-flag method for partial MUT, partial CFI, reverse RCI, CFI/MUT combo, and thru-cut intersections**,** Luo et al. (2022) found that partial MUT and CFI/MUT combo had the lowest and highest pedestrian travel times, respectively. Additionally, partial MUT and partial CFI had the lowest and highest number of flags, respectively. Overall, partial MUT was found to be the most pedestrian-friendly three-phase design, and CFI/MUT combo was the least. 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. Based on past studies on alternative designs with two-phase signals (such as RCIs), initial concerns from businesses in proximity to alternative intersections were found in multiple studies to be disproven.

Descriptions of each of the studies included in this literature review are in Tables 15 and 16.

Table 15. Summary of Three-Phase Performance Studies

Researchers/Year	Intersection Type	Location
Qu (2023)	QR	-
Cunningham (2022)	Partial CFI	Multiple States
Luo (2022), Luo (2024)	Partial MUT, Partial CFI, CFI/MUT Combo, Reverse RCI, Thru-Cut	-
Ahmed (2021)	Partial CFI	-
Ingle (2021)	Offset-T	Michigan
Qu (2021)	CFI, Partial CFI	-
Schroeder (2021)	QR, CFI, MUT, RCI, DDI	-
Cunningham (2020)	Offset-T	North Carolina
Hummer (2020)	CFI/MUT Combo, QR	North Carolina
Reid and Hummer (2020)	QR	Multiple States
Hummer (2019)	Seven-Phase	Maryland
Zlatkovic (2015)	DDI, RCI, CFI, MUT, QR	Utah
Hughes (2010)	DLT, RCI/RCUT, MUT, QR	Multiple States
Inman (2009)	Partial CFI	Louisiana

Table 16. Summary of Public Acceptance Studies

Researchers/Year	Intersection Type	Methods Used	Sample Size	Location	Results Summary
Barnes (2022, draft)	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 roundabouts were less safe than conventional intersections
Chilukuri (2011)	DDI	Survey	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

Chapter 2: Methodology

Important note: this thesis is based heavily on the work completed in NCDOT Research Project 2023-20, of which the author of this thesis was just one of several contributors. This thesis will focus specifically on tasks where the author completed all or most of the work for the larger research project except where necessary to provide context. In these instances, the term "research team" will be used to provide credit to the work of other members of the research project who contributed to the task.

2.1 Data Collection and Case Study Selection

In order to better understand possible locations where alternative intersections might work well, the research team contacted DOTs throughout the United States who had already built them. Specifically, the research team contacted traffic engineers at North Carolina DOT, Virginia DOT, and Idaho DOT. These engineers were asked for information related to how alternative intersections were performing in their jurisdictions.

As mentioned in the literature review, the research team contacted Idaho DOT for information regarding a partial MUT in Boise, and they provided ten years' worth of crash data and AADT data for the intersection as shown in Tables 6 and 7. The AADT values reveal that this is a busy intersection with possible capacity issues. 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.

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 their alternative intersections. In response, we received both statewide and divisional data on RCIs from NCDOT. Specifically, 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.

The research team met with engineers from NCDOT highway division two via zoom. The division two engineers provided feedback regarding observed public reception to the implementation of alternative intersections in their division. The division two engineers mentioned residents were initially hesitant about the implementation of RCIs in the division. One specific residential concern mentioned was the challenge of large vehicles like dump trucks being able to get up to speed after making a U-Turn. Despite initial worries, after the first couple of weeks, the residents liked the new intersections. We also inquired about the signaling and signage division 2 used when constructing these intersections. They informed us that the intersections were not signalized and that MUTCD standards were used for signage. Due to their intersections being unsignalized, we did not consider them as case studies for our project. Lastly, we asked about observed pedestrian performance at these intersections. Unfortunately, the RCIs in division two are located along highways and not accessible to pedestrians so they did not have any information to share.

Outside of this zoom meeting, most of the data received from NCDOT highway divisions was locational and in the form of google earth KML files and lat/long coordinates. Alongside location data, we received information regarding the specific type of intersection for most of the RCIs. Public perception, traffic flow, and safety data was more difficult to acquire but we were able to receive this data from VDOT for intersections along the US 220 thru-cut corridor.

In addition to the data received from NCDOT highway divisions, Dr. Hummer provided the research team with a spreadsheet of all the RCIs in the state of North Carolina which included: location, intersection type, and construction date. The document contained information about 160 intersections in North Carolina and included details about the division, county, municipality, location, year built, jurisdiction, latitude, and longitude. Of the provided 160 intersections, 34 were in Division 5 which is where all of the case study intersections are located. A summary of the data collected for these intersections is provided in Table 17.

The research team received a NCDOT Traffic Safety Unit crash analysis study for a recently implemented thru-cut intersection from Dr. Hummer. The thru-cut intersection at SR 1114 (S Main St.) and Village Walk Dr. showed great safety performance with a 67% reduction in crashes per year and a 61% reduction in injury crashes per year. This reduction in crashes occurred despite traffic volumes along SR 1114 more than doubling during the period of study. There was an increase in left-turn crashes after the thru-cut implementation, but the study attributes this to the increase in volume along SR 1114. Of note, this thru-cut added a signal to a previously unsignalized intersection. Additionally, given that thru-cuts force would-be thru movements to make U-turns downstream, the study analyzed U-turn crash rates for intersections along SR 1114. None of the downstream intersections had U-turn crashes during the after period of the study.

Virginia DOT also provided data on thru-cut designs under planning/construction throughout their state. Specifically, they sent AADT data, turning counts, crash data, and construction cost estimates for the thru-cut intersections along the US 220 corridor.

Table 17. Summary of Data for Conventional Intersections in North Carolina

	Minimum	Maximum	Average
Lanes EB - R/Thru/L	0.33/0.33/0.33	2/3.5/3	0.79/1.56/1.23
Lanes WB - R/Thru/L	0.33/0.33/0.33	2/3.5/3	0.77/1.51/1.23
Lanes NB - R/Thru/L	0.33/0.33/0	2/4/2.5	0.86/1.77/1.27
Lanes SB - R/Thru/L	0.33/0.33/0	2/4/2	0.92/1.71/1.18
EB/WB AADT	3200	75000	22479.69
NB/SB AADT	670	65000	29245.42
EB/WB Street Width	25	225	89.42
NB/SB Street Width	35	170	95.13
EB/WB Speed Limit	35	45	40.71
NB/SB Speed Limit	35	50	43.57
PM PHV EB - R/Thru/L/U/Total	13/0/4/0/17	450/1546/695/151/2117	179.3/1030.3/234.7/45.3/1489.6
PM PHV WB - R/Thru/L/U/Total	14/1/52/0/126	641/836/295/58/1389	181.1/565.3/122.3/18.1/886.9
PM PHV NB - R/Thru/L/U/Total	42/60/32/0/254	252/2858/587/5/3036	131.6/745.4/234.6/1.7/1113.3
PM PHV SB - R/Thru/L/U/Total	10/73/17/0/211	684/1548/351/7/1817	238/635.3/121/1.7/996
Pedestrian PH	0	6	2
V/C	0.60	1.12	0.83

Tables 18 and 19 summarize the data received from NCDOT and VDOT.

Table 18. Summary of Data Received from NCDOT and VDOT

Data Source	Location Data	Construction Date	Intersection Type	Safety Data	Public Perception Data	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					
Virginia DOT (VDOT)	X	X	X			X	X	X

Table 19. Detailed Summary of VDOT Data Received

VA Thru-Cut Corridor Locations	AADT	Turning Counts	Crash Reports	Crash Summary	Project Costs	Synchro Models
US 220 at Route 619-816 Sontag Rd	X	X	X	X	X	X
US 220 at Route 675 Indian Grave Rd	X	X	X	X	X	
US 220 at Route 679 Buck Mountain Rd	X	X	X	X	X	
US 220 at Route 697 Wirtz Rd	X	X	X	X	X	X
US 220 at Route 862 Valley Ave	X	X	X	X	X	
US 220 at Route 1210 Dyer St	X	X	X	X	X	X
US 220 at Route 1290 Crossbow Circle	X	X	X	X	X	

After receiving data from NCDOT, Idaho DOT, and VDOT, the research team collected AADT and lane geometry data at 160 intersections from four cities in North Carolina: Raleigh, Cary, Durham, and Chapel Hill. After evaluating the sites, and with guidance from Dr. Joe Hummer regarding ongoing NCDOT improvement projects at the sites, the list of study intersections was reduced to eight preliminary sites.

As shown below in Table 20, the eight preliminary case study sites are located throughout Raleigh and Cary. 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. As explained later in this section, sites 3 and 6 were later removed as shown in Table 25. These two sites are included in the majority of this section to explain the data collection process in greater detail.

Table 20. Preliminary List of Case Study Sites

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

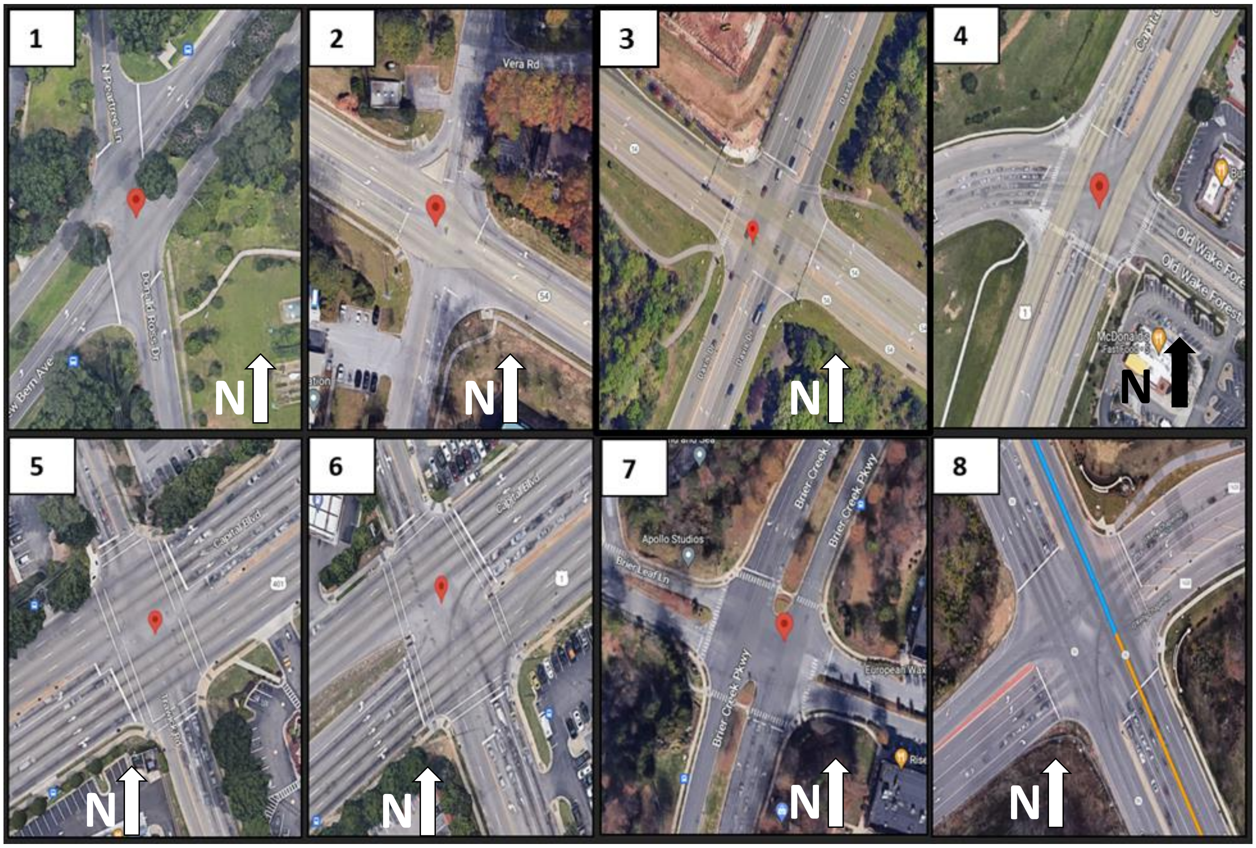

Figure 17. Aerial Photos of Preliminary Case Study Sites (Google Maps)

Table 21 shows the statistical summary of the data collected on the case study intersection sites, which have no existing plans for future improvement in Raleigh and Cary. The different categories of data displayed in the summary are AADT (veh/day), speed limit (mph) and spacing to the adjacent signalized intersections (which includes previous and next intersection) (ft). Each data category was further divided into the major and the minor street of the intersection, with the major street having the higher AADT.

Table 21. Statistical Summary of Selected 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

Once case study locations were selected, the research team analyzed which alternative intersection designs could perform well at each site. Alternative designs were suggested based on AADT rates, available right-of-way (ROW), and safety considerations. The final suggested treatments chosen are shown in Table 21. The alternatives and their phasing 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. Thus, the ninth row of the table shows that a Redirect 2L&T design was selected for only one site. The bottom row of Table 21 shows the total number of possible alternative treatments that could be considered at each location. For example, for location 7, only a single thru-cut treatment is recommended based on AADT and ROW.

Table 22. Alternative Intersections Suggested for Case Study Sites

		Intersection #						
Suggested Alternative		**1**	**2**	**4**	**5**	**7**	**8**	**Total**
Three-Phase	7-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**

It should be noted that the suggested intersection designs were based on the initial analysis using AADT rates and ROW considerations. Two-phase CFI was not considered because it is not common to implement two-phase CFIs due to the significant cost and ROW considerations needed. Based on the best knowledge of the author, to date, there are only a few two-phase CFI currently built. 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 22.

Out of the six case study sites represented in Table 22, five are located in Raleigh, and only one of the six intersection sites is located in Cary. In Raleigh, MUT was most frequently recommended for both three-phase and two-phase intersections. The reverse RCI, redirect 2L&T, quadrant, and CFI were the least frequently recommended, with only one site being recommended for them. Intersection #1 had eight suggested alternative intersections, while intersection #7 had just one suggested intersection. Intersection #8 (located in Cary) has three suggested alternatives: two for three-phase and one for two phases. These alternatives are CFI/MUT combo, single quadrant, and quadrant (with two-phase signal), respectively. Overall, there are 21 suggested alternatives for all the sites displayed in Table 21. The most frequently suggested alternative is MUT (1 & 2) with a frequency of three each (six overall).

Our 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 23. This table was compiled using the SaFID, BOFID, and POFID tables created by Dr. Hummer in the papers (2020), "Developing, Using, and Improving Tables: Showing the Safest Feasible Intersection Design", and "Developing and Using Tables Showing the Pedestrian Optimum and Bicyclist Optimum Feasible Intersection Designs", as well as the data we collected regarding the number of lanes and AADT for the eight case study sites.

Table 23 shows the SaFID based on all crashes for the eight case study sites. The safest intersection and the CMFs were determined by matching the number of through lanes and the AADT for the minor and major streets.

Table 23. Study Site SaFID (All Crashes), SaFID (Injury Crashes), POFID, and BOFID

Site #	Number of Thru Lanes Major	Number of Thru Lanes Minor	AADT Major	AADT Minor	SAFID (All Crashes)	SAFID CMF (All Crashes)	SAFID (Injury Crashes)	SAFID CMF (Injury Crashes)	POFID	BOFID
1	4	2	23000	5000	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
2	4	2	27000	5500	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig.RCI or TWSC
3	4	2	27500	NA	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
4	7	3	53500	25500	MUT	0.8	MUT	0.7	MUT	MUT
5	8	2	73000	9000	Sig. RCI	0.8	MUT	0.7	Bowtie or MUT	Sig. RCI
6	8	2	75000	10000	Sig. RCI	0.8	MUT	0.7	Bowtie or MUT	Sig. RCI
7	4	2	25500	NA	Unsig. RCI	0.7	Unsig. RCI	0.5	TWSC or Signal	Unsig. RCI or TWSC
8	6	4	17500	17000	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 23, the recommended intersection types based on all safety considerations are the unsignalized/signalized RCI, TWSC (two way stop signal), MUT (Median U-Turn) and Bowtie. While the RCI and MUT have been also considered in this study in two (sites 1 and 3) and four sites (sites 1, 3, 4, and 6), respectively, based on Table 22, they were not recommended in the other sites due to ROW restrictions such as limited space for constructing an appropriate U-turn crossover and/or concerns due to the short spacings with adjacent intersections.

Peak hour traffic data counts were provided by NCDOT for most of the case study sites and their adjacent intersections. Where this data was unavailable, peak hour traffic data was collected on site. This occurred at the intersection of New Bern and Peartree/Donald Ross (site 1), New Bern and West Campus Drive (adjacent to site 1), and the intersection of Chapel Hill Road and I-40 eastbound ramps (adjacent to site 2). The data was collected by hand tallies from 0745-0845 (AM peak), 1,130-1,230 (MD peak), and 1,630-1,730 (PM peak). All of the traffic volume data for each case study site is attached as Appendix A.

After traffic data was collected at each of the study intersections, the volumes were grown using a standard growth equation at a rate based on the trendlines of AADT data at each of the sites. For example, at site 1 the trendline equation of previous AADT data was found to be $y = -66.67x + 156567$ 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) which resulted in a growth rate of -0.3%. Table 24 shows the growth rates used at each case study site.

Table 24. Growth Rates used at Case Study Sites

Case Study Site	Heavy Vehicle Percentage
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%

Unfortunately, the research team was unable to collect peak hour traffic data for NC-54 and Davis Drive, so it was not included in the simulation modeling for this project. Table 25 provides the final list of case study intersections. Also of note, given the proximity of site 5 and site 6 to one another, they were modeled as one corridor in Transmodeler. Of note, the same numbering convention was kept for the final list of study intersections that was used for the preliminary list.

Table 25. 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

2.2 Simulation

2.2.1 Simulation Terminology

For clarity, the following standardized terminology will be used when discussing simulation. “Model” refers to completed works in VISSIM or Transmodeler (geometric layout, traffic counts, signal timing, etc.). For this research, I modeled the six case study sites discussed earlier. These are intersections that are located in Raleigh and Cary, which were chosen by the research team due to their potential to be improved with an alternative intersection design. The six case study sites were modeled with varying quantities of alternative intersection designs. We are modeling nine (9) three-phase intersection designs and two (2) two-phase intersection designs across the six case study sites for a total of 27 models. The specific alternative designs that were modeled for each case study intersection are shown in Table 23. Each of the 27 models will have six different “scenarios” (2023/2043 AM, MD, and PM). 27 models times six scenarios per model means a total of 162 scenarios. Additionally, each scenario was modeled ten times with fixed random seeds for a total of 1,620 simulation runs.

2.2.2 Modeling in TransModeler

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 the progression mentioned previously.

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 since 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 intersection 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 access points 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 case study site as shown in Table 26.

Table 26. 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%

Roadways were classified based on the NCDOT "functional class" GIS dataset. Free flow speeds were modeled as the existing speed limit of each site plus 5 mph (FHWA, HCM). 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 off of TransModeler's optimization using Webster's equation. Alternative intersections used the phasing sequences provided in Appendix B and were subsequently optimized using TransModeler's optimization feature. This method did not always provide the best signal timing for alternative intersections and often required multiple manual adjustments. There is almost certainly further optimization of three-phase signals.

Minimum cycle lengths varied based off of 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 off of 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.

Chapter 3: Results

3.1 Model Validation

GEH statistics were used for existing conditions for each case study site to assess the validity of each model. This method uses the following formula: $GEH = \sqrt{\frac{2*(M-C)^2}{M+C}}$ where M is the traffic volume output of the model and C is the traffic volume input of the model. Acceptable GEH values are 8.5 and below. This analysis was performed for each turning movement in the existing conditions models for each case study site. The vast majority of turning movements were found to be good or very good matches. Only the EBL movement for site 5 was found to be above 8.5 with a value of 14.3. Given the good GEH statistics for every other movement, the models were deemed valid.

3.2 Weighted Average Travel Time

Travel time results from simulations with only the main intersection for each case study site are shown in Tables 27-32. Overall, most three-phase designs had lower average travel times compared to conventional intersections across multiple scenarios. Notably, the seven-phase design was the only three-phase intersection in this study that had mixed results regarding travel times.

Of the seven alternative designs studied at site 1, the partial MUT #1 design had the lowest average travel time with an average reduction of 9% across all scenarios as shown in Table 27. The full MUT was the only other design with significant travel time reductions at site 1 with an average reduction of 8% across all scenarios. As mentioned previously, 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 the minor lefts both 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. This means that at this particular site, the existing conditions should perform better when compared to alternative intersections than at other sites.

Table 27. Case Study Site 1 New Bern Ave and Peartree Ln

Weighted Average Travel Times (minutes)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM
Existing	1.45	1.45	1.49	1.44	1.45	1.49
Seven-Phase	1.52	1.52	1.54	1.52	1.51	1.53
Full MUT	1.36	1.35	1.33	1.35	1.35	1.37
MUT 1	1.35	1.33	1.31	1.34	1.33	1.35
MUT 2	1.44	1.44	1.49	1.42	1.44	1.49
RLT	1.41	1.41	1.44	1.40	1.41	1.43
Reverse RCI	1.45	1.42	1.47	1.44	1.45	1.46
Thru-cut	1.40	1.41	1.46	1.41	1.42	1.47

As shown in Table 28, 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 RLT reduced travel time by an average of 8% across all scenarios.

Table 28. Case Study Site 2 Chapel Hill Rd and Trinity Rd

Weighted Average Travel Times (minutes)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM
Existing	1.61	1.59	1.70	1.81	1.65	2.12
Seven-Phase	1.63	1.52	1.66	1.70	1.62	2.84
RLT	1.51	1.46	1.57	1.67	1.51	1.95

At case study site 4, six different alternative intersections were evaluated as shown in Table 29. Over all scenarios, the CFI/MUT Combo design had the largest average reduction in travel time at 34%. Partial CFI had the second largest average travel time reduction at 31%. Partial MUT 1 and full MUT also performed well at site 4 with average travel time reductions of 21% and 19% respectively.

Table 29. Case Study Site 4 Capital Blvd and Old Wake Forest Rd
Weighted Average Travel Times (minutes)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM
Existing	1.94	1.83	1.91	5.45	3.83	5.33
CFI MUT Combo	1.72	1.51	1.59	2.32	1.61	3.03
Full MUT	1.71	1.91	1.75	3.99	2.68	3.00
MUT 1	1.68	1.81	1.73	4.80	2.36	2.55
MUT 2	2.06	1.66	1.80	4.71	2.55	5.23
Partial CFI	1.67	1.52	1.68	1.91	1.72	4.00
Redirect 2LT	1.75	1.54	1.71	5.41	2.56	3.45

For case study site 5, partial MUT 1 and partial MUT 2 were compared to existing conditions as shown in Table 30. 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 major roads at site 4 compared to site 5. Of note, site 4 had one of the highest heavy vehicle percentages at 4.5%.

Table 30. Case Study Site 5 Capital Blvd and Trawick Rd
Weighted Average Travel Time (minutes)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM
Existing	2.32	2.05	2.18	2.32	1.99	2.18
MUT 1	2.17	1.66	1.91	2.28	1.63	1.81
MUT 2	1.69	1.71	1.87	1.82	1.67	1.79

At case study site 7, the Thru-cut reduced travel times by an average of 30% across all scenarios as shown in Table 31. The reduction in travel time was most significant in future scenarios where traffic volumes were at their highest. Of note, site 5 had one of the highest heavy vehicle percentages at 4.5%.

Table 31. 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
Existing	1.97	2.18	2.05	3.54	8.82	7.89
Thru-cut	1.92	2.10	2.11	1.91	3.22	2.48

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 32. The reduction in travel time was most significant in the 2043 PM scenario for 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 turns movements which are allowed to turn simultaneously at the main intersection with the Partial CFI design. Of note, site 7 had the lowest heavy vehicle percentage at 1.5%.

Table 32. Case Study Site 8 NC-55 and O'Kelly Chapel Rd

Weighted Average Travel Time (minutes)

Intersection Type	2023 AM	2023 MD	2023 PM	2043 AM	2043 MD	2043 PM
Existing	1.72	1.69	1.87	2.38	2.11	8.45
CFI MUT Combo	1.47	1.50	1.62	1.61	1.72	5.55
Partial CFI	1.49	1.51	1.55	1.61	1.63	4.24

The average percent reduction in weighted average travel time for each design across all case study intersections are shown in Table 33. According to this table, three-phase designs with a CFI element (Partial CFI and CFI MUT Combo) reduce travel time the most, followed by R2LT and Partial MUT 1. Of all the three-phase designs tested, the seven-phase signal is the only alternative that consistently performed worse than a conventional signal in terms of weighted average travel time.

Table 33. 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%
R2LT	18%
MUT 1	17%
Thru-Cut	16%
MUT 2	14%
Full MUT	14%
RLT	5%
Seven-Phase	-4%

Chapter 4: Conclusions and Recommendations

4.1 Conclusions

The conclusions listed below summarize the important findings extracted from the literature, dealing with the evaluation of the current state of the art regarding three-phase alternative intersections. These findings from this literature review were characterized in the following sections: (a) three-phase intersection performance (traffic operation, safety, and pedestrian performance), (b) public acceptance, (c) construction costs and (d) study gaps. Following the literature review, conclusions regarding the microsimulation portion of this thesis are discussed.

4.1.1 Three-Phase Intersection Performance

From the literature review, multiple studies have shown the safety and operational benefits of alternative intersection designs. In theory, redirected movements result in fewer conflict points that are spread out over multiple intersections. While there is not an abundance of before/after safety data for existing three-phase designs (given their relatively new emergence), the data that is available confirms this theory suggesting there will possibly be favorable CMFs from future implementation of these designs.

- Overall, there is limited literature available regarding three-phase intersections.
- From this limited research, three-phase intersections should outperform conventional intersections in terms of safety and traffic operation.
- The partial CFI and the MUT/CFI combo should result in shorter travel times and higher capacity than the four-legged conventional intersection.
- The thru-cut design could result in travel times similar to the partial MUT but should fit better in signal progression.
- Three-phase intersections have mixed results regarding pedestrian travel times and safety compared to conventional intersections with four legs.
- Partial MUT has the fewest flags (2 yellow, 10 red) according to the 20-flag method from NCHRP Research Report 948 making it possibly the most pedestrian-friendly design included in this literature review.
- Partial CFI has the highest number of flags (6 yellow, 14 red), which means it is possibly one of the least pedestrian-friendly three-phase intersections.

4.1.2 Public Acceptance

- Patrial CFI should be the only three-phase intersection included in past studies.
- Most studies reveal initial local public resistance towards alternative intersections (most studies did not include three-phase intersections though).
- One common public concern is anticipated safety issues resulting from navigating an unfamiliar intersection.
- Another common concern from businesses is that redirected movements at an intersection could dissuade or impede customers from reaching their business.
- The more familiar the public becomes with an alternative intersection design, the more likely they are to acknowledge the benefits of that design.

4.1.3 Construction Costs

- Quadrant intersections were estimated to cost between $1.8 and $3 million in 2019.
- Partial MUT, reverse RCI, and thru-cuts were estimated to cost $5 million for replacing intersections with four-phase signals in California in 2022.
- CFI/MUT combo and partial CFI were estimated to cost $7.6 million and $10.2 million, respectively in 2022.
- Transportation agencies might consider the MUT/CFI combo design at intersection sites where ROW costs are significant for implementing a partial CFI.

4.1.4 Gaps in Literature

The gaps found in this literature review include the following:

- There are limited safety studies and CMFs for three-phase intersections.
- There are limited studies on the traffic operation of three-phase intersections in different case studies with different traffic conditions.
- Development of signage guidelines for specific three-phase intersection designs.
- Development of geometric design guidelines for three-phase intersection designs.
- Development of guidelines for pedestrian navigation through the new three-phase intersections, such as thru-cut intersection.

- Development of recommendations for addressing obstacles related to public and political resistance.

4.1.5 Microsimulation

From the microsimulation results, three-phase intersections consistently lowered travel time across multiple case study sites and various traffic scenarios. The worst performing alternative in this study was the Seven-Phase signal which, in most cases, performed worse than a conventional intersection in terms of travel time. It is important to note that the Seven-Phase signal was initially proposed as a way to improve three-legged intersections that are adding a fourth leg which was not the case for any of the study intersections in this research.

The most drastic improvements in travel time appear to come from sites where traffic volumes are highest (especially left turn volumes). Of note, as shown with site 8, locations where left turns are permitted may not result in as drastic of travel time improvements with the implementation of three-phase signals. However, the safety benefits of alternative intersections would still be intact at these locations.

The process of manually optimizing signal timing for three-phase signals was tedious and probably unrealistic for most traffic engineers trying to make a timely decision. This would be especially true when considering the increased challenge of coordinating a corridor of intersections.

4.2 Recommendations

Every intersection is a unique and dynamic case study. Researchers and traffic engineers should consider multiple factors such as traffic conditions, available right of way, budget, pedestrian volumes, and safety when determining which design is the best fit for a specific intersection. When a conventional, all-movement intersection is having issues with safety or congestion, traffic engineers should strongly consider the three-phase designs proposed in this thesis as possible alternatives.

Three-phase designs generally provide both operational and safety benefits over conventional four-phase designs; however, achieving optimal signal timing can be tedious using only microsimulation software. Future studies are need to improve signal optimization of simulation packages for alternative designs. A network analysis considering adjacent signals is also recommended for future research.

Regarding simulation software, it could be worthwhile to simulate three-phase designs using multiple software packages (like TransModeler and VISSIM) and compare the results. Researchers would have to take care to model the designs as closely as possible between the two software packages for a fair comparison.

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.

One major concern that business owners have regarding three-phase designs is the impact that they could have on adjacent businesses. Future research could address these concerns using publicly available cell phone location data to perform a comparison between the number of customers at a business before/after the implementation of an adjacent three-phase signal (similar to Barnes et al. 2022).

Lastly, this study focused largely on whether or not three-phase designs could provide some of the benefits of two-phase designs while redirecting fewer movements but did not fully explore the factors that could influence three-phase design performance. Future research should focus on the specific causes of good or bad performance of three-phase designs at specific locations.

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APPENDICES

Appendix A (Case Study Site Traffic Volumes)

Case Study Site 1 Peak Hour Traffic Volumes

Year	Peak Hour	Truck %	Minor Road (PearTree/Donald Ross)						Major Road (New Bern Ave)						Total Demand
			NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	
2023	AM	2	7	10	101	4	4	5	2	525	40	64	897	6	1665
	MD	3	21	4	86	5	4	2	3	694	23	83	726	7	1658
	PM	1	20	4	101	1	10	5	6	1015	33	124	646	4	1969
2043	AM	2	7	9	95	4	4	5	2	494	38	60	845	6	1568
	MD	3	20	4	81	5	4	2	3	654	22	78	684	7	1561
	PM	1	19	4	95	1	9	5	6	956	31	117	608	4	1854

Case Study Site 2 Peak Hour Traffic Volumes

Year	Peak Hour	Truck %	Minor Road (Trinity Road)						Major Road (Chapel Hill Road)						Total Demand
			NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	
2023	AM	4.4	17	45	29	159	21	216	217	1072	21	55	823	151	2826
	MD	3.9	31	35	59	139	32	257	170	758	25	46	612	88	2252
	PM	1.7	28	45	76	249	48	413	180	1131	12	54	1018	106	3360
2043	AM	4.4	23	61	39	214	28	291	292	1444	28	74	1108	203	3806
	MD	3.9	42	47	79	187	43	346	229	1021	34	62	824	119	3033
	PM	1.7	38	61	102	335	65	556	242	1523	16	73	1371	143	4525

Case Study Site 4 Peak Hour Traffic Volumes

Year	Peak Hour	Truck %	Major Road (US-1 Capital Blvd)						Minor Road (Old Wake Forest Road)						Total Demand
			NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	
2017	AM	6%	72	1325	119	959	2372	180	26	130	405	175	218	201	6182
	MD	5%	205	1463	181	393	1500	367	77	330	498	319	251	300	5884
	PM	3%	198	2400	156	396	1807	302	66	315	791	307	223	215	7176
2023	AM	6%	89	1440	129	1060	2578	196	28	141	440	190	237	218	6749
	MD	5%	264	1590	197	447	1630	399	84	359	541	347	273	326	6457
	PM	3%	244	2609	170	454	1964	328	74	342	860	338	242	234	7859
2043	AM	6%	118	1902	171	1400	3405	258	37	187	581	251	313	289	8912
	MD	5%	348	2100	260	591	2153	527	111	474	715	458	360	431	8527
	PM	3%	323	3445	224	600	2594	434	97	452	1135	446	320	309	10379

Case Study Site 5 Peak Hour Traffic Volumes

Year	Peak Hour	Truck %	Major Road (US-1 Capital Blvd)						Minor Road (Trawick Rd/Huntleigh Drive)						Total Demand
			NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	
2017	AM	6%	23	1942	98	17	3221	43	246	42	24	72	69	298	6095
	MD	6%	51	2482	105	48	2403	99	124	48	54	106	56	151	5727
	PM	2%	35	3251	115	25	2540	79	147	77	57	90	90	140	6646
2023	AM	6%	23	1907	96	17	3163	42	242	41	24	71	68	293	5986
	MD	6%	50	2438	103	47	2360	97	122	47	53	104	55	148	5625
	PM	2%	34	3193	113	25	2495	78	144	76	56	88	88	137	6527
2043	AM	6%	21	1796	91	16	2979	40	228	39	22	67	64	276	5637
	MD	6%	47	2295	97	44	2222	92	115	44	50	98	52	140	5297
	PM	2%	32	3007	106	23	2349	73	136	71	53	83	83	129	6147

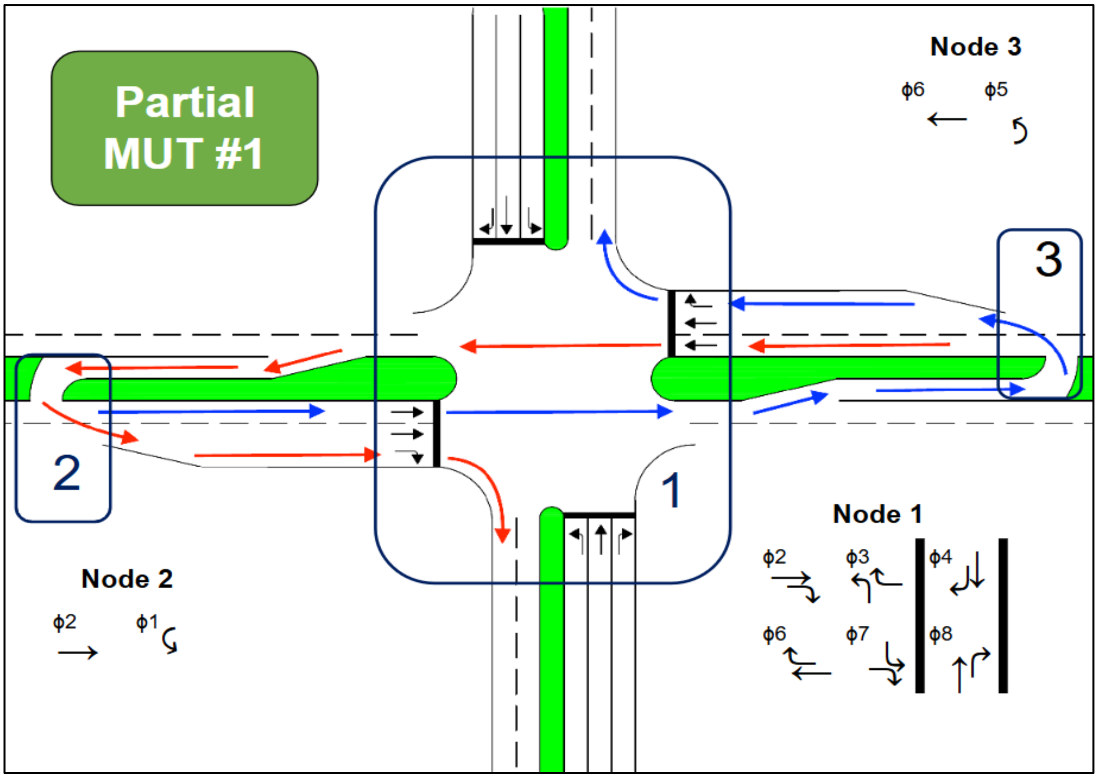
Case Study Site 7 Peak Hour Traffic Volumes

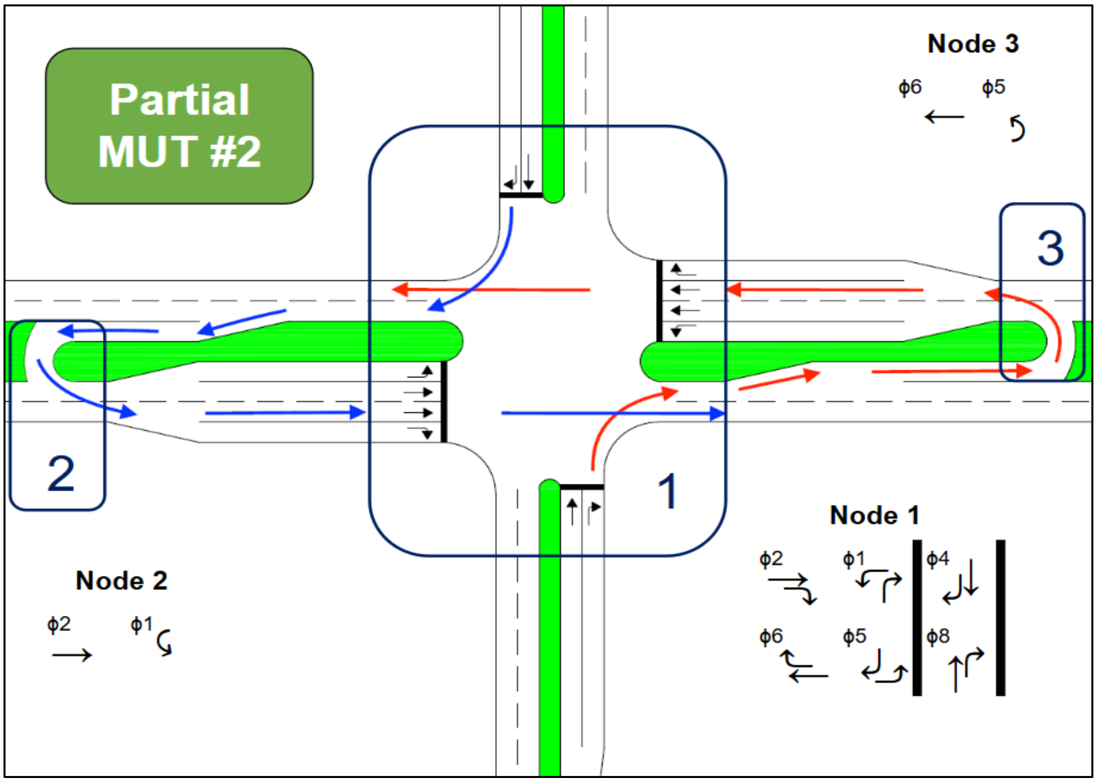
Year	Peak Hour	Truck %	Major Road (Brier Creek Pkwy)						Minor Road (Brier Leaf Ln)						Total Demand
			NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	
2023	AM	2%	44	590	93	347	598	9	34	18	31	86	18	227	2095
	MD	2%	48	756	100	416	711	19	51	20	69	151	22	306	2669
	PM	1.00%	83	810	79	374	842	23	47	31	69	93	22	300	2773
2043	AM	2%	69	930	147	547	942	14	54	28	49	136	28	358	3301
	MD	2%	76	1191	158	656	1120	30	80	32	109	238	35	482	4206
	PM	1.00%	131	1276	124	589	1327	36	74	49	109	147	35	473	4370

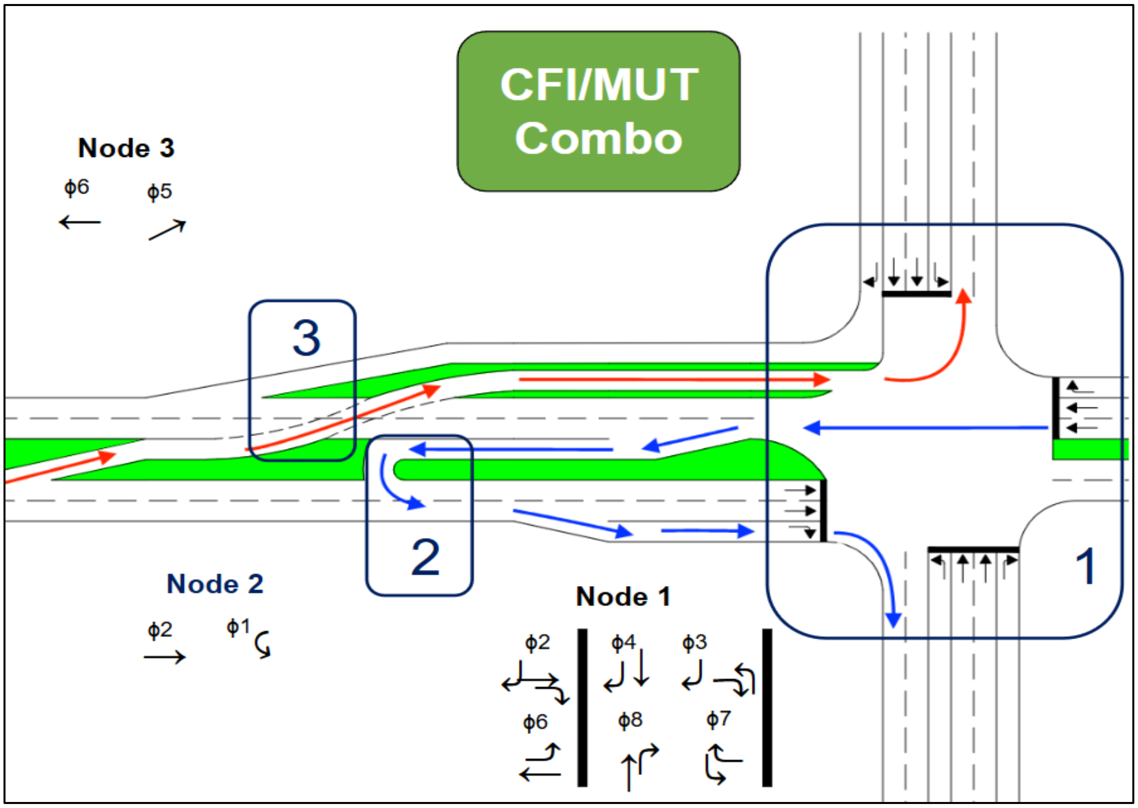
Case Study Site 8 Peak Hour Traffic Volumes

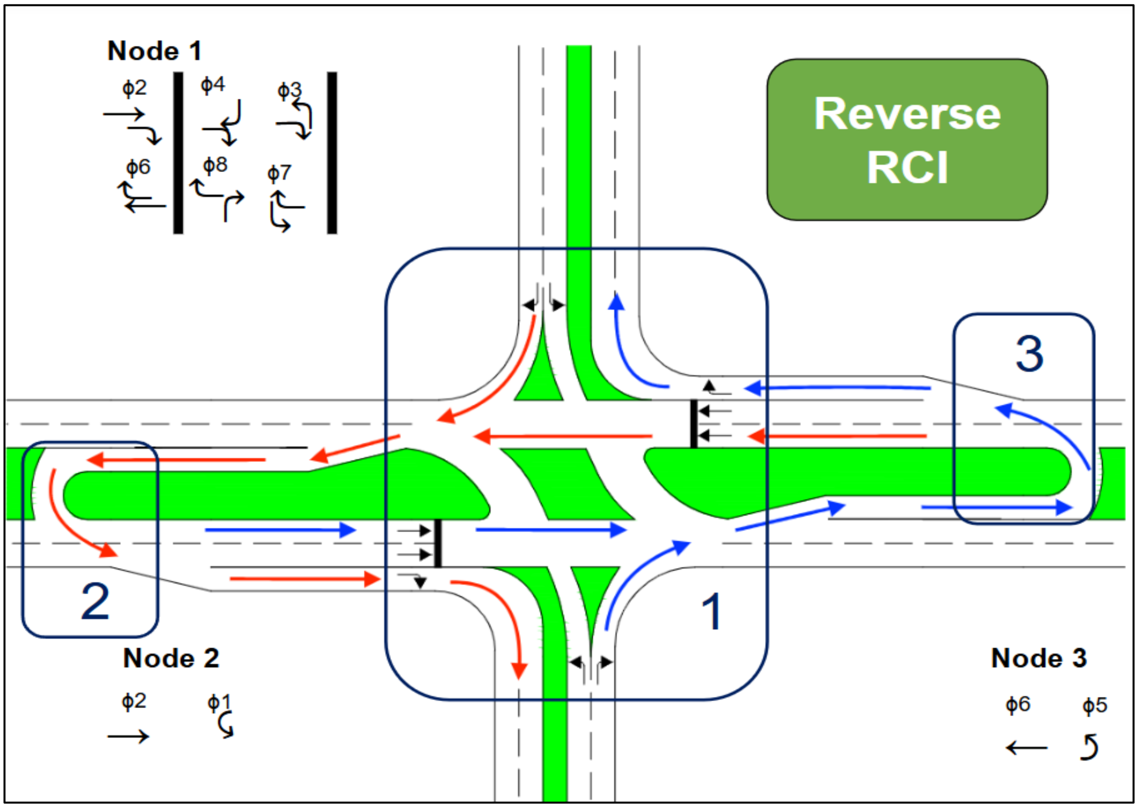
Year	Peak Hour	Truck %	Major Road (NC-55)						Minor Road (O'Kelly Chapel Rd)						Total Demand
			NBL	NBT	NBR	SBL	SBT	SBR	EBL	EBT	EBR	WBL	WBT	WBR	
2021	AM	3%	270	620	106	53	395	83	136	216	312	137	181	55	2564
	MD	2%	219	388	162	145	414	81	87	240	231	284	261	161	2673
	PM	0.70%	328	556	169	140	889	118	96	221	349	249	297	134	3546
2023	AM	3%	293	672	115	57	428	90	147	234	338	148	196	60	2779
	MD	2%	237	420	176	157	449	88	94	260	250	308	283	174	2897
	PM	0.70%	355	603	183	152	963	128	104	239	378	270	322	145	3843
2043	AM	3%	654	1501	257	128	956	201	329	523	755	332	438	133	6206
	MD	2%	530	939	392	351	1002	196	211	581	559	687	632	390	6470
	PM	0.70%	794	1346	409	339	2152	286	232	535	845	603	719	324	8583

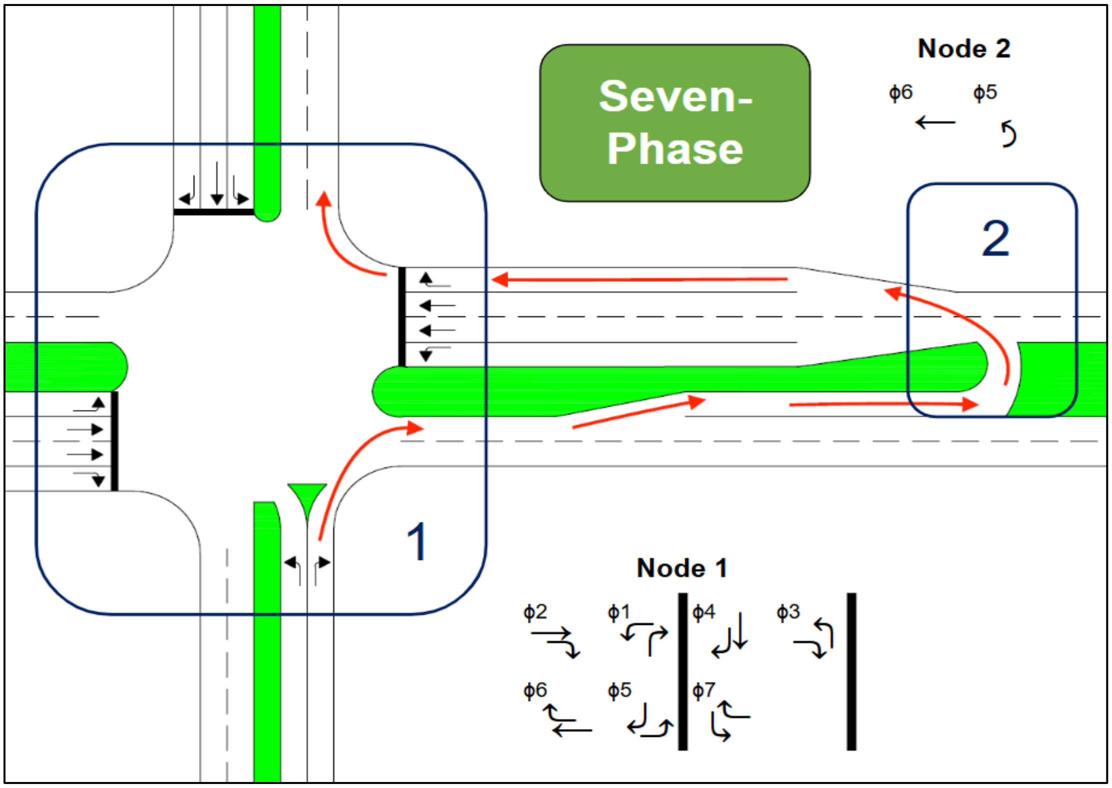
Appendix B (Three-Phase Design Signal Phasing Diagrams)

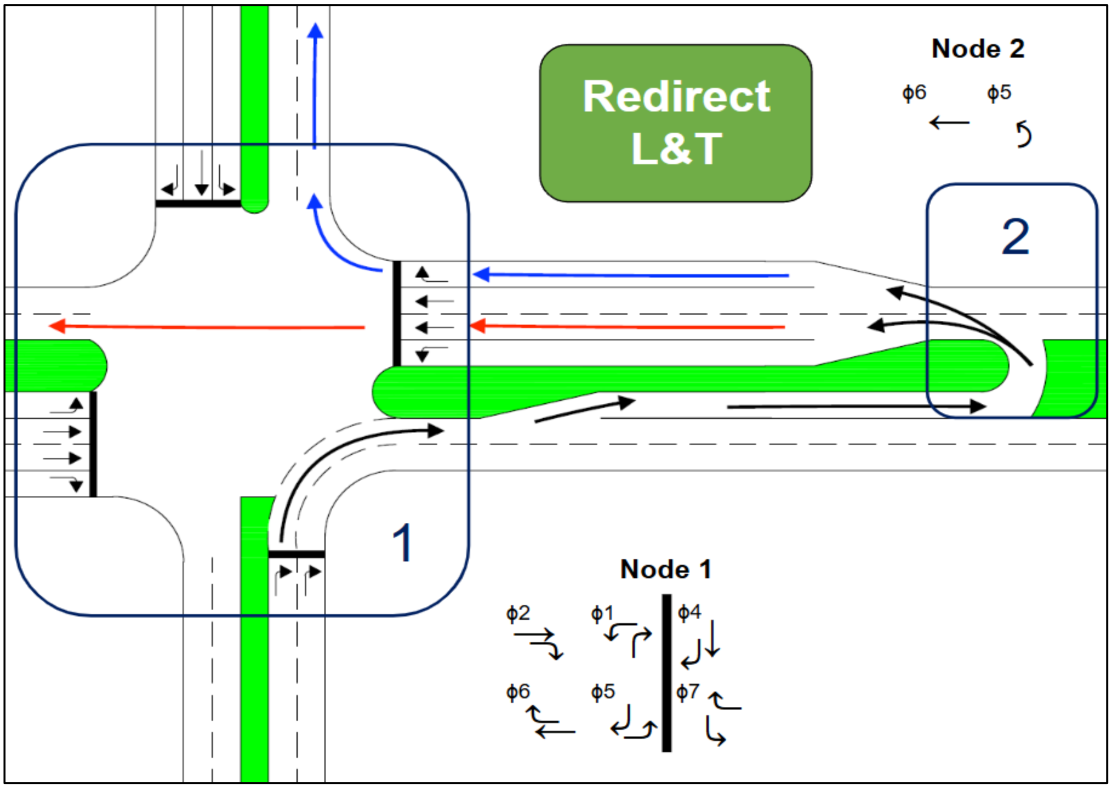


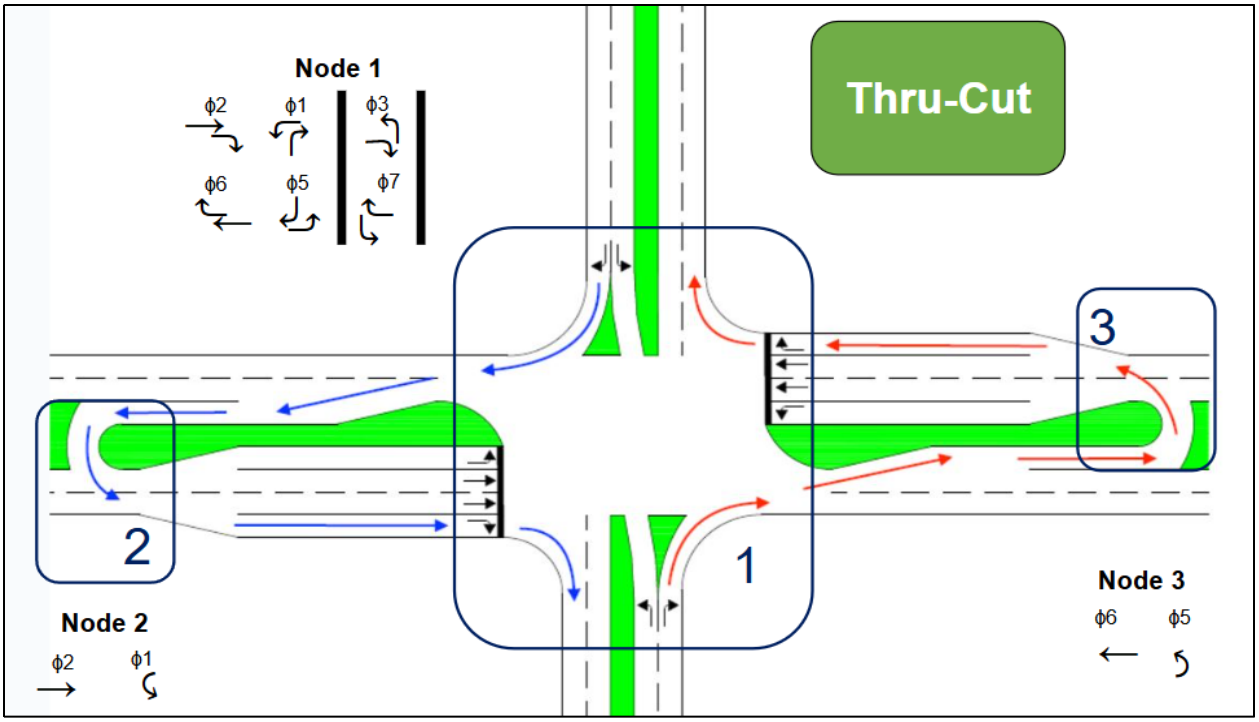


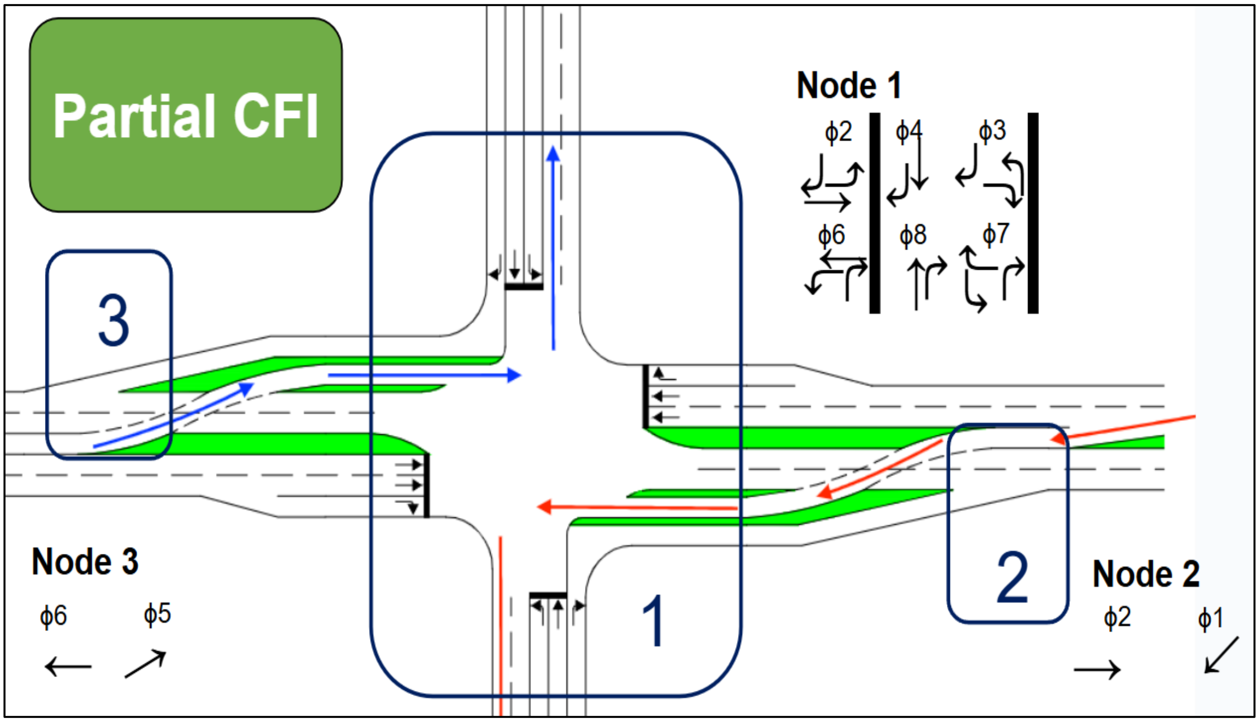

CFI/MUT Combo
Node 3
ϕ6
ϕ5
3
2
1
Node 2
ϕ2
ϕ1
Node 1
ϕ2
ϕ4
ϕ3
ϕ6
ϕ8
ϕ7

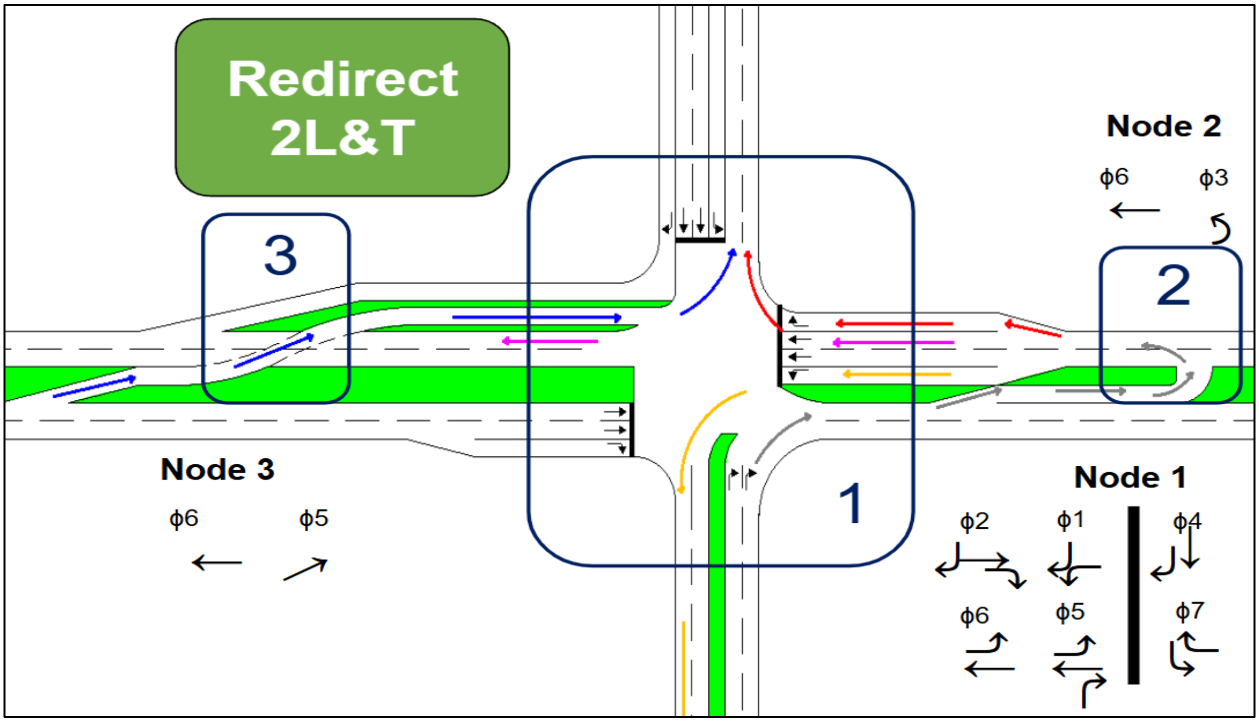

Node 1
ϕ2
ϕ4
ϕ3
ϕ6
ϕ8
ϕ7
Reverse RCI
3
2
1
Node 2
ϕ2
ϕ1
Node 3
ϕ6
ϕ5


Seven-Phase
Node 2
ϕ6
ϕ5
2
1
Node 1
ϕ2
ϕ1
ϕ4
ϕ3
ϕ6
ϕ5
ϕ7


Redirect L&T
Node 2
ϕ6
ϕ5
2
1
Node 1
ϕ2
ϕ1
ϕ4
ϕ6
ϕ5
ϕ7


Node 1
ϕ2
ϕ1
ϕ3
ϕ6
ϕ5
ϕ7
Thru-Cut
3
2
1
Node 2
ϕ2
ϕ1
Node 3
ϕ6
ϕ5


Partial CFI
Node 1
ϕ2
ϕ4
ϕ3
ϕ6
ϕ8
ϕ7
3
2
1
Node 3
ϕ6
ϕ5
Node 2
ϕ2
ϕ1


Redirect
2L&T
Node 2
ϕ6
ϕ3
3
2
1
Node 3
ϕ6
ϕ5
Node 1
ϕ2
ϕ1
ϕ4
ϕ6
ϕ5
ϕ7