Development of a Crash Modification Factor for Conversion of a Conventional Signalized Intersection to a CFI

NCDOT Project 2020-29
FHWA/NC/2020-29
August 2022

RESEARCH & DEVELOPMENT

Chris Cunningham, MSCE, P.E.
Taehun Lee, Ph.D.
Institute for Transportation Research & Education
North Carolina State University

Taha Saleem, Ph.D.
Raghavan Srinivasan, Ph.D.
Highway Safety Research Center
UNC Chapel Hill

RESEARCH & DEVELOPMENT

Development of a Crash Modification Factor for Conversion of a Conventional Signalized Intersection to a CFI

<u>Prepared by:</u>
Institute for Transportation Research & Education
North Carolina State University
Chris Cunningham, MSCE, PE
Taehun Lee, PhD

Highway Safety Research Center
The University of North Carolina at Chapel Hill
Taha Saleem, PhD
Raghavan Srinivasan, PhD

NCDOT Project 2020-29

FINAL REPORT
August 2022

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA/NC/2020-29</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Development of a Crash Modification Factor for Conversion of a Conventional Signalized Intersection to a CFI</td><td>5. Report Date
August 29, 2022</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Chris Cunningham and Taehun Lee (ITRE)
Taha Saleem and Raghavan Srinivasan (HSRC)</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Institute for Transportation Research and Education
North Carolina State University
Centennial Campus Box 8601
Raleigh, NC 27606</td><td>10. Work Unit No. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
North Carolina Department of Transportation
Research and Analysis Group
104 Fayetteville Street
Raleigh, NC 27601</td><td>13. Type of Report and Time Period
Final Report
Aug. 2019 to April 2022</td></tr>
<tr><td>14. Sponsoring Agency Code
RP2020-29</td></tr>
<tr><td colspan="3">Supplementary Notes:</td></tr>
</table>

16. Abstract

North Carolina is considered a progressive state in terms of alternative intersection implementation. The service life of many roadways has been extended because the profession is willing to push the envelope of traditional intersection and interchange designs to consider alternatives – alternatives that in many cases extend the service life without the need for costlier designs. This research follows prior research in the unconventional intersection/interchange domain, which has helped bolster the use of promising alternatives that look at possible safety and operational benefits. Specifically, this project helps build on the current knowledgebase of continuous flow intersections (CFIs) by answering "Are these intersections a safe unconventional design form compared to other design alternatives?"

An Empirical Bayes study was conducted on 16 typical CFIs. Overall, CFIs were found to significantly reduce total crashes by 12.2%. The most significant feature impacting safety at CFIs was the use of parallel vs. standard right turns, with parallel right turns having significant safety benefits (29.6% reduction) across the board and standard right turns increasing crashes (15.6% increase) in nearly all categories. Looking ***only at sites with parallel right turns***, skewed intersections showed significant reductions (29.4% and 30.1% reductions for both no-skew and skew, respectively); however, the findings for the no-skew condition for crash severity and type were better overall. Area type was not found to *increase* crashes; however, rural locations were significantly safer overall compared to urban/suburban designs (40.3% vs. 26.0% reduction). Although both site types were safe, 4-legged sites provide the best overall results for all crash category types and 3-legged sites were only significant in one of the categories. Last, although the number of crossover lanes did not increase crashes in either category, 2-lane crossovers were the only one that was found to significantly decrease crashes (34.9% reduction).

<table>
<tr><td colspan="2">17. Key Words
Continuous flow intersection, CFI, divergent left turn, DLT, crash modification factor, CMF, Alternative Intersection</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classif. (this report)
Unclassified</td><td>20. Security Classif. (this page)
Unclassified</td><td>21. No. of Pages
80</td><td>22. Price</td></tr>
</table>

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

DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the views of the North Carolina Department of Transportation. The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation or North Carolina State University at the time of publication. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

This project was funded by the North Carolina Department of Transportation. The research team wishes to thank the many individuals of the North Carolina Department of Transportation who contributed to the project. Special appreciation is also given to the Steering and Implementation Committee for their valuable support of the study.

EXECUTIVE SUMMARY

North Carolina is considered a leader in the implementation of alternative intersection and interchange designs nationally. Many alternative designs are implemented regularly such as roundabouts, restricted crossing u-turns, median u-turns, and diverging diamond interchanges, to name a few. However, the most promising alternative intersection in terms of operational efficiency, the continuous flow intersection (CFI), is often not considered due to the relative unease around the issue of safety. Research findings over the past decade have very mixed results, were based on limited numbers of sites, and even worse were often using evaluation methods that do not account for many known biases in safety studies. Although no one questions the operational efficiencies gained by using a CFI, the lack of solid evidence that this roadway design will not negatively impact safety often leads decision-makers to veer away from utilizing it in practice.

The research effort conducted by the Institute for Research and Education, in concert with UNC's Highway Safety Research Center, sought to fill the gap in research related to CFI safety to determine if the alternative intersection should be considered as a future design alternative. An Empirical Bayes crash analysis was utilized to account for time, seasonality, historical trends, and regression-to-the-mean. A total of 27 "typical" CFIs were initially considered; however, further investigation into the date of installation, availability of data requested from states, and any designs that included unusual geometric features not evident in the first pass were removed. In total, 16 treatments sites were studied along with 76 reference sites for safety performance function (SPF) development.

Crashes were analyzed at both the aggregate and disaggregate levels using five separate crash categories. First, total crashes were used as an overall measure of safety. A breakdown of total collisions used crash severity groupings of fatal + injury (KABC) and PDO crashes separately, while crash type used angle and rear end crashes. Using these five categories, disaggregated crashes were analyzed further based on the right turn treatment type (standard vs. parallel), presence of intersection skew (skew angle < 70°), area type (rural vs. urban/suburban), number of approaches (3 vs. 4), and the maximum number of left turn crossover lanes (1 vs. 2).

Overall, the following findings in each crash category for aggregate and disaggregate categories were as follows:

- Overall, CFIs were found to provide a positive, and significant, safety benefit of 12.2% when looking at *total crashes* (95% CI).
    - Looking at the *severity of crashes*, CFIs were found to significantly reduce fatal and injury as well as PDO crashes by 13.9% and 11.8%, respectively (95% CI).
    - Looking at *crash type*, CFIs were found to significantly reduce angle and rear end crashes by 29.4% and 13.2%, respectively (95% CI).

- Right Turn Treatment: Overall, this was the predominant determining factor for whether a CFI site would be safe. The findings showed that parallel right turns significantly reduced total crashes by 29.6%; whereas sites with standard right turns increased crashes significantly by 15.6%.
- Other Factors: The four other four factors were analyzed as a subset of the right turn treatment. In nearly all cases, these factors showed significant improvements in safety when considering them with the parallel right turn; however, these factors in combination with a standard right turn primarily found significant increases in crashes. Looking ***ONLY at sites with parallel right turns***, the following can be said:
    - Skew: Intersections with little-to-no skew showed significant reductions in all crash types, ranging from 28.4% to 54.0%. Skewed intersections showed solid findings also, with three 3 of the 5 crash categories decreasing significantly by 30.1% to 40.6%. The other two crash categories showed no significant change.
    - Area Type: Rural sites showed the most significant reduction overall by 40.3%; however, urban/suburban sites also significantly reduced crashes overall by 26.0%. All crash types and severities were found to significantly reduce for both area types from 25.0% to 54.2%.
    - Number of Approaches: 3- and 4-legged approach CFI's showed positive safety benefits with a 14.1% and 32.5% decrease in overall crashes, respectively. The 4-legged showed the most promise because all crash types and severities decreased significantly from 28.3% to 46.4%; however, the sample size of crashes was very limited for 3-legged sites which likely led to statistically insignificant findings in 4 of the 5 crash categories.
    - Number of Crossover Lanes: Sites with 2 crossover lanes were much more promising than sites with 1 crossover lane, with a significant reduction in overall crashes by 34.9%. By comparison, single crossover lane sites reduced crashes by an insignificant 4.8%. In addition, all other crash categories for 2-lane crossover sites reduced significantly from 31.2% to 45.1%; whereas only angle crashes reduced significantly by 32.7% at single lane crossover sites. However, rear-end crashes appear to be negatively impacted with single lane crossovers compared to dual lane.

The results presented in this report indicate that if a CFI is being considered as a design option, it can be designed safely if careful consideration is taken up front in the specific design elements one can control – the most important of which is the right turn treatment. Sites with dual lane crossovers will perform best, allowing queued traffic to safely and efficiently utilize the available green time, thus reducing the potential for rear end crashes.

TABLE OF CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

North Carolina is considered a very progressive state in terms of alternative intersection design and implementation. The service life of many roadways has been extended because the profession is willing to push the envelope of traditional design to consider alternatives – alternatives that in many cases extend the service life without the need for costly interchange designs. However, many urban and suburban roadways have exhausted the capacity available to service motorist reasonably. The benefits of traditional widening are not justifiable, and far-to-often expensive grade separation is considered as the solution when not necessary or expedient to do so.

One very promising alternative design that has gained traction in NC over the last two decades is the Superstreet, or Reduced Conflict Intersection, which has been implemented at scores of locations across the State. These intersections have been proven to move more vehicles efficiently and safely through the same arterial pavement as conventional arterials, at-grade, with minimal disruptions to the surrounding environment and businesses (Haley, 2011; Ott, 2012; Holzem, 2015; and Haley, 2015). More than a decade ago, the NCDOT adopted the superstreet as an appropriate design for important segments of strategic highway corridors. However, other promising alternative designs exist that are not faring as well in NC on the spectrum of alternative intersection designs. One such promising design is the Continuous Flow Intersection, or CFI.

Prior studies have showed that the CFI is a very efficient intersection design that can extend the life of intersections for decades – even offering a near permanent solution in some cases (Jagannathan, 2004; Reid, 2001; Carroll, 2013; and Cook, 2003). In addition, pedestrian and bicycle facility options are being considered to help ease concern of other road users (Ahmed, 2021 and Schroeder, 2021). However, due to the limited construction of CFI's nationally, little is known about the safety of this intersection. Given the complexity of the intersection design and the high volume of traffic volume it processes, designers often tend to agree that although it is efficient, it may not be a safe solution compared to other alternatives. This "on the fence" mentality – especially with regards to safety and pedestrian and bicycle options – is the most likely reason the CFI is less prominent at the state and national level.

2. RESEARCH OBJECTIVE

This research follows prior research in the unconventional intersection domain, which has helped bolster the use of promising alternatives that look at possible safety and operational benefits. This effort builds on the current knowledgebase of continuous flow intersections (CFIs) by answering "Are CFIs a safe unconventional design form compared to other design alternatives?" The findings from this research can help roadway designers and decision-makers weigh the various trade-offs of design alternatives leading to a more informed design selection that provides a safe, efficient, and cost-effective alternative that meets the publics expectation upon completion.

To answer this question, the research team was tasked with filling the gap in safety research that has been conducted to date on the CFI. Although CFIs are the most efficient intersection of any intersection form; the research completed at this time related to safety has mixed results. Therefore, the research team sought to answer the following questions:

- Primary: What is the anticipated overall safety impact of installing a CFI
- Secondary:
    - Are there certain crash types that are more likely to increase or decrease when a CFI is installed?
    - What happens to injury severity at these sites following installation?
    - Are there any geometric or other features of the CFI that seem to be more problematic that others?

It should be noted that this effort will not focus on pedestrian or bicycle safety due to the limited sample size of sites and crashes specific to those two modes. As a surrogate, readers should know that safety with respect to pedestrian and bicycle effects was recently studied in depth at the national level (Schroeder, 2021). This research and the associated design recommendations are summarized in Section 3.3 of this report. As such, although pedestrian and bicycle crashes were included in our crash studies, no detailed efforts with respect to these modes was completed.

3. LITERATURE REVIEW

This section reviews previous studies that investigated the safety impacts of a CFI. A host of qualitative and quantitative studies are summarized, including strengths and weaknesses in application.

3.3 Qualitative Assessment Methods

3.3.1 Conflict Point Diagram Comparison

According to the FHWA Displaced Left Turn (DLT) Information Guide, a DLT (referred to here as CFI, or continuous flow intersection) *has the potential to offer safety improvements* over a conventional intersection based on the design and operation of the intersection (FHWA, 2014). Exhibit 1, Exhibit 2, and Exhibit 3 show the vehicle conflict points for a standard intersection, a partial CFI, and a full CFI, respectively. Based on the vehicle conflict point diagrams, the partial CFI includes 30 total conflict points and the full CFI included 28 conflict points, both of which were less than 32 conflict points at a conventional intersection.

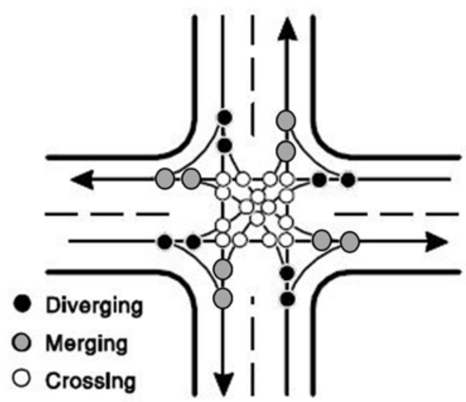


Exhibit 1. Vehicle Conflict Point Diagram for a Standard Intersection

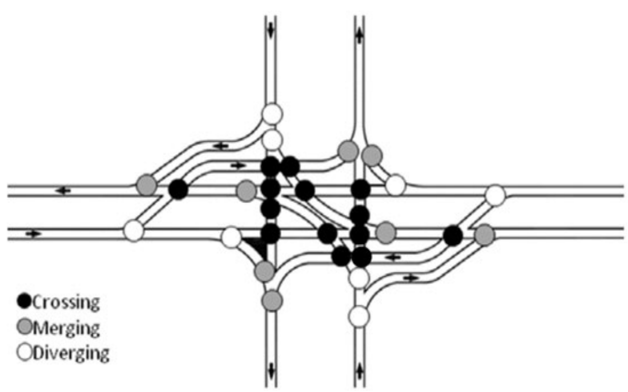


Exhibit 2. Vehicle Conflict Point Diagram for a Partial CFI

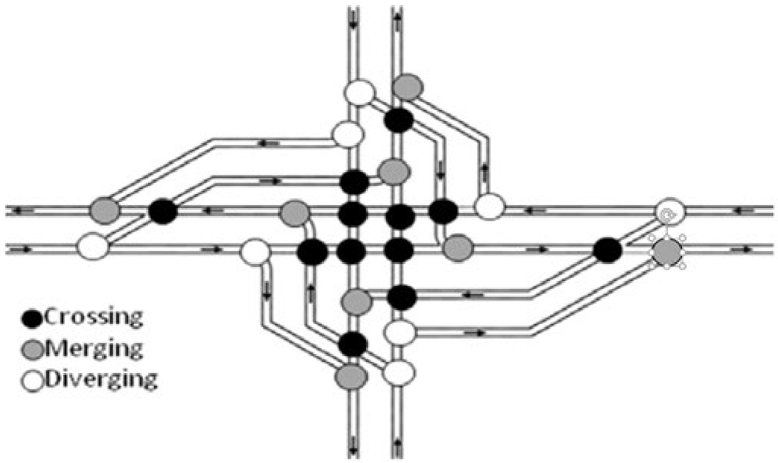


Exhibit 3.Vehicle conflict point diagram for a full CFI

Exhibit 4 provides an overall summary by intersection (standard, partial CFI, and full CFI) and conflict type (diverge, merge, and crossing). Each of the three intersection types have equal merging and diverging conflicts; however, the more serious crossing conflict is reduced. In FHWA's DLT Guide, it is stated that the slightly lower number of total conflict points in partial/full CFIs *could* translate to fewer collisions.

Exhibit 4. Summary of Vehicle Conflict Points by Intersection and Type

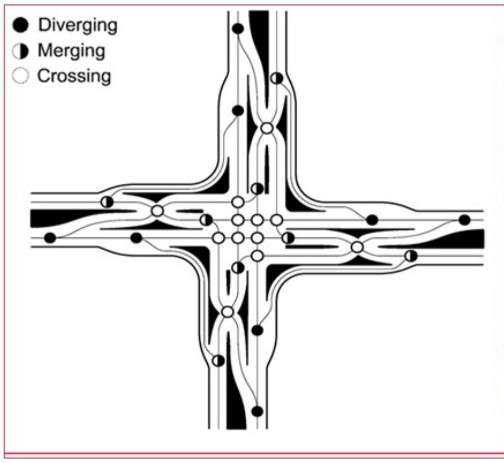
Intersection Type	**Number of Vehicle Conflict Points by Type**			
	Total	***Crossing***	***Merging***	***Diverging***
Standard Intersection	32	16	8	8
Partial CFI (2 legs)	30	14	8	8
Full CFI (4 legs)	28	12	8	8

In looking at conflict points alone, two inherent problems surface. First, although the type of conflicts is highly correlated to the severity of collisions, the number and type of conflict points alone do not account for exposure in any way. Second, conflicts alone do not account for driver confusion which may be present in unconventional intersection forms such as the CFI.

Previous studies argued that CFIs could cause confusion to drivers who were unfamiliar with its unique design and operation, especially at the location of displaced left turn lanes. Park and Rakha (2010) conducted a field-based conflict analysis to investigate driver confusion using video. The video data was recorded during the first year after the implementation at two partial CFIs at Baton Rouge, LA and West Valley City, UT. The analysis results showed more than 90% of driver maneuver errors were related to improper lane changing, diverging, and red-light violations. These errors decreased significantly over time as drivers became familiar with the CFIs. The primary limitation of this study is that the results could not reliably confirm the CFIs safety impacts from the before-to-after period since the analysis is based only on the after-period conflict data.

3.3.2 VDOT Junction Screening Tool

The Virginia DOT developed their own qualitative method for comparing safety among various alternatives – especially when alternatives have little-to-no current safety data for comparative purposes. The tool, dubbed the VDOT Junction Screening Tool (VJuST), is a planning level operational and safety performance evaluation screening tool. In the safety evaluation method, VJuST utilizes the total crash frequency for severities and conflict point (CP) types using statewide crash data to calculate a "weight" for CP types. Exhibit 5 shows the safety evaluation process of the weighted CP comparison method in VJuST.



Conflict Type	Count
Crossing	12
Merging	8
Diverging	8
Total	**28**

Conflict Type	Weight
Crossing	2
Merging	1
Diverging	1

Weighted Total Conflict Points
40

Step 1 Count the Conflict Points

Step 2 Weight x CPs

Step 3 Weighted Total Conflict Points

Exhibit 5. Conflict Point Comparison Method in VJuST

Although this method is based on sufficient amounts of crash records in Virginia, the weighted CP comparison method provides reasonable comparison results while also being very easy to use in application. However, it still has significant limitations – namely, that it cannot account for the impact of traffic volume on crashes and different crash rate for CP types. In addition, the crash classifications used in the study show a large proportion of crashes (such as side swipe and rear end) not accounted for because they do not meet the merge, diverge, or crossing conflict point criteria. The "non-conflict point" crashes can be quite significant in some cases.

3.3.3 Safe System for Intersections

The Safe System for Intersections (SSI) method evaluates the safety for a conflict point based on three primary factors. First, exposure is utilized to determine safety based on conflicting traffic volumes. More traffic crossing at a conflict point means a lower anticipated score. Second, severity is captured using vehicular movement, speed, and conflicting angle. The likelihood of a crash is assumed to be higher for crossing conflicts and movements with higher speeds. Last, the movement "complexity" is captured using the traffic control type, the number of conflicting lanes, traffic speed, etc.

Based on these three primary factors, the SSI method calculates a qualitative measure using a "safety index" for intersection design alternatives using the following equation.

$$SSI\ Score = (Product\ of\ volumes)x(Prob. of\ fatal\ or\ serious\ injury)x(Complexity\ Factors)$$

The lower the SSI score, the worse the intersection is considered, with scores ranging from 0 to 100. Shown in Exhibit 6, SSI scores were calculated for a standard signalized intersection and CFI with protected left turns using typical AADTs for minor (25,000 – 40,000) and major (30,000 – 40,000) roads, a k-factor of 0.1, a directional split of 50/50, single exclusive turning lanes, two or three through lanes in each direction, and each turning demand equal to 10% of the major street AADT.

Exhibit 6. SSI Scores (Overall and Non-Motorized) for a Std. Intersection and CFI

Major Road		Minor Road		SSI (Overall)		SSI (Non-Motorized)	
# Lanes	AADT	# Lanes	AADT	Std. Signal	CFI	Std. Signal	CFI
4	30000	4	25000	43	34	38	13
4	30000	4	30000	38	30	36	12
6	40000	4	25000	22	14	23	4
6	40000	4	30000	17	11	21	3
6	40000	6	40000	10	6	15	2

Based on the assumptions above, the SSI score for a CFI is 31% to 36% lower than a standard intersection, indicating that the CFI would be expected to increase crashes for all crash types. This aligns with some of the findings in the literature, while for some, it doesn't align at all. When looking at the non-motorized SSI score, the findings were even more concerning, with the SSI score for nonmotorized traffic at a CFI lower by 66% to 87%. Since the SSI scoring method is more qualitative and not based on actual crash data, the SSI score should only be utilized if no other valid crash studies were available, or possible to conduct.

3.3.4 Design Flag Assessment

A previous study sponsored by FHWA using a "design flag" method for safety assessment of pedestrian and bicyclist according to intersection designs being considered (Schroeder, 2021). This evaluation method uses two types of design flags to identify safety areas of concern: 1) "red flags" warranting attention because specific design elements present serious safety concerns for pedestrians or bicyclists and 2) "yellow flags" which may need attention because design elements negatively affect user comfort (i.e., increasing user stress) or the quality of the walking or cycling experience.

The method compares safety performance between design alternatives by calculating the percentage of yellow and red as performance measures. Percent yellow (or percent red) can be calculated by dividing the number of applied flags by the total possible number of flags and multiplying by 100 and can be calculated for pedestrians and bicycles separately. The design flags were assessed for the four pedestrian crossing movements between adjacent quadrants, as well as the twelve bicycle turning movements (left, thru, right for each approach), for a total of twenty possible flag types. For pedestrians, 13 out of the 20 possible flags apply, for a total of 52 potential flags (13 flags times four pedestrian flows). For bicycles, 17 out of the 20 possible flags apply, for a total of 204 potential flags (17 flags times 12 bicycle movements).

Percent yellow and percent red can be calculated for pedestrians and bicycles, separately. An example assessment for four design alternatives (A through D) is shown in Exhibit 7. It shows that alternative C results in the fewest yellow and red design flags for both pedestrians and bicycles.

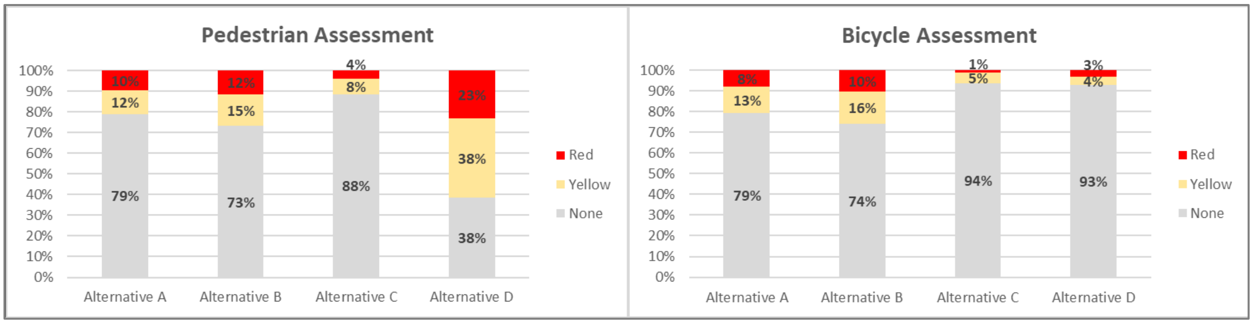


Exhibit 7. Examples of Percent Yellow and Red for Pedestrians and Bicycles

A design flag does not necessarily represent a fatal flaw for an alternative; rather, it presents a design issue that should be addressed in the iterative development and evaluation of the alternative. Some design flags depend on signalization decisions and designs of pedestrian and bicycle pathways. So, this section only discusses applicable design flags and descriptions for the genetic CFI design.

At CFIs, five flags were applicable to pedestrians (sections 4.4.1, 4.4.3, 4.4.7, 4.4.8, and 4.4.10) and four design flags were applicable to bicycles (sections 4.4.8, 4.4.15, 4.4.17, and 4.4.18). Exhibit 9 and Exhibit 10 show the design flags and descriptions applicable to pedestrians and bicycles at CFIs.

Sec.	Design Flag	Bikes	Peds.	Flag Type	Flag Description
4.4.1	Motor Vehicle Right Turns		X	Y/R	Permissive motor vehicles right turns across pedestrian paths
4.4.2	Uncomfortable/Tight Walking Environment		X	Y	Pedestrian facilities of narrow width
4.4.3	Nonintuitive Motor Vehicle Movements		X	Y/R	Motor vehicle movements arriving from unexpected direction
4.4.4	Crossing Yield- or Uncontrolled Vehicle Paths	X	X	Y/R	Yield or uncontrolled pedestrian crossings
4.4.5	Indirect Paths	X	X	Y/R	Paths resulting in out of direction travel
4.4.6	Executing Unusual Movements	X	X	Y	Movements that are unexpected given local context
4.4.7	Multilane Crossings	X	X	Y/R	Crossing distances of significant length across multiple lanes
4.4.8	Long Red Times	X	X	Y/R	Excessive stopped delay at signalized crossings
4.4.9	Undefined Crossing At Intersections	X	X	Y	Unmarked paths through intersections
4.4.10	Motor Vehicle Left Turns	X	X	Y/R	Permissive and protected left turns across pedestrian and bicycle paths
4.4.11	Intersection Driveways and Side Streets	X	X	Y/R	Driveways or streets within intersection area of influence
4.4.12	Sight Distance for Gap Acceptance Movements	X	X	R	Providing adequate sight distance to conflict points
4.4.13	Grade Change	X	X	Y/R	Vertical curves adjacent to intersections
4.4.14	Riding in Mixed Traffic	X		Y/R	On street bicycle facilities on high speed/volume roads
4.4.15	Bicycle Clearance Times	X		Y/R	Bicycles require longer clearance times than vehicles at signals
4.4.16	Lane Change Across Motor Vehicle Travel Lane(s)	X		Y/R	Lane changes by bicycles across motor vehicle lanes
4.4.17	Channelized Lanes	X		Y/R	Bicyclist Traveling in Channelized Lane Adjacent to Motor Vehicles
4.4.18	Turning Motorists Crossing Bicycle Path	X		Y/R	Lane changes by motor vehicles across bicycle facility
4.4.19	Riding between Travel Lanes, Lane Additions, or Lane Merges	X		Y/R	Bicycle lanes with motor vehicle lanes on both sides
4.4.20	Off-Tracking Trucks in Multi-Lane Curves	X		Y/R	Tendency of trucks to swing into bicycle lanes while turning

Note: Sec. = Section in this Guide; Peds. = Pedestrians; Trad. Intx. = Traditional Intersection

Exhibit 8. Summary of Design Flags for Pedestrians and Bicyclists

Exhibit 9. Design Flags Applicable to Pedestrians at a CFI

Design Flag	Description	Mode/Travel Path
Motor Vehicle Right Turns (Section 4.4.1)	This flag would carry forward to the final design stage. The right turns at full or partial DLT intersections were typically channelized, so sight distance and control must be considered for pedestrian safety.	Pedestrian, all main intersection crossings
Nonintuitive Motor Vehicle Movements (Section 4.4.3)	Pedestrians crossing the displaced left turn would not typically expect vehicles in the given direction—whether crossing the is on the departing or receiving end of the displaced left turn.	Pedestrian, all main intersection crossings
Multilane crossing (Section 4.4.7)	DLTs typically include multiple through lane approaches plus one or two displaced left turns, bringing a major street crossing to six or seven lanes, in some cases without refuge.	Pedestrians, major street crossings and often minor street crossings
Long Red Times (Section 4.4.8)	Due to high volumes, DLTs typically have longer cycle lengths even though they may have only two or three phases. Additionally, the presence of signalized channelized right turns may result in a high number of stages required to cross the intersection.	Pedestrians, all crossings
Motor Vehicle Left Turns (Section 4.4.10)	As discussed in Section 8.2, pedestrians compete in time and space with the displaced left turns. Signal phasing can reduce the impact to pedestrians, and geometric design can promote appropriately slow left-turn speeds.	Pedestrians, all main intersection crossings

Exhibit 10. Design Flags Applicable to Bicycles at a CFI

Design Flag	Description	Mode/Travel Path
Long Red Times (Section 4.4.8)	Because the preferred bicycle left turn options include either a two-stage left turn or off-street path with crossings, bicyclists' travel time is particularly sensitive to the entire cycle length and red times. The intersection design will optimally minimize excessive delay for bicyclists to discourage risk-taking behavior.	Bicyclists, left turn movements along approaches with displaced left turn
Bicycle Clearance Times (Section 4.4.15)	The typically relatively large footprint of a DLT means that yellow and all-red phases designed around motor vehicle trajectories is probably insufficient for bicyclists to clear the intersection during the intended phase.	Bicyclists, through movements
Channelized Lanes (Section 4.4.17)	The displaced left turn is a channelized movement, and DLT intersections typically feature channelized right-turn movements. Riding alongside vehicles in either channelized movement creates stress.	Bicyclists, left turns and right turns
Turning Motorists Crossing Bicycle Path (Section 4.4.18)	The development of a right turn lane creates a motorist movement crossing over a bicycle path.	Bicyclists, through movements

3.2 Crash-Based Assessments

3.2.1 Crash Studies

The Louisiana Department of Transportation (LADOT, 2007) analyzed the safety impact of a CFI installed at US-61 and LA-3246 in Baton Rouge, LA. The study was completed only 18 months after the construction of the CFI, so the analysis is conducted with limited data. The results of the naïve study showed a reduction in total crashes between 21% and 27%, as well as a reduction in serious injury crashes. Although the initial results were encouraging, the study only included 1.5 years of after period crash data and did not account for changes in other factors, such as traffic volume, seasonality, historical effects, and regression-to-the-mean (RTM). They also conducted driver and business surveys which showed positive feedback on travel time reduction and increased road safety at the CFI.

Yahl (2013) studied the safety impacts of CFIs using the comparison group (C-G) method (Yahl, 2013). Since CFIs were primarily installed for the operational efficiency, they didn't account for RTM. For this analysis, the crash data for five CFIs in Colorado, Louisiana, Mississippi, and Utah were used with fifteen months of after data. The comparison group analysis results for individual sites and overall grouped results by crash type are shown in Exhibit 11.

Exhibit 11. Comparison Group Individual Analysis Results (Yahl, 2013)

Crash Type (All Sites)	Impacts (%)	Std. Dev. (%)
Total	23.9*	6.2
Fatal & Injury	40.5*	13.4
Rear End	39.8*	9.5
Angle	-0.3	10.4
Sideswipe	45.1*	19.6
Other	-2.6	20.8
Treatment Site	**Impacts (%)**	**Std. Dev. (%)**
Eisenhower Blvd. & Madison Ave. (CO)	35.8	40.6
Airline Hwy. & Siegen Ln. (LA)	7.5	25.9
Johnson St. & Camellia Blvd. (LA)	57.7*	25.2
John R Junkin Dr. & Sgt. Prentiss Dr. (MS)	41.1	25.6
Bangerter Hwy. & W. 3500 S. (UT)	17.7	23.7

*Statistically Significant with 95% Confidence (2 standard deviations)

The results of the comparison group method using all five sites combined showed a statistically significant increase in total, fatal and injury, rear end, and sideswipe crashes. When looking at individual site impacts, the only statistically significant finding was an increase in crashes at the

Johnston Street site in Louisiana. One other site worth noting is in Mississippi where there appears to be a likely increase in crashes, though only outside of one standard deviation from the mean. Unfortunately, the findings from this effort have several limitations. First, it is based on a very limited number of sites and crash data. Second, the use of the comparison group does not account for any potential increase in traffic due to the increased efficiencies at the CFI. Last, the comparison groups chosen were not found to be sound based on the odds ratio test, with all sites having a mean over 1.0 (many greater than 1.2) and not falling within one standard deviation.

Zlatkovic (2015) developed a crash modification factor (CMF) for CFIs using one four-legged and seven partial CFI conversions for Utah DOT. The researchers stated that the developed CMFs were only valid for partial CFIs with displaced left turns only on two approaches since seven of the eight CFIs were partial. The Empirical Bayes (EB) method was applied to before and after crash data for all sites in the treatment group and a total of five comparison sites (four-legged signalized intersections) in the comparison group. The study presents a preliminary analysis using two-to-three years of crash data for the after period (the implementation year is not included in the EB models) at the eight treatment sites in Utah. The analysis results noted a CMF of 0.877 for total crashes for local conditions, meaning that the partial CFI has the potential to reduce total crashes by about 12.3%. However, as noted by the authors, the analysis result is based on a limited data set – especially considering the number of comparison sites used to calibrate the model. Therefore, the authors recommend that the suggested methodology can be used as general guidance but to update the analysis as a part of a future study.

Abdelrahman et al. (2020) developed CMFs for the conversion of a conventional intersection to a CFI for different crash severities and types. In the study, the CMFs were developed by two different methods: one is to use the before-and-after comparison-group method; and the other one is to use the cross-sectional analysis method. The detailed results for developed CMFs by two methods were presented in Exhibit 12. In the cross-sectional analysis method, the CMFs were developed based on the coefficient of a dummy variable for CFI in the estimated safety performance function. The crash data was collected for multiple years from 2010 to 2018 from 13 CFIs in Utah, Colorado, Louisiana, and Ohio. The crash influence area utilized included a 250-foot buffer from the center point of the main intersection and 50-foot buffer from the center of each left turn crossover intersection. According to the analysis results from both methods, the CMFs commonly showed CFIs increase the total number of crashes, injury crashes, and some specific crash types (e.g. single vehicle, angle, etc.). Anecdotally, they noted that CFIs *have the potential to decrease* non-motorized crashes, which may be due to the exclusion of left turn movements at the main intersection.

However, this study still has limitations in evaluating the safety performance of CFIs since the CMFs developed provided differing results for several crash types. Using the CMFs developed by the C-G method, the CFI decreased the number of rear-end, head-on, and sideswipe crashes while the C-S method implied the CFI increased the crash frequency of these crash types. In addition, the fixed data collection area of 250 feet from the center of main intersection and 50 feet from the center point of crossover were applied to all CFI sites. However, this buffer distance may not appropriately cover the effected range (e.g. pocket of left turning crossover lane) for some sites – especially rear-end or side swipe collisions that may be taking place outside this buffer.

Exhibit 12. Summary of Developed CMFs by Two Methods (Abdelrahman et al., 2020)

Crash Type	CMFs Using Comp.-Group Method	CMFs Developed by Cross-Sectional Analysis Method			
		Crash Modification Functions	Crash Modification Factors (CMFs)		
			Low traffic volumes (DVMT=3000)	*Moderate traffic volumes (DVMT=6000)*	*High traffic volumes (DVMT=9000)*
Total	1.112**	$DVMT^{0.050***}$	1.492***	1.545***	1.577***
Fatal & Injury	1.224**	$DVMT^{0.040***}$	1.377***	1.416***	1.439***
Property Damage Only	1.069**	$DVMT^{0.067***}$	1.710***	1.791***	1.840***
Single-Vehicle	1.519**	$DVMT^{0.064***}$	1.669***	1.745***	1.791***
Non-Motorized	0.612	$DVMT^{-0.062*}$	0.609*	0.583*	0.569*
Angle	1.244	$DVMT^{0.039*}$	1.366*	1.404*	1.426*
Rear-End	0.946	$DVMT^{0.051***}$	1.504***	1.558***	1.591***
Head-On	0.713	$DVMT^{0.070}$	1.751	1.839	1.891
Sideswipe	0.967	$DVMT^{0.081}$	1.913	2.023	2.091

*** significant at 99% confidence level, ** significant at 95% confidence level, and * significant at 90% confidence level; DVMT: Daily Vehicle Miles Traveled

The findings from prior research were limited, lack sufficient data, and were contradictory. As such, they provide no solid proof whether CFIs were truly safe or not. Even a result that shows no change in safety could provide enough justification to use CFIs where efficiency gains were worthwhile given the cost of retrofit. Given the lack of information available, this study seeks to provide an update to prior studies using a more robust sample size (more locations, more collisions over time, etc.) that can provide guidance to NCDOT on whether CFIs should be considered in their toolbox of alternative intersections considered during the planning phases of projects.

3.2.2 Movement-Based Safety Performance Function Method

3.2.2.1 Concept of MB-SPF

Movement-based safety performance functions (MB-SPF) estimate the crash frequency for an intersection using two models: conflict point SPF (CP-SPF) and non-conflict point SPF (NCP-SPF). The MB-SPF was developed through a prior NCDOT grant related to grade separated intersections (Chase et al., 2020; Lee et al., 2020). CP-SPF estimates the CP crash frequency for a single CP using traffic volumes of two conflicting movements and conflict point type (crossing, merging, and diverging). NCP-SPF estimates the NCP crashes for an intersection using annual average daily traffic (AADT) on major and minor roads. To estimate the intersection total crashes, the estimated CP crashes for multiple CPs in an intersection were aggregated into the total CP crashes, and then, the NCP crashes were added. The following equation shows how the intersection total crashes can be estimated using MB-SPFs.

$$N_{Tot} = \sum_{i=1}^{n} N_{CP_i} + N_{NCP}$$

Where;

N_{Tot} = Intersection total crashes (crashes/year·intersection);

N_{CP_i} = CP crashes for the CP i (crashes/year·CP) ⋯ ($\mathrm{i} = 1, \cdots, \mathrm{n}$); and

N_{NCP} = NCP crashes for an intersection (crashes/year·intersection).

The following equation shows the CP-SPF that estimates the CP crash frequency for a CP. The conflict point type and the major and minor conflicting movement volumes were used as explanatory variables in the model for the estimation of the CP crash frequency.

$$N_{CP_i} = \exp\left(\alpha + \beta_1 \cdot CP_{Diverge,i} + \beta_2 \cdot CP_{Merge,i} + \beta_3 \cdot \ln\left(CMV_{Major}\right) + \beta_4 \cdot \ln(CMV_{Minor})\right)$$

Where;

$N_{CP,i}$ = CP crashes for the CP i (crashes/year·CP) ⋯ ($\mathrm{i} = 1, \cdots, \mathrm{n}$);

$CP_{Diverge,i}$ = Diverging CP type for the CP i (= 1 if CP type is diverging, 0 otherwise);

$CP_{Merge,i}$ = Merging CP type for the CP i (= 1 if CP type is merging, 0 otherwise);

CMV_{Major} = the major conflicting movement volume for the CP i; and

CMV_{Minor} = the minor conflicting movement volume for the CP i.

** The crossing CP type for the CP i was used as the baseline intercept in the CP-SPF model.*

The following equation shows the NCP-SPF that estimates the NCP crash frequency for an intersection. The major and minor AADT were used as explanatory variables in the model for the estimation of NCP crash frequency.

$$N_{NCP} = \exp\left(\alpha + \beta_1 \cdot \ln\left(AADT_{Major}\right) + \beta_2 \cdot \ln(AADT_{Minor})\right)$$

where;

N_{NCP} = NCP crashes for an intersection (crashes/year);

$AADT_{Major}$ = the major road AADT (veh/day); and

$AADT_{Minor}$ = the minor road AADT (veh/day).

Exhibit 13 shows the estimation results for the CP-SPF and NCP-SPF. The table was provided in the North Carolina Department of Transportation's (NCDOT) previous research project report (Chase et al., 2020).

Exhibit 13. Estimated Parameters for MB-SPF (Chase et al., 2020)

Model	Variable	Coefficient	Std. Error	z value	P-value	Stat. Sig.
CP-SPF	CP Type_Crossing	-8.501	0.65539	-12.971	< 2e-16	***
	CP Type_Diverging	-9.873	0.672	-14.691	< 2e-16	***
	CP Type_Merging	-9.316	0.66855	-13.934	< 2e-16	***
	ln(CPV_Major)	0.689	0.08435	8.164	3.24E-16	***
	ln(CPV_Minor)	0.109	0.04939	2.202	0.0276	*
NCP-SPF	(Intercept)	-10.874	1.08321	-10.038	< 2e-16	***
	ln(AADT_Major)	0.792	0.1076	7.362	1.81E-13	***
	ln(AADT_Minor)	0.521	0.05469	9.534	< 2e-16	***

*** significant at 99% confidence level, ** significant at 95% confidence level, * significant at 90% confidence level

3.2.2.2 Safety Impact Measure

For a planning level safety impact assessment of CFI installations, the ratio of the estimated crash frequencies for a CFI and a conventional four-leg signalized intersection (e.g., N_{CFI} / N_{4SG}) were used as a safety performance measure. The MB-SPFs were used to estimate crash frequencies for a given set of turning movement volumes.

3.2.2.3 Traffic Volume Data

To compare the crash ratio (e.g., N_{CFI} / N_{4SG}) with prior developed CMFs in the literature, this effort used AADT data collected from 2008 to 2013 at the eight CFI sites studied by Zlatkovic (2015). The major and minor AADTs, and the periods after CFI conversion for the eight sites are shown in Exhibit 14.

Exhibit 14. Major and Minor AADTs for CFI Sites (Adopted from Zlatkovic (2015))

CFI Site (periods after CFI conversion)	AADT	2008	2009	2010	2011	2012	2013
Bangerter @ 3100 S (CFI: 2011-2013)	Major AADT	47,390	47,345	44,360	48,124	47,980	49,230
	Minor AADT	17,440	17,335	17,265	17,207	16,870	16,445
Bangerter @ 4100 S (CFI: 2011-2013)	Major AADT	50,710	51,065	51,115	49,633	49,485	50,770
	Minor AADT	30,885	30,700	30,580	30,473	29,875	29,130
Bangerter @ 4700 S (CFI: 2010-2013)	Major AADT	51,265	51,625	51,675	54,724	54,560	55,980
	Minor AADT	33,085	33,320	31,840	30,917	30,825	31,625
Bangerter @ 5400 S (CFI: 2010-2013)	Major AADT	55,915	56,305	56,360	54,724	54,560	55,980
	Minor AADT	30,715	33,600	33,465	40,086	39,300	38,320
Bangerter @ 6200 S (CFI: 2011-2013)	Major AADT	55,840	56,230	56,285	54,653	54,490	55,905
	Minor AADT	30,460	30,280	30,160	30,054	29,465	28,730
Bangerter @ 7000 S (CFI: 2011-2013)	Major AADT	55,840	56,230	56,285	54,653	54,490	55,905
	Minor AADT	18,120	18,010	19,855	19,795	19,400	18,915
Redwood @ 5400 S (CFI: 2010-2013)	Major AADT	63,115	62,735	62,485	62,271	61,050	59,525
	Minor AADT	39,960	43,700	41,635	39,798	38,865	39,195
Redwood @ 6200 S (CFI: 2010-2013)	Major AADT	37,360	37,620	37,660	36,760	36,650	37,605
	Minor AADT	22,430	22,295	22,210	22,134	21,700	21,155

3.2.2.4 Turning Movement (TM) Volume Scenarios

For crash prediction, CP-SPF requires turning movement (TM) volumes collected from the CFI sites. However, only major and minor AADTs were available for the eight CFI sites. So, this study assumed TM volumes proportions assumed using the directional approaches in a CFI. Given the CMF of 0.877 was developed for a conversion from conventional intersection to partial CFI (Zlatkovic (2015)), this study concentrated on a partial CFI that has Eastbound (EB) and Westbound (WB) approaches with treated (crossover left turn) lanes, and Northbound (NB) and Southbound (SB) without treatment. Since the crossover left turn lanes of a CFI are usually installed on approaches with heavy left turn volume, the TM volume proportions for directional approaches were assumed as follows[1].

- EB & WB: left turn = 30%, through = 60%, and right turn = 10%
- NB & SB: left turn = 15%, through = 70%, and right turn = 15%

3.2.2.5 Crash Analysis Results

The crash frequencies predicted by MB-SPFs for a conventional four-leg signalized intersection (4SG) and CFI are shown in the following table. In crash prediction, a full CFI was assumed only for Bangerter @ 4700 S, which is the only full CFI, and a partial CFI was assumed for the other seven sites. The crash ratio between predicted crashes for CFI and 4SG is also shown at the bottom of the table. The crash ratio of 0.991 implies the crash frequency predicted using MB-SPFs for a CFI is 0.9% less than the crash frequency predicted for 4SG. Although they are the planning level analysis results based only on intersection designs and observed AADTs, the results imply that the design conversion from a conventional intersection to a CFI is expected to yield a slight improvement in safety performance for the eight sites in this study effort.

Exhibit 15. Estimated Crash Frequency for a Four-leg Conventional Intersection (4SG) and a CFI

Estimated Crash Frequency	After - 4SG				After - CFI			
	2010	***2011***	***2012***	***2013***	***2010***	***2011***	***2012***	***2013***
Bangerter @ 3100 S		21.8	21.5	21.7		21.6	21.3	21.5
Bangerter @ 4100 S		28.7	28.4	28.6		28.5	28.2	28.4
Bangerter @ 4700 S*	30.2	31.0	30.9	31.9	29.7	30.6	30.5	31.4
Bangerter @ 5400 S	32.9	35.0	34.6	34.8	32.6	34.8	34.4	34.6
Bangerter @ 6200 S		30.6	30.3	30.5		30.4	30.0	30.2
Bangerter @ 7000 S		25.4	25.1	25.4		25.2	24.9	25.1
Redwood @ 5400 S	39.2	38.3	37.4	36.8	39.0	38.1	37.1	36.6
Redwood @ 6200 S	20.4	20.0	19.8	19.9	20.2	19.8	19.6	19.7
Total	810.9				803.9			
Crash Ratio (N_{CFI}/N_{4SG}) =	803.9 / 810.9 = **0.991**							

* Full CFI

[1] TM proportions for the heavy left turn scenario were adopted NCDOT project "Reasonable Alternatives for Grade-

4. METHODOLOGY

We considered at least two methods to conduct this evaluation. One method is the before-after comparison group method, and the second method is the before-after empirical Bayes (EB) method. The comparison group method is simpler and probably easier for practitioners to follow. In the comparison group method, the comparison group is identified from sites that have similar trends in crashes to the treated sites before the treatment is implemented. By itself, the comparison group method does not account for the safety effects due to changes in traffic volume in the after period. In treatments such as the CFI that have been shown to improve traffic flow, it is possible that treated sites may experience a large increase in traffic volume compared to the comparison group. For this reason, the EB before-after method was selected for this evaluation.

The EB methodology is considered rigorous in that it accounts for the possible bias due to the RTM using a reference group of similar but untreated sites, safety performance functions (SPFs) to account for changes in exposure, and time trends making it the preferred safety evaluation method for reducing the level of uncertainty in the estimates of the safety effect.

The five groups identified in Exhibit 16 form a grid with the dimension of reference and treated groups crossed by the dimension of before and after periods. The goal here is to seek a CMF (or crash reduction rate, CRR from Exhibit 16) through a safety comparison between groups 4 and 5. The EB approach estimates the expected safety improvement of the treatment that is being evaluated (Chen, 2013).

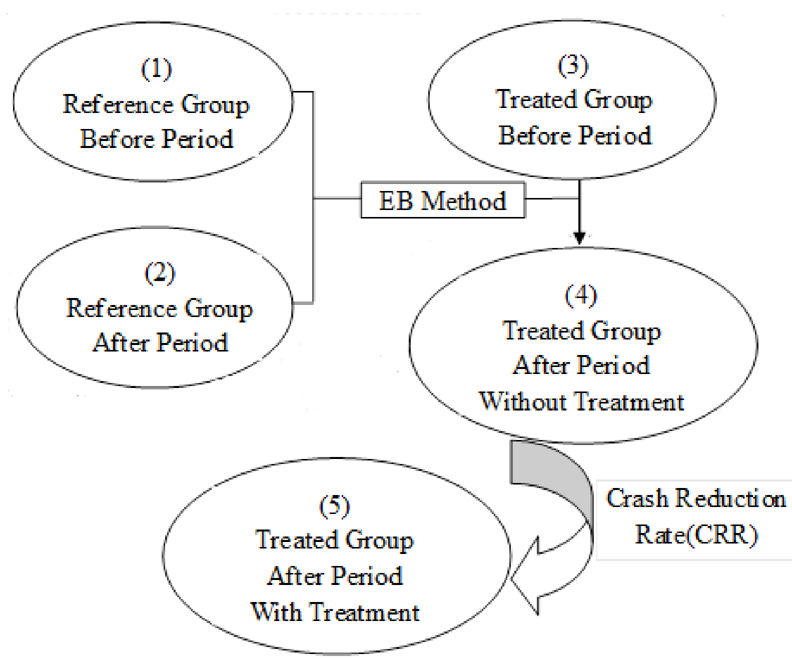


Exhibit 16. Logical Framework of Before-After Evaluations

The following steps are needed to conduct an EB before-after evaluation:

1. Identify a reference group of intersections without the treatment (i.e., non-CFI), but similar to the treatment entities (i.e., CFI) in terms of the major factors that affect crash risk.
2. Estimate SPFs using data from the reference entities relating crashes to the characteristics of the entity. In some cases, if it is not possible to find a reference group similar to the treatment group, or when the treatment is not implemented widely, the before data from the treatment entities is used along with reference or comparison entities to estimate the SPFs (Persaud and Lyon, 2007)[2]. In fact, in this evaluation, the before data from the treatment sites were combined with the reference sites for estimating SPFs.
3. Use the SPFs and site characteristics[3] for each year in the before period for the treatment sites to estimate the number of crashes that would be predicted for the before period.
4. Calculate the EB estimate of the expected crashes in the before period at each treatment site as the weighted sum of the actual crashes in the before period and predicted crashes from step 3. In high volume locations with long after periods, the predicted crashes are high, and in these situations, the EB estimate of the expected crashes in the before period may be closer to the actual crashes in the before period rather than the predicted crashes. In fact, in this evaluation, the EB estimate was almost identical to the actual crashes in the before period.
5. For each treatment site, estimate the product of the EB estimate of the expected crashes in the before period and the SPF predictions for the after period divided by the SPF predictions for the before period. This is the EB expected number of crashes in the after period that would have occurred had CFI not been built (i.e., no treatment). The variance of this expected number of crashes is also estimated in this step. The expected number of crashes without the treatment along with the variance of this parameter and the number of reported crashes after the treatment is used to calculate the safety effect

---

[2] Recently, this approach was used to estimate CMFs to determine the safety evaluation of flashing yellow arrow as part of a FHWA study (https://www.fhwa.dot.gov/publications/research/safety/19036/19036.pdf).

[3] Typically, at this stage, Annual Calibration Factors (ACFs) are estimated and used alongside SPFs and site characteristics to account for the temporal effects (e.g., variation in weather, vehicle population, and crash reporting) on safety. Due to the nature of the data used for this evaluation, the research team did not use ACFs in the evaluation. A discussion (including the rationale for making this decision) is included in Section 6 of this report.

of the treatment (θ) along with the standard error (an estimate of the precision of the estimate of the safety effect).

Based on the safety effect (θ), the percent change in crashes is calculated as $100(1-\theta)$. Therefore, a value of $\theta = 0.9$ with a standard of error of 0.05 indicates a 10% reduction in crashes with a standard error of 5%. Conversely, a value of $\theta = 1.2$ with a standard of error of 0.1 indicates a 20% increase in crashes with a standard error of 10%. Further details about the equations involved in estimating θ and its standard error are available in Appendix A.

5. DATA COLLECTION

To conduct the before-after study, the research team considered 45 CFIs across 13 states, shown in Exhibit 17. For site selection, the team reviewed the availability of crash and traffic volume data for both before and after periods. The team also reviewed historical satellite imagery for the study period and eliminated the CFIs with any significant development near the site in the after period. In addition, any CFIs with significant changes in geometry were also excluded. Significant changes could include additional site modifications to the intersection or alternative/unique geometric considerations (such as unique driveway frontage) that were not typical in CFI design and construction, thus making them combined treatment effects.

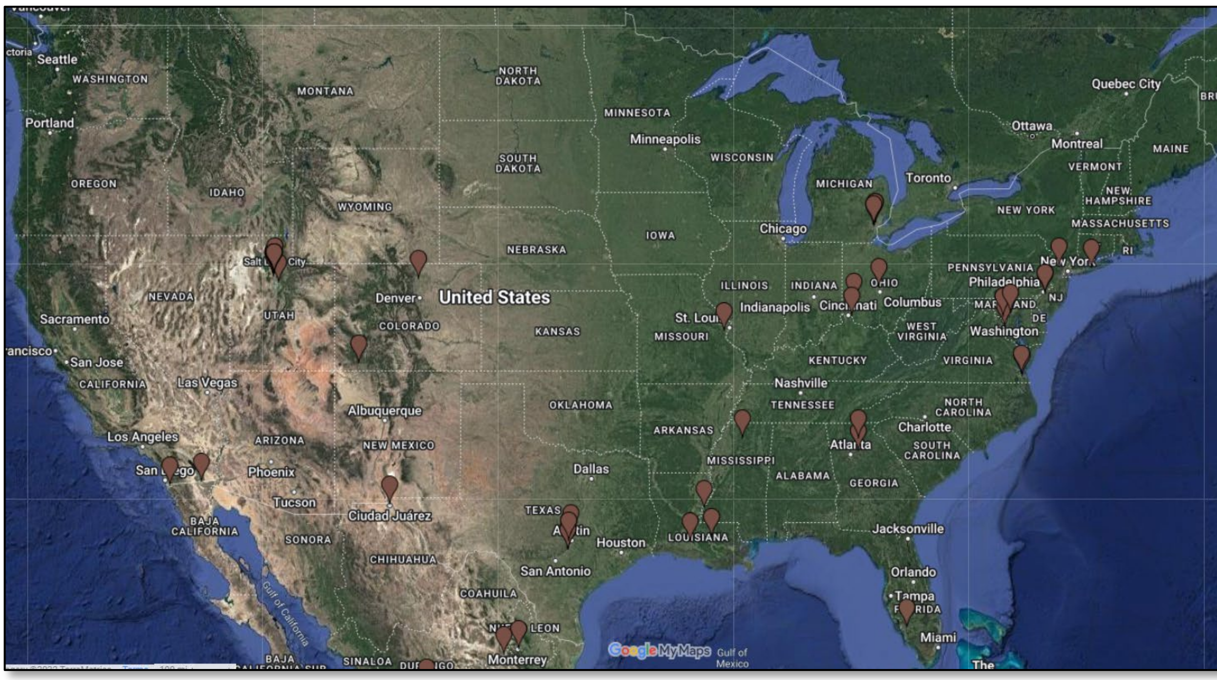


Exhibit 17. CFI Sites Across the United States (go.ncsu.edu/aii)

After pairing down the sites, a total of 19 three-leg or four-leg CFIs were chosen across eight states with 76 reference sites for comparison purposes.

5.1 Site Selection

5.1.1 Treatment Sites

The nineteen CFIs treatment sites have varying numbers of treated *approaches*, which is the leg with the left-turn crossover treatment. Exhibit 18 shows the summary of the 19 three- and four-leg treatment sites (CFIs) and the specific number of approaches studied at each site. The 19 study sites include four CFIs with a single treatment approach, fourteen CFIs with two treatment approaches, and one CFI with four treatment approaches. For quick reference, before and after pictures are provided in Appendix B. Exhibit 19 shows the list of treatment sites (CFIs) by specific location.

Exhibit 18. Summary of Treatment Sites (CFIs)

Number of CFIs	Number of Treatment Approaches				SUM
	1	***2***	***3***	***4***	
Total	4	14	0	1	19
3-leg	4	0	0	0	4
4-leg	0	14	0	1	15

Exhibit 19. List of Treatment Sites (CFIs)

Site Code	City	State	Name	Number of Legs	Area Type
T1	Durango	CO	US 550 & US 160	3-leg	Rural
T2	Loveland	CO	US 34 & Madison Ave	4-leg	Urban
T3	Dawsonville	GA	US-19 & Hwy 53	4-leg	Rural
T4	Snellville	GA	Scenic Hwy S & Main St W	4-leg	Suburban
T5	Baton Rouge	LA	US 61 & Sherwood Forest Blvd / Siegen Ln	4-leg	Urban
T6	Accokeek	MD	MD 210 & MD 228	3-leg	Suburban
T7	Oxford	MS	US 278 & Jackson Ave	3-leg	Suburban
T8	Cincinnati	OH	Beechmont Ave & Five Mile Rd	4-leg	Suburban
T9	Austin	TX	US 290 & W William Cannon Dr	4-leg	Suburban
T10	Austin	TX	US 290 & TX 71	3-leg	Suburban
T11	Cedar Park	TX	Whitestone Blvd & Ronald Reagan Blvd	4-leg	Suburban
T12	Taylorsville	UT	5400 S & Redwood Rd	4-leg	Urban
T13	Riverton	UT	SR 154 & 13400 S	4-leg	Suburban
T14	Taylorsville	UT	SR 154 / Bennion Blvd & 6200 S	4-leg	Suburban
T15	Taylorsville	UT	SR 154 & 4700 S	4-leg	Urban
T16	Taylorsville	UT	SR 154 & 4100 S	4-leg	Urban
T17	West Valley City	UT	SR 154 & SR 171	4-leg	Urban
T18	West Valley City	UT	SR 154 & 3100 S	4-leg	Urban
T19	Salt Lake City	UT	Redwood Rd & Bennion Blvd	4-leg	Urban

The selected 19 treatment sites include eight CFIs in UT, three CFIs in TX, two CFIs each in CO and GA, and one CFI each in MD, OH, MS, and LA. The team determined the area type for the treatment sites according to the characteristics of urban and rural highways stated in the FHWA's report, "Highway Functional Classification: Concepts, Criteria and Procedures" (FHWA, 2013). The selected treatment sites include 2 CFIs in rural areas, 8 CFIs in urban areas, and 9 CFIs in suburban areas.

For the classification of data into the before and after periods, the team contacted each state DOT's design staff and obtained the construction beginning and completion dates. When the exact dates were not available, the team made reasonable assumptions based on input from DOT staff and Google Earth historical imagery. For example, the team assumed a one-year construction period (from January 1st to December 31st) for the CFIs in UT because only the construction year was available.

5.1.2 Reference Sites

For the EB before-and-after study, the research team considered 76 reference sites for the 19 treatment sites, i.e., four reference sites for each treatment site. Some of the reference sites were used more than once because they were in close proximity to more than one treated site. During the site selection of reference sites, the team used the following criteria.

- Sites should be three- or four-leg conventional signalized intersections and all legs should have two-way approaches.
- Sites were selected through inspection of similar characteristics (e.g., similar geometry and traffic conditions for each site).
- Sites should be located in the same region (city or county) where the treatment site is located to account for seasonality.
- Sites should have no significant change in geometry and traffic control (e.g., a newly installed fourth leg, change in left turn signal phasing, addition of a turning lane, etc.) during the study period from the beginning of the before period to the end of the after period.
- Sites should be 150 feet away from any extraneous geometric feature of other intersections (e.g., 150 feet away from a channelized turn lane merge point) and at least 800 feet away from the center of the closest nearby intersection.

5.2 Exposure Data

5.2.1 Time Period and Influence Area

For crash and traffic volume data collection, the research team first determined the data collection period and area. For the data collection period, the team set the five years prior to the CFI construction beginning year as the before period. The after period was set as the period from the year following CFI construction completion to the most recent crash data collection date. Doing so ensured that no data were used for the CFI construction years, thus allowing for a "burn-in" period for drivers.

The research team determined the y-line for crash data collection as 150 feet from stop bars at both treatment and comparison sites. For treatment sites, since there is more than one signalized intersection, the y-line is measured 150 feet from the stop bar of the central intersection stop bar for untreated approaches and from the left turn cross-over point of any treated approach. For a conventional intersection at a reference site, 150 feet was measured from the stop bar of the standard intersection approaches. For reference, Exhibit 20, Exhibit 21, and Exhibit 22 show the crash data collection areas for a four-leg partial CFI, a three-leg CFI, and a four-leg conventional intersection, respectively.

This provided the same "influence" area for all intersection types being analyzed.

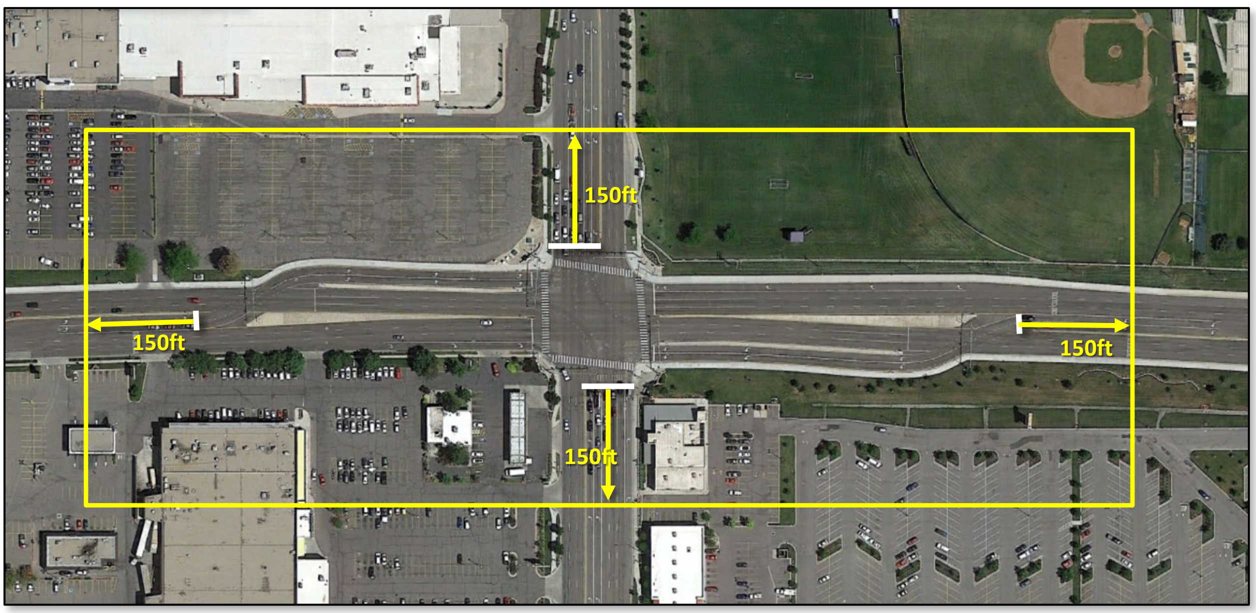


Exhibit 20. Crash Data Collection Area for a Four-leg Partial CFI

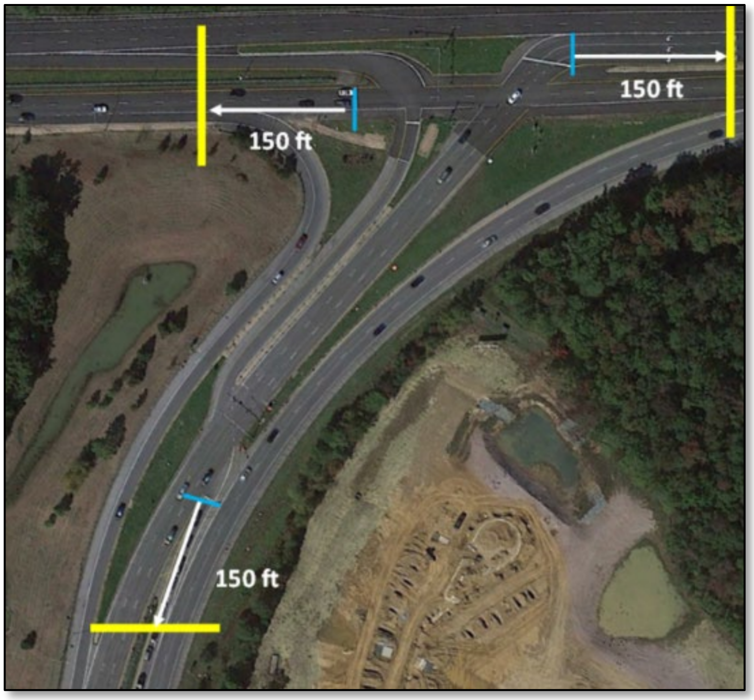


Exhibit 21. Crash Data Collection Area for a Three-leg CFI

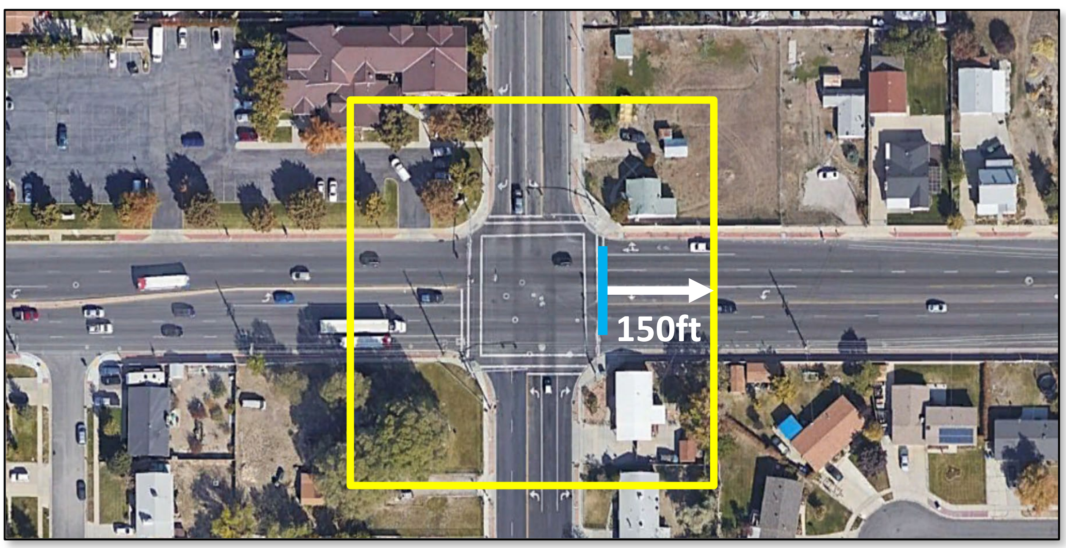


Exhibit 22. Crash Data Collection Area for a Four-leg Conventional Intersection

5.2.2 Crash Data

For the crash data collection effort, the team requested that representative state DOT staff and engineers query crash data based on the influence areas discussed earlier and crash attributes. For Texas and Utah, the states with an open access GIS-based crash data querying system, the research team queried crashes through the querying system. For crash data querying, any crashes that occurred on the crossing roads within the y-line were collected. Crashes were queried by the location and road where the crash occurred only. No crash was filtered out by its crash type or whether it is a crash involved with an intersection or not. Exhibit 23 shows an example of GIS-based crash query system acquired through Texas DOT's Crash Records Information System (CRIS).

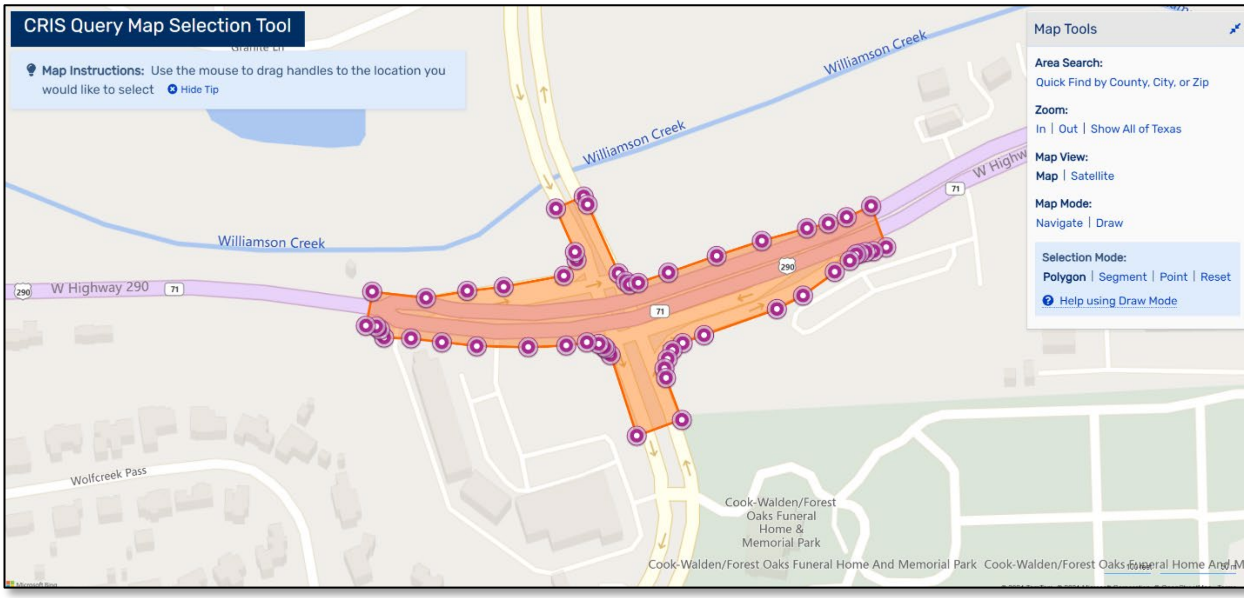


Exhibit 23. An Example of GIS-based Crash Query System (Texas DOT's CRIS).

The team collected several types of crash information including the year, date, and time that the crash occurred, crash severity, crash type (e.g., angle or rear-end), the number of crash-involved vehicles, and the related vehicles' directions and maneuvers. Exhibit 24 shows the summary of collected crashes by severity and period for treatment and reference sites. For the 19 treatment sites and the reference sites, a total of 16,737 crashes were collected, including 5,588 crashes for the treatment sites and 11,149 crashes for the comparison sites.

Exhibit 24. Summary of Crash Data

Summary by Crash Severities					
Crash Severity	**Treatment Sites**		**Reference Sites**	**Grand Total**	
	Before	*After*		***SUM***	***Proportion***
Total	2,579	3,009	11,149	16,737	100%
Fatal & Injury	699	864	3,685	5,248	31.36%
Property Damage Only	1,880	2,145	7,464	11,489	68.64%
Summary by Crash Types					
Crash Type	**Treatment Sites**		**Reference Sites**	**Grand Total**	
	Before	***After***		***SUM***	***Proportion***
Total	2,579	3,009	11,149	16,737	100%
Angle	622	590	3,810	5,022	30.01%
Rear End	1,425	1,614	4,455	7,494	44.78%
Side Swipe	242	146	617	1,005	6.00%
Head On	22	10	113	145	0.87%

5.2.3 Traffic Volume Data

The team collected annual average daily traffic (AADT) data for all roads for treatment and comparison sites. AADT data were collected from GIS or interactive-map based databases. Exhibit 25 shows an example of a GIS-based database from US 290 & W William Cannon Dr, Austin, TX.

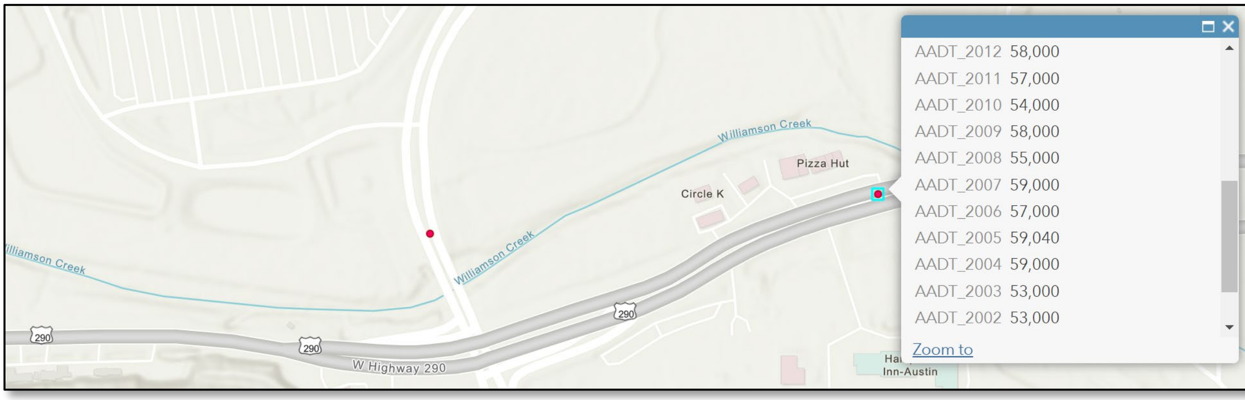


Exhibit 25. Example of GIS-based AADT Database (US 290 & W William Cannon Dr, Austin, TX)

Exhibit 26 shows an example of AADT data collected in Taylorsville, UT. As shown in this table, AADT data were collected for the five years in the before and after periods, respectively. When AADT data were missing in some years, the team estimated the missing AADT using interpolation.

Exhibit 26. Example of AADT Data Collected for a Treatment Site

Site	Road Name	Before Period		After Period	
		Year	*AADT*	*Year*	*AADT*
5400 S & Redwood Rd, Taylorsville, UT	5400 S- W leg	2005	36,000	2011	40,000
		2006	40,000	2012	39,000
		2007	42,000	2013	39,000
		2008	40,000	2014	40,000
		2009	44,000	2015	41,000
	5400 S- E leg	2005	28,000	2011	28,000
		2006	29,000	2012	27,000
		2007	30,000	2013	26,000
		2008	29,000	2014	28,000
		2009	29,000	2015	27,000
	Redwood Rd- N leg	2005	63,000	2011	62,000
		2006	65,000	2012	62,000
		2007	66,000	2013	34,000
		2008	63,000	2014	34,000
		2009	63,000	2015	36,000
	Redwood Rd- S leg	2005	63,000	2011	62,000
		2006	65,000	2012	61,000
		2007	66,000	2013	60,000
		2008	63,000	2014	60,000
		2009	63,000	2015	63,000

5.3 Contextual Variables Considered

Five explanatory variables were considered in addition to the overall aggregate safety study – four geometric and one location type variable. These include: 1) right turn treatment, 2) intersection skew, 3) area type, 4) number of approaches, and 5) number of crossover lanes. Each are described below.

5.3.1 Right Turn Treatment

"Parallel" or "standard" right turn describes how the right turn interacts with the left turn crossover. A "standard" right turn would make the right turn movement at the normal position in the intersection, whereas the "parallel" right turn makes the right turn movement just before the opposing left turn drivers on their right. The parallel right turn movement, in theory, should be safer than the standard right because the conflict with the left turning drivers is removed at two locations – the main intersection AND the left turn crossover. These two right turn movements are illustrated in the two examples shown in Exhibit 28.

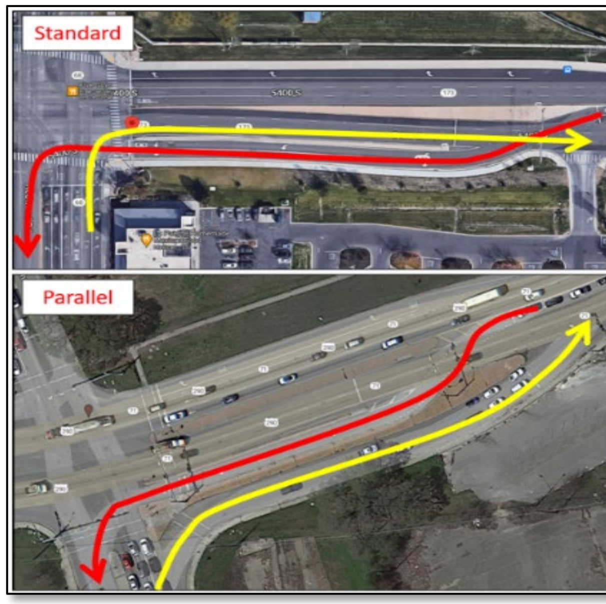


Exhibit 27. Example Right Turn Treatments at CFIs

5.3.2 Intersection Skew

In addition to the right turn movement, intersection skew is analyzed in relation to the right turn treatment since skewed intersections are often considered unsafe, especially as it relates to the right turn movement (Garcia, 2007 and Nightingale, 2017). Garcia found that intersections should be designed with entry angles of 70° or greater to decrease the likelihood of increased crashes. Nightingale found that for every 10° decrease in the entry angle would increase crashes by 4%, and even noted that you would expect even higher crash rates with higher volumes. Therefore, the team measured the skew angle using

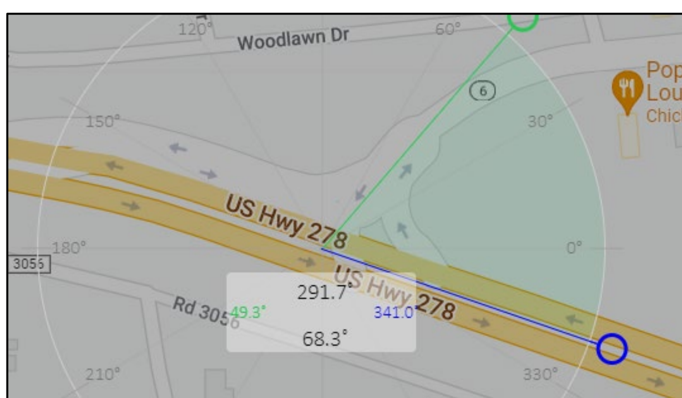


Exhibit 28. Measurement of Intersection Skew (US 278 & Jackson Avenue_Oxford, MS). Skew = 68.3°

a protractor via a Google extension overlaid onto Google Maps. The angle is measured as the angle from the treated right turn approach to the conflicting through movement as shown in Exhibit 27 (Skew = 68.3°). A measurement of less than 70° is considered “skewed”, whereas anything greater than 70° is considered to have “little-to-no” skew. Based on prior research we would anticipate better findings for intersections with little-to-no skew compared to those with skew.

5.3.3 Area Type

Two primary bins were created to describe area type – namely, “rural” and “suburban/urban”. The team determined the area type for the treatment sites according to the characteristics of urban and rural highways stated in the FHWA’s report, “Highway Functional Classification: Concepts, Criteria and Procedures” (FHWA, 2013). These areas were defined based on proximity to the central business district (CBD), the surrounding land uses, and traffic volumes on the two major intersecting roads. Sites further from the CBD, that had sporadic housing developments and business land uses, only significant traffic volumes on one major approach, and/or were less than ±30% built out in the surrounding area were considered rural. A determination was made to group urban and suburban because the distinction of the two area types was very hard to distinguish in some cases. Although land uses were harder to distinguish along with proximity to the CBD, all sites in these two categories had significant traffic volumes on both approaches, and for this reason, they were grouped together.

5.3.4 Number of Approaches

Sites were categorized as 3- or 4-lane approach sites based on the number of approach legs present at the site. This variable does not capture the number of CFI legs/approaches as there were not sufficient sample size (i.e., the overwhelming majority had two CFI legs per intersection).

5.3.5 Crossover Lanes

The number of crossover lanes is simply the maximum number of lanes present for any given crossover at a given CFI. The value for this is 1 or 2 lanes. If more than one crossover is present AND those crossovers do not have the same number of lanes, the maximum value is used to describe the site. This was only the case at one site.

6. RESULTS AND DISCUSSION

In this section, CMFs were estimated to determine the net safety effect of CFIs. Analysis of specific crash types and severities were conducted to see if impacts could be determined for the following crash types and crash severities:

- Crash Types:
  - Total (also referred to as KABCO crashes),
  - Angle (angle and turning crashes),
  - Rear end,
  - Side swipe, and
  - Head-on.
- Crash Severities:
  - Fatal and all injury crashes (also referred to as KABC crashes), and
  - Property damage only crashes (also referred to as PDO crashes).

In addition, to develop aggregate CMFs across all sites, various disaggregate CMFs were also developed for the following categories:

- Number of intersection legs (3-legged and 4-legged),
- Area type (rural and urban/suburban),
- Presence / non-presence of intersection skew (skew ≤ 70°)
- Type of right turn movement (parallel vs. standard), and
- Maximum number of crossover lanes (1 vs. 2).

6.1 Safety Performance Functions

As described in Section 4, the evaluation's first step is to estimate a safety performance function (SPF). Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of practice in developing these models. SPFs were estimated for each of the target crash types and crash severities (Exhibit 29). The relationship between the crash frequency and the independent variables is as follows:

$$SPF = e^{\alpha+\beta_3+\beta_4+\beta_5} \times Maj\ AADT^{\beta_1} \times Min\ AADT^{\beta_2} \times Years$$

where:

α = intercept, and

β = coefficient estimates (note the β_3 , β_4, and β_5 are coefficient estimates for categorical variable representing the number of legs, states, and the area type).

Exhibit 29. SPFs for Target Crash Types/Severities

Variable	Category	Total	Fatal & Injury (KABC)	Property Damage Only (PDO)	Angle Crashes	Rear End Crashes
		Estimate (Pr<ChiSq)	Estimate (Pr<ChiSq)	Estimate (Pr<ChiSq)	Estimate (Pr<ChiSq)	Estimate (Pr<ChiSq)
α		-10.0575 (<0.0001)	-9.9870 (<0.0001)	-11.2198 (<0.0001)	-8.4353 (<0.0001)	-14.5737 (<0.0001)
β1		0.7432 (<0.0001)	0.7357 (<0.0001)	0.7558 (<0.0001)	0.7203 (<0.0001)	1.0439 (<0.0001)
β2		0.5761 (<0.0001)	0.4597 (<0.0001)	0.6429 (<0.0001)	0.3250 (0.0017)	0.6368 (<0.0001)
β3	*3-Leg*	-0.5338 (0.0277)	-0.6933 (0.0125)	-0.4607 (0.0745)	-0.7812 (0.0155)	-0.4948 (0.1170)
	4-Leg	0	0	0	0	0
β4	*CO*	-0.4516 (0.0306)	-0.1695 (0.4633)	-0.6970 (0.0020)	-0.3958 (0.1159)	-0.6470 (0.0023)
	GA	0.6214 (0.0010)	0.4794 (0.0246)	0.6565 (0.0006)	0.5514 0.0162)	0.8632 (<0.0001)
	MS	0.3399 (0.2464)	0.2595 (0.4355)	0.3902 (0.2095)	-0.9833 (0.0127)	0.8422 (0.0158)
	OH	0.2699 (0.1823)	-0.2224 (0.3440)	0.4623 (0.0273)	0.2362 (0.3365)	0.4196 (0.0290)
	TX	-0.5210 (0.0008)	-0.1948 (0.2609)	-0.7172 (<0.0001)	-1.1092 (<0.0001)	-2.1325 (<0.0001)
	UT	0	0	0	0	0
β5	*Rural*	0.4188 (0.0717)	0.2000 (0.4503)	0.5622 (0.0185)	-0.0720 (0.7992)	0.7001 (0.0018)
	Urb/Sub	0	0	0	0	0
Overdispersion (K)		0.1544	0.1773	0.1628	0.2121	0.1236

As can be seen for Exhibit 29, the estimates of both β1 (major road AADT) and β2 (minor road AADT) were highly significant for all models. β3, β4, and β5 represent the number of intersection legs, state, and area type, respectively. These were included in the models as categorical variables, i.e., observations for these variables were classified into groups. The group showing an estimate of 0 for each categorical variable represents the base condition used in the model (i.e., 4-leg intersections, state of Utah, and Urban/Suburban area type).

The research team also attempted to develop SPFs for side swipe and head-on crashes. However, their low crash occurrence (as can be seen in Exhibit 24) led to the models not converging. Hence, CMFs were not developed for these two crash types. Last, of the total of 19 CFIs considered for inclusion in this analysis (shown in Exhibit 19), three CFIs were not included in the analysis/SPF estimations.

- T6 in Maryland was excluded because there was no AADT data available for this site. Following up with MDOT confirmed that data were not available in the before and after periods for this site for all approaches.
- T17 in Utah was excluded because there was no crash data available for the before period. In discussions with the UDOT safety unit, the site was installed during a transition to the current GIS-based system. The data queries would have caused inconsistencies in the two data pulls.
- T5 in Louisiana was initially included in SPF estimations, however, when estimating the CMFs, the research team looked closely at the results to see if any obvious outliers might be present that need further exploration. In doing so, the team noticed the expected number of crashes in the after period were significantly low compared to the actual crashes in the after period for treatment site T5 in Louisiana. The research team investigated this site to determine why actual crashes may be so much higher and found that a very probable cause was the presence of a frontage road with a parallel right turn, shown in Exhibit 30. This was a unique situation that was not present at other treatment sites since driveway access and service roads were accommodated through the channelized movement and the two right turns were accommodated at the main intersection (the parallel right AND the frontage road right turn). Hence, the research team intentionally dropped treatment site T5 from CMF calculations to avoid this anomaly from skewing the CMFs. As such, a total of 16 treatment sites were used to estimate SPFs presented in Exhibit 29.

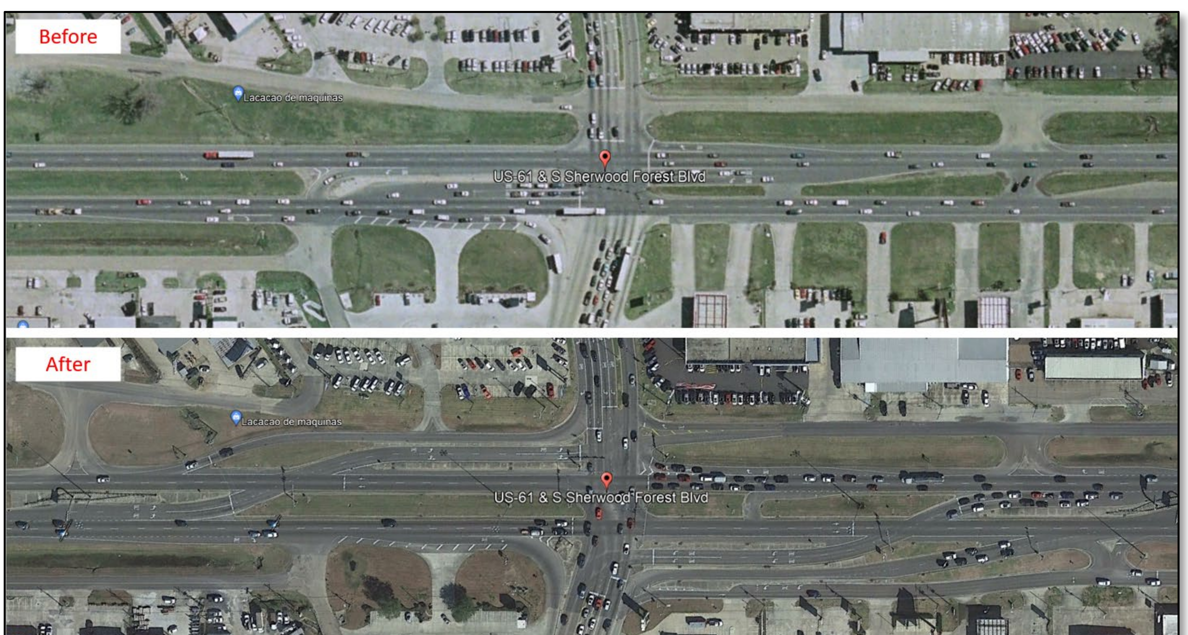


Exhibit 30. Before and After Construction of CFI with Service Roads at US 61 & Sherwood Forest Blvd / Siegen Ln (Baton Rouge, Louisiana)

Exhibit 31 presents summary statistics for the 16 treatment sites used to estimate SPFs presented in Exhibit 29.

Exhibit 31. Summary Statistics for 16 Treatment Sites Used for SPF Estimations

Variable	Minimum	Maximum	Average
Years Before	2	5	3.7
Years After	1	5	4.3
Number of Legs	3	4	3.8
Major Road AADT Before	21750	64000	41009.7
Minor Road AADT Before	7442	39220	22368.1
Major Road AADT After	21699	56200	42862.3
Minor Road AADT After	8050	35150	23115.5
Total Crashes per Site Before	10	403	148.1
Fatal & Injury Crashes per Site Before	5	99	40.1
Property Damage Only Crashes per Site Before	5	304	108.0
Angle Crashes per Site Before	2	87	34.8
Rear End Crashes per Site Before	0	294	84.0
Total Crashes per Site After	20	294	147.8
Fatal & Injury Crashes per Site After	7	81	41.4
Property Damage Only Crashes per Site After	12	219	106.4
Angle Crashes per Site After	3	93	30.4
Rear End Crashes per Site After	3	193	77.7

6.2 Annual Calibration Factors

As discussed in Section 4, annual calibration factors (ACFs) are typically used alongside SPFs and site characteristics to account for the temporal effects (e.g., variation in weather, vehicle population, and crash reporting) on safety. The nature of the data used for this evaluation, i.e., the study period ranging from 1995 – 2020, meant that there was limited overlap between the before and after periods for treatment sites. As such, reliable ACFs could not be estimated for use in this analysis.

To check whether the SPFs were predicting crashes close to the observed values, the research team instead estimated period calibration factors (PCFs) by grouping three years of data starting from 2007. Earlier data was not used for PCF estimation as the period before 2007 represented very few sites. The PCFs for total, fatal & injury, and property damage only are presented in Exhibit 32, Exhibit 33, and Exhibit 34.

Exhibit 32. PCFs for Total Crashes

Period	Site-Years	Observed Crashes	Predicted Crashes	PCF
2007 - 2009	117	2366	2370.13	**1.00**
2010 - 2012	132	2673	2578.99	**1.04**
2013 - 2015	150	3580	3517.88	**1.02**
2016 - 2018	80	1694	1718.95	**0.99**
2019	31	746	770.32	**0.97**
2020	21	584	606.36	**0.96**

Exhibit 33. PCFs for Fatal and Injury Crashes

Period	Site-Years	Observed Crashes	Predicted Crashes	PCF
2007 - 2009	117	755	771.78	**0.98**
2010 - 2012	132	818	821.30	**1.00**
2013 - 2015	150	1099	1078.52	**1.02**
2016 - 2018	80	517	553.91	**0.93**
2019	31	216	229.86	**0.94**
2020	21	200	183.11	**1.09**

Exhibit 34. PCFs for Property Damage Only Crashes

Period	Site-Years	Observed Crashes	Predicted Crashes	PCF
2007 - 2009	117	1611	1601.66	**1.01**
2010 - 2012	132	1855	1769.43	**1.05**
2013 - 2015	150	2481	2442.72	**1.02**
2016 - 2018	80	1177	1173.43	**1.00**
2019	31	530	542.43	**0.98**
2020	21	384	424.53	**0.90**

It can be seen that PCFs were mostly within the +/- 5% range showing that the SPFs predict crashes close to the observed values, indicating that trends due to the temporal effects (e.g., variation in weather, vehicle population, and crash reporting) were not significant in the data as a whole. PCFs cannot be used in place of ACFs in the analysis, because they were developed for sets of years without differentiating between the before and after periods for each individual site. However, they do provide a good indication of whether the SPF alone is able to account for temporal effects on safety.

6.3 Aggregate Safety Effects

The aggregate estimated crash safety effects for target crash types and severities are shown in Exhibit 35. For each crash type and severity, the EB expected crashes in the after period had CFIs not been installed are shown along with the actual number of crashes observed in the after period, the CMF, the standard error of the CMF, and 95% confidence interval (CI) of the CMFs. Naïve estimates are provided for reference only as if no bias been accounted for.

Exhibit 35. Estimated Aggregate Crash Safety Effects

Crash Type	**Crashes in the After Period**	**Expected Crashes in the After Period without Treatment**	**CMF (Naïve)**	**CMF (EB)**	**Std. Error of CMF**	**Range of CMFs (95% CI)**
Total	2365	2691.11	0.896	**0.878***	**0.027**	0.825 - 0.931
Fatal & Injury (KABC)	662	767.77	0.867	**0.861***	**0.050**	0.763 - 0.959
Property Damage Only (PDO)	1703	1930.25	0.907	**0.882***	**0.032**	0.819 - 0.945
Angle Crashes	486	686.41	0.704	**0.706***	**0.046**	0.616 - 0.796
Rear End Crashes	1243	1430.39	0.919	**0.868***	**0.036**	0.797 - 0.939

** Statistically Significant at the 95-percent Confidence Level*

Based on the findings provided in Exhibit 35, the results indicate that installing CFIs had a positive impact on aggregate intersection crashes. A 12.2% reduction was seen in total crashes, alongside a 13.9% reduction in fatal & injury (KABC) crashes and a 11.8% reduction is property damage only (PDO) crashes, all statistically significant (95% CI). When looking at specific crash types, angle and rear end crashes saw 29.4% and 13.2% reductions, respectively, both of which were also statistically significant (95% CI).

Exhibit 36. Aggregated Safety Effects for All "Other" Crash Type(s)

Crash Types	**Total Crashes**	**Angle + Rear End Crashes**	**All "Other" Crashes** *(excluding Angle and Rear End Crashes)*
Crashes in the After Period	2365	1729	636
Expected Crashes in the After Period without Treatment	2691.11	2116.80	574.31
% Change in Crashes	**-12.12%**	**-18.32%**	**+10.74%**

Last, when looking at crash type alone, there appears to be a trade-off present that should be noted. When summing angle and rear end crashes, there were 1729 crashes in the after-period crashes, and 2116.80 expected crashes in the after period without treatment. Subtracting these numbers from the actual total crashes and expected total crashes in the after period without treatment nets 636 after-period crashes and 574.31 expected crashes in the after period without treatment (see Exhibit 36). These numbers indicate that although reductions in angle crashes and rear-end were significant, they were accompanied by increases in some other crash type(s). Looking at other individual crash types; however, did not provide any insight into the trade-off of one or more certain crash types.

6.4 Disaggregate Safety Effects

The disaggregate estimated crash safety effects for target crash types and severities are shown in the following sections by right turn treatment, presence of skew, area type, 3- vs. 4-leg intersection approaches, and number of crossover lanes. For each crash type and severity, the EB expected crashes in the after period had CFIs not been installed are shown along with the actual number of crashes observed in the after period, the CMF, the standard error of the CMF, and 95% confidence interval of the CMFs. Naïve estimates are provided for reference only but do not account for confounding factors.

6.4.1 Right Turn Treatment

The most obvious variation in geometric design alternatives for the CFI is related to the right turn. Noted in Section 5.3.1, this movement can take the form of a standard or parallel right turn. In practice, the parallel right turn is preferred over the standard movement because it removes a conflict and allows right turning drivers to enter traffic in conjunction with the concurrent left turn crossover. The standard right turn is usually considered only if there were right-of-way concerns that prevent the right turn from running parallel. To better understand the safety implications of one design over another, our team analyzed both right turn treatment types separately.

Shown in Exhibit 37, of the 16 treated CFI sites used for CMF calculations, eleven sites had parallel right turns and five had standard right turns. For intersections with *parallel right turn* movements, statistically significant (95% CI) reductions of 29.6%, 26.7%, and 31.0% were seen in total, fatal & injury (KABC) and property damage only (PDO) crashes, respectively. When looking at specific crash types, angle and rear end crashes also saw statistically significant reductions of 42.8% and 26.7% (95% CI), respectively. However, at intersections with *standard right turn* movements, the same cannot be said. In fact, looking at crash severity, total and PDO crashes were found to significantly increase by 15.6% and 21.5%, respectively (95% CI) while fatal and injury crashes increased an insignificant 2.9%. Looking at crash type, angle crashes were found to decrease an insignificant 11% while rear end crashes increased significantly by 24% (95% CI).

Overall, based on the 16 CFI intersection analyzed in this study, the findings indicate that CFIs installed with parallel right turns at intersections will definitely yield the best safety results. If a site does not allow for parallel right turns due to right-of-way constraints, the trade-offs should be considered carefully, and parallel right turns should be considered on other approaches where a CFI leg is being considered that does not have the right-of-way constraint. Approaches that use the standard right turn should consider a no right-turn-on-red provision also.

Exhibit 37. Estimated Disaggregate Crash Safety Effects (Right Turn Treatment)

Right Turn Type	Crash Type	Crashes in the After Period	Expected Crashes in After Period w/o Treatment	CMF (Naïve)	CMF (EB)	Std. Error of CMF	Range of CMFs (95% CI)
Parallel Right Turn **(n = 11)**	Total	1170	1659.67	0.735	**0.704***	**0.029**	0.649 - 0.761
	Fatal & Injury (KABC)	324	440.68	0.749	**0.733***	**0.058**	0.619 - 0.847
	Property Damage Only	846	1226.03	0.729	**0.690***	**0.033**	0.625 - 0.755
	Angle Crashes	229	398.90	0.569	**0.572***	**0.051**	0.472 - 0.672
	Rear End Crashes	557	878.47	0.715	**0.633***	**0.036**	0.565 - 0.704
Standard Right Turn **(n = 5)**	Total	1195	1031.45	1.141	**1.156***	**0.054**	1.050 - 1.262
	Fatal & Injury (KABC)	338	327.09	1.023	**1.029**	**0.087**	0.857 - 1.200
	Property Damage Only	857	704.22	1.195	**1.215***	**0.068**	1.082 - 1.348
	Angle Crashes	257	287.50	0.892	**0.890**	**0.083**	0.727 - 1.053
	Rear End Crashes	686	551.92	1.196	**1.240***	**0.078**	1.087 - 1.393

** Statistically Significant at the 95-percent Confidence Level*

Last, because the right turn treatment has such significant impacts on safety at CFIs, the following sections looking at additional geometric and locational factors as a subset of these two right turn treatments to better understand the optimal use cases for CFIs.

6.4.2 Intersection Skew

The combination of intersection skew and right turn treatment were considered in this section to determine if the presence of skew is problematic at CFIs. For this analysis, three CFI intersections were *skewed* (<70°) and thirteen intersections that had *little-to-no skew (≥70°).* The three skewed intersections were all present at sites with parallel right turns; however, the 13 sites with little-to-no skew present had eight parallel and five standard right turn movements, respectively. Exhibit 38 shows disaggregate estimated crash safety effects looking the effect of skew with parallel and standard right turns. ***Note: The results for skewed intersections with standard right turns (n=0) were not possible based on the population of sites studied in this effort.***

For intersections with *little-to-no sk*ew *with parallel right turns*, statistically significant (95% CI) reductions of 29.4%, 32.6%, and 28.4% were seen in total, fatal & injury (KABC) and PDO crashes, respectively. When looking at specific crash types, angle and rear end crashes also saw statistically significant reductions of 52.4% and 34.0% (95% CI), respectively. Intersections where *skew was present with parallel right turns* found similar results; although, not across all crash or severity types. Statistically significant (95% CI) decreases of 30.1%, 36.3% and 40.6% for were shown for total, PDO, and rear end crashes, respectively. Although not significant, fatal and injury crashes seem to decrease while angle crashes may increase with skew present and parallel right turns.

Comparing subsets of intersections with little-to-no skew in parallel and standard right turn configurations, the findings show the right turn treatment impacts were even more staggering than in the previous section. By removing the 3 skewed intersections from the parallel right turn population, nearly all crash types and severity decrease even more, giving even more credence to the use of parallel right turns.

Exhibit 38. Estimated Disaggregate Crash Safety Effects (No Skew and Parallel Right Turn)

Right Turn Type	Skew	Crash Type	Crashes in the After Period	Expected Crashes in After Period w/o Treatment	CMF (Naïve)	CMF (EB)	Std. Error of CMF	Range of CMFs (95% CI)
Parallel	Not Present (n = 8)	Total	790	1117.05	0.713	**0.706***	**0.036**	0.635 - 0.777
		Fatal & Injury (KABC)	219	323.52	0.679	**0.674***	**0.065**	0.547 - 0.801
		Property Damage Only	571	795.55	0.726	**0.716***	**0.043**	0.633 - 0.800
		Angle Crashes	163	340.65	0.471	**0.476***	**0.049**	0.380 - 0.572
		Rear End Crashes	337	509.36	0.723	**0.660***	**0.049**	0.564 - 0.756
	Present (n = 3)	Total	380	542.61	0.785	**0.699***	**0.050**	0.601 - 0.797
		Fatal & Injury (KABC)	105	117.16	0.952	**0.887**	**0.123**	0.646 - 1.128
		Property Damage Only	275	430.48	0.736	**0.637***	**0.052**	0.535 - 0.739
		Angle Crashes	66	58.25	1.171	**1.112**	**0.200**	0.720 - 1.504
		Rear End Crashes	220	369.11	0.701	**0.594***	**0.054**	0.488 - 0.700
Standard	Not Present (n =5)	Total	1195	1031.45	1.141	**1.156***	**0.054**	1.050 - 1.262
		Fatal & Injury (KABC)	338	327.09	1.023	**1.029**	**0.087**	0.858 - 1.200
		Property Damage Only	857	704.22	1.195	**1.215***	**0.068**	1.082 - 1.348
		Angle Crashes	257	287.50	0.892	**0.890**	**0.083**	0.727 - 1.053
		Rear End Crashes	686	551.92	1.196	**1.240***	**0.078**	1.087 - 1.393
	Present (n = 0)	n/a	n/a	n/a	n/a	n/a	n/a	n/a

** Statistically Significant at the 95-percent Confidence Level*

Overall, the results indicate that CFIs installed with parallel right turns at intersections with little-to-no skew will likely yield the best safety results. If a CFI is installed at an intersection with skew, a parallel right turn movement should also yield solid safety results; however, there appears to be a tradeoff of increased (though insignificant compared to the before condition) angle crashes. In contrast, the standard right turn movements studied at intersections with little-to-no skew should not be utilized unless absolutely necessary because they yield no significant positive safety benefits. Instead, significant increases were found in total (15.6%) and PDO (21.5%) crashes.

Although no sample of standard right turns at skewed intersections exists for this study effort, the findings in the literature clearly documenting the safety problem of right turns at skewed intersections would tend to argue that the standard right turn would not be advisable in either skew scenario. Therefore, a standard right turn should be carefully considered if an intersection quadrant with right-of-way (ROW) concerns makes it the only viable option. As noted in the prior section, in the case where ROW concerns exist, a site with multiple CFI crossover movements should use parallel right turns on any other quadrants while also considering a right-turn-on red restriction.

6.4.3 Area Type

Disaggregate estimated crash safety effects for area type with varying right turn treatments for target crash types and severities are shown in Exhibit 39. Of the sixteen treated CFI sites used for CMF calculations, two sites were rural intersections with parallel right turns; whereas, the 14 urban/suburban intersections were split between sites with nine parallel right turns and five with standard right turns. For sites with *parallel right turns*, both rural and urban/suburban areas yielded statistically significant (95% CI) reductions in all crash severity and types. Comparing *both rural and urban/suburban area types, reductions of* 40.3% vs. 26.0%, 33.0% vs. 25.0%, and 42.8% vs. 27.2% were seen for total, fatal and injury, and PDO, respectively. When looking at crash type, angle crashes and rear end crashes saw notable decreases of 29.4% vs. 45.9% and 54.2% vs. 28.3%, respectively. Even though the disaggregate sample for rural intersections was small, i.e., 2 sites, the observed crash sample is large enough to provide statistically significant results.

The results for CFIs with *urban/suburban sites with parallel and standard right turns* followed the same pattern as previous sections, with standard right turn types showing statistically significant increases in most crash categories while parallel right turn sites showed statistically significant decreases.

Exhibit 39. Estimated Disaggregate Crash Safety Effects (Area Type)

Right Turn Type	Area Type	Crash Type	Crashes in the After Period	Expected Crashes in After Period w/o Treatment	CMF (Naïve)	CMF (EB)	Std. Error of CMF	Range of CMFs (95% CI)
Parallel	Rural (n = 2)	Total	238	397.60	0.620	**0.597***	**0.047**	0.505 - 0.689
		Fatal & Injury (KABC)	61	90.35	0.692	**0.670***	**0.106**	0.462 - 0.878
		Property Damage Only	177	308.59	0.598	**0.572***	**0.052**	0.470 - 0.674
		Angle Crashes	50	69.98	0.721	**0.706***	**0.124**	0.463 - 0.949
		Rear End Crashes	132	287.39	0.520	**0.458***	**0.047**	0.366 - 0.550
	Urban/Suburban (n = 9)	Total	932	1262.07	0.771	**0.740***	**0.036**	0.669 - 0.811
		Fatal & Injury (KABC)	263	350.33	0.763	**0.750***	**0.068**	0.617 - 0.883
		Property Damage Only	669	917.43	0.774	**0.728***	**0.041**	0.648 - 0.808
		Angle Crashes	179	328.92	0.537	**0.541***	**0.056**	0.431 - 0.651
		Rear End Crashes	425	591.08	0.808	**0.717***	**0.050**	0.619 - 0.815
Standard	Rural (n = 0)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Urban/Suburban (n = 5)	Total	1195	1031.45	1.141	**1.156***	**0.054**	1.050 - 1.262
		Fatal & Injury (KABC)	338	327.09	1.023	**1.029**	**0.087**	0.858 - 1.200
		Property Damage Only	857	704.22	1.195	**1.215***	**0.068**	1.082 - 1.348
		Angle Crashes	257	287.50	0.892	**0.890**	**0.083**	0.727 - 1.053
		Rear End Crashes	686	551.92	1.196	**1.240***	**0.078**	1.087 - 1.393

** Statistically Significant at the 95-percent Confidence Level*

Overall, the findings for area type indicate that installing CFIs at rural and urban/suburban intersections with parallel right turns had a consistent positive safety impact on all target crash types and severities, with rural intersections seeing a larger overall safety benefit; however, urban/suburban sites showed more significant decreases in angle crashes. Even so, the rural sites saw larger decreases in fatal and injury crash severities, which may be attributable to higher speeds at rural sites. Last, area type was not found to positively impact sites with standard right turn movements based on the samples analyzed.

6.4.4 Number of Approaches

Disaggregate estimated crash safety effects based on the *number of approaches* with varying right turn treatments for target crash types and severities are shown in Exhibit 40. Of the 16 treated CFI sites used for CMF calculations, three sites were 3-legged intersections with parallel right turns, whereas the thirteen 4-legged intersections were split between sites with eight parallel and five standard right turn lane geometries.

Exhibit 40. Estimated Disaggregate Crash Safety Effects (Number of Approaches)

Right Turn Type	No. of Legs	Crash Type	Crashes in the After Period	Expected Crashes in After Period w/o Treatment	CMF (Naïve)	CMF (EB)	Std. Error of CMF	Range of CMFs (95% CI)
Parallel	3-Legged (n = 3)	Total	231	267.63	0.903	**0.859**	**0.083**	0.696 – 1.022
		Fatal & Injury (KABC)	60	73.81	0.850	**0.797**	**0.148**	0.507 - 1.087
		Property Damage Only	171	195.30	0.923	**0.870**	**0.096**	0.682 - 1.058
		Angle Crashes	27	23.79	1.225	**1.073**	**0.313**	0.460 - 1.686
		Rear End Crashes	123	161.62	0.846	**0.755***	**0.094**	0.571 - 0.939
	4-Legged (n =8)	Total	939	1392.04	0.702	**0.674***	**0.031**	0.613 - 0.735
		Fatal & Injury (KABC)	264	366.87	0.728	**0.717***	**0.063**	0.594 - 0.840
		Property Damage Only	675	1030.72	0.693	**0.654***	**0.035**	0.585 - 0.723
		Angle Crashes	202	375.12	0.531	**0.536***	**0.051**	0.436 - 0.636
		Rear End Crashes	434	716.85	0.685	**0.604***	**0.039**	0.532 - 0.680
Standard	3-Legged (n =0)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	4-Legged (n = 5)	Total	1195	1031.45	1.141	**1.156***	**0.054**	1.050 - 1.262
		Fatal & Injury (KABC)	338	327.09	1.023	**1.029**	**0.087**	0.858 - 1.200
		Property Damage Only	857	704.22	1.195	**1.215***	**0.068**	1.082 - 1.348
		Angle Crashes	257	287.50	0.892	**0.890**	**0.083**	0.727 - 1.053
		Rear End Crashes	686	551.92	1.196	**1.240***	**0.078**	1.087 - 1.393

** Statistically Significant at the 95-percent Confidence Level*

For sites with *parallel right turns*, *4-legged intersections* showed statistically significant reductions (95% CI) across all crash types and severities, ranging from 28.3% to 46.4%. *3-legged sites with parallel right turns* showed promising results also; although, the only statistically significant reduction was found in rear end crashes with reduction of 24.5%. All other crash types/severities showed insignificant reductions or stayed the same. Comparing 4-legged intersections with standard or parallel right turn types yielded similar results to previous sections, with standard right turn sites showing significant increases in most crash categories and parallel right turns yielding significant reductions across every crash type/severity.

Overall, the findings here seem to indicate that installing CFIs at 3- and 4-leg intersections with parallel right turns will not increase any major crash types and severity of crashes, with most showing significant decreases in crashes and severity. Of the two types, 4-leg intersections appear to be safer with statistically significant reductions across all crash categories of severity and crash type – especially angle crashes which were found to reduce by 46.4%; however, limited sample size for 3-legged sites makes this finding somewhat inconclusive. Last, the number of approaches was not found to positively impact sites with standard right turn movements based on the samples analyzed.

6.4.5 Max Number of Crossover Lanes

Disaggregate estimated crash safety effects based on the *maximum number of crossover lanes* with varying right turn treatments for target crash types and severities are shown in Exhibit 41. Of the 16 treated CFI sites used for CMF calculations, 6 sites had a single crossover lane (4 with parallel right turns and 2 without); whereas the 10 had at least one crossover with 2 lanes (7 with parallel right turns and 3 without).

For sites with parallel right turn lane sites, *2-lane crossover* sites showed statistically significant (95% CI) reductions for all crash severities and types, ranging from 31.2% to 45.1%. *Single lane crossover* sites showed promise also with angle crashes reducing significantly by 32.7%; however, other crash types and severities showed no significant findings. Interestingly, although not significant, there was a notable uptick in rear end crashes (16.7%) at single lane crossover sites with parallel right turns. When looking at sites with s*tandard right turn lanes*, the overall findings show that nearly all crash types and severities increased significantly (95% CI) in both crossover lane categories, with one exception where angle crashes at *2-lane crossover sites* reduced significantly by 17.9% and fatal and injury crashes showed no change.

Overall, the results indicate that CFI sites with 2 crossover lanes were safer than single crossover lanes, especially where 2-lane crossovers were used at parallel right turns. If a single lane crossover is desired and parallel right turns were used, you would expect no change in crashes with the exception of angle crashes which should still reduce significantly. If standard right turns were required, a 2-lane crossover should offer the best chance for minimal safety impacts; however, you would still expect that the overall safety would likely diminish.

Exhibit 41. Estimated Disaggregate Crash Safety Effects (Number of Crossover Lanes)

Right Turn Type	Max. # of C/O Lanes at Site	Crash Type	Crashes in the After Period	Expected Crashes in After Period w/o Treatment	CMF (Naïve)	CMF (EB)	Std. Error of CMF	Range of CMFs (95% CI)
Parallel	1 Crossover Lane (n = 4)	Total	275	287.20	0.962	**0.952**	**0.092**	0.772 - 1.132
		Fatal & Injury (KABC)	83	91.86	0.914	**0.887**	**0.157**	0.577 - 1.193
		Property Damage Only	192	197.60	0.984	**0.965**	**0.109**	0.750 - 1.178
		Angle Crashes	45	65.35	0.691	**0.673***	**0.140**	0.399 - 0.947
		Rear End Crashes	100	84.51	1.211	**1.167**	**0.177**	0.820 - 1.514
	2 Crossover Lanes (n =7)	Total	895	1372.47	0.685	**0.651***	**0.030**	0.592 - 0.710
		Fatal & Injury (KABC)	241	348.82	0.705	**0.688***	**0.061**	0.568 - 0.808
		Property Damage Only	654	1028.43	0.678	**0.636***	**0.034**	0.569 - 0.703
		Angle Crashes	184	333.56	0.545	**0.549***	**0.054**	0.441 - 0.657
		Rear End Crashes	457	793.97	0.656	**0.575***	**0.036**	0.504 - 0.646
Standard	1 Crossover Lane (n = 2)	Total	382	310.02	1.219	**1.227***	**0.104**	1.023 - 1.431
		Fatal & Injury (KABC)	127	134.08	0.937	**0.937**	**0.126**	0.690 - 1.184
		Property Damage Only	255	176.14	1.434	**1.436***	**0.156**	1.130 - 1.742
		Angle Crashes	87	81.77	1.072	**1.046**	**0.174**	0.705 - 1.387
		Rear End Crashes	198	171.68	1.113	**1.144**	**0.130**	0.889 - 1.399
	2 Crossover Lanes (n = 3)	Total	813	721.43	1.108	**1.125***	**0.063**	1.002 - 1.248
		Fatal & Injury (KABC)	211	193.03	1.083	**1.085**	**0.118**	0.854 - 1.316
		Property Damage Only	602	528.07	1.117	**1.137****	**0.074**	0.992 - 1.282
		Angle Crashes	170	205.73	0.821	**0.821****	**0.092**	0.641 - 1.001
		Rear End Crashes	488	380.23	1.233	**1.279***	**0.096**	1.091 - 1.467

** Statistically Significant at the 95-percent Confidence Level*

*** Statistically Significant at the 90-percent Confidence Level*

7. CONCLUSION AND FUTURE RESEARCH

This research effort sought to fill the gap in safety research related to the CFI to determine if the alternative intersection should be considered as a future design alternative. Although CFIs are the most efficient intersection form known-to-date; they are often touted as unsafe for all road users. To answer the question on whether CFIs can be designed safely, an Empirical Bayes crash analysis was utilized to account for time, seasonality, historical trends, and regression-to-the-mean. An initial list of 45 sites were considered – 8 sites were removed because they were not true CFIs, and 10 others were removed because the CFI was an interchange or a very unconventional CFI design. Of the remaining 27 "typical" CFIs, further investigation into the date of installation, and availability of data requested from states, provided a total of 19 sites for consideration. During the data collection and analysis stages, 3 final sites were removed – one for lack of AADT data, one for lack of before data (the database changed), and a discovery of an unusual frontage road design that was non-typical. In total, 16 treatments sites were used along with 76 reference sites for SPF development.

Crashes were analyzed at both the aggregate and disaggregate level using five separate crash categories. For both aggregate and disaggregate results, total crashes were used as an overall measure of safety. Severity was analyzed looking at injury (KABC) and PDO crashes separately while crash type used angle and rear end crashes. Using the same five categories, disaggregated crashes were analyzed further based on the right turn treatment (standard vs. parallel), the presence of intersection skew (skew angle < 70°), area type (rural vs. urban/suburban), number of approaches (3 vs. 4), and the maximum number of left turn crossover lanes (1 vs. 2).

Using *aggregated crashes*, the following can be said with confidence:

- Overall, CFIs were found to provide a positive, and significant, safety benefit of 12.2% when looking at *total crashes* (95% CI).
  - Looking at *severity of crashes*, CFIs were found to significantly reduce fatal and injury as well as PDO crashes by 13.9% and 11.8%, respectively (95% CI).
  - Looking at *crash type*, CFIs were found to significantly reduce angle and rear end crashes by 29.4% and 13.2%, respectively (95% CI).

Although pedestrian and bicycle crashes were not excluded from the analysis, the lack of available sample did not allow for those road users to be analyzed separately.

Using *disaggregated crashes*, the following can be said with confidence:

- Right Turn Treatment: CFIs installed with parallel right turns were found to be much safer than sites with standard right turns. Sites with parallel right turns significantly reduced crashes in all categories from 26.7% to 42.8%, while standard right turns increased three of the five crash categories significantly, ranging from 15.6% to 24.0%. Sites that were right-of-way constrained that need to use a standard right turn movement should carefully consider the trade-offs of increased crash rates and even strongly consider using parallel right turn movements on other quadrants of the same site that need a left turn crossover movement and were not right-of-way constrained. An additional treatment consideration could be removal of right-turn-on-red for the standard approach.

- Intersection Skew: CFIs installed at intersections with parallel right turns and little-to-no skew will likely yield the best safety results, with reductions ranging from 28.4% to 52.4%. If a CFI is installed with parallel right turns at an intersection *with skew*, the right turn should still yield acceptable safety results; however, a small trade-off of increased (though not significant) angle crashes exists compared to the no skew condition.
- Area Type: Overall, the installation of CFI sites in rural and urban/suburban locations with parallel right turns were both found to significantly decrease total crashes by 40.3% and 26.0%, respectively (95% CI), with rural sites clearly providing the biggest benefit. Sites with standard right turns were all located in urban/suburban locations and showed no reductions in crashes and significant increases in 3 of the 5 crash categories.
- Number of Approaches: The installation of CFIs at 4-leg sites with parallel right turns were found to significantly decrease total crashes by 32.6% (95% CI). 4-leg intersections with parallel right turns appear to be safer (compared to 3-leg intersections) with statistically significant reductions across all crash categories of severity and crash type, ranging from 28.3 to 46.4% – with the largest decrease in angle crashes, whereas no significant change was noted in angle crashes at 3-leg facilities in this category. Sites with standard right turns were all 4-leg intersections and the findings were the same as past categories with significant increases in crashes in 3 of the 5 crash categories.
- Number of Crossover Lanes: Sites that used 2-lane crossovers with parallel right turns were found to be safer, reducing total crashes 34.9% and other crash categories ranging from 31.2% to 45.1% (all at 95% CI). Single-lane crossover sites with parallel right turns were only found to reduce angle crashes significantly by 32.7% (95% CI), with all other crash categories reporting no significant change. When looking at crossover lanes at sites with standard right turn sites, all crash categories for single and dual left turn crossover reported increases or no change in crashes. The only exception was the 2-lane crossover site where angle crashes decreased significantly by 17.9% (90% CI). Interestingly, this finding is similar to the 2-lane with parallel right turns which also shows the most significant impact of 1 vs. 2 lane crossovers is the reduction of angle crashes. Based on these results, the research team believes sites with heavy left turn volumes should benefit from higher capacity left turn movements (i.e., 2-lane crossovers) which would reduce cycle failures and drivers potentially running the red light.

In summary, the installation of a CFI, if designed well, should provide a net safety benefit while also providing improved safety performance. When considering total crashes only, the only standalone feature that has a negative safety impact is the standard right turn treatment, so designers should use this design feature carefully if right-of-way is not available while also considering ways to lessen the effect of this conflict such as using “no-right-turn-on-red” signalization. Considering other contextual variables ***with a parallel right turn treatment only***, sites having skew or little-to-no-skew would expect significant improvements in safety, with the little-to-no-skew condition having the most significant impacts for all crash types/severities Although not optional, designs considered in rural areas would likely have the best overall impact, with crashes likely increasing over time as traffic volumes increase and sites become more urbanized. The exception to this would be that angle crashes would likely improve as the site is more urbanized and the CFI is surrounded by similar signalized intersections and speeds would likely reduce. When looking at the number of legs of a CFI, 4-leg approach sites with parallel right turns provides slightly better safety benefits compared to a 3-leg facility with parallel turns since all crash types/severities decrease significantly. Even so, no crash category increases for 3-legged sites in this category, making them a very viable option also. Last, CFI designs with parallel right turns and 2 crossover lanes perform better than single lane crossover sites because all crash types and severities reduced significantly. Even so, single lane crossovers, in conjunction with parallel right turns, performed well also with a significant decrease in angle crashes.

Based on prior efforts documented in the literature, there were significant shortcomings that needed to be addressed with regards to CFI safety. The findings above were a big step in answering questions around safety for the CFI design type once and for all. Interestingly, surrogate analysis techniques such as “Safe Systems for Intersections” show that this design would not be a safe design alternative; however, the crash data analyzed in this report tells a different story. Therefore, although surrogates are certainly useful tools when data is not available, they can be misleading at times (especially surrogates that are not based on crash data directly and are more “qualitative” assessments). For that reason, surrogate analysis techniques based on crash data would be the best alternative compared to more qualitative assessments.

Although the results of this study were solid, there is still room for improvement in future analyses. First, of the 26 “typical CFIs” remaining (minus the late removal of the site with frontage roads), several states were not responsive to our data collection request or had sites which were too new to consider in our analysis. For this reason, we see value in a future analysis of more sites which have available AADT and crash data to continue looking at the specific features that make the best overall CFI designs. Second, the researchers struggled with categorizing crashes at CFIs from multiple states. For one, the crash data was captured from multiple intersections in the after period which makes identifying the actual location of a crash very challenging. Second, states vary somewhat in how they record crashes and even use different systems for recording the data in their databases. For this reason, researchers should do everything possible to capture data that includes narratives as well as crash diagrams to allow careful cleaning and location of crashes for analysis, especially at alternative intersections where multiple intersections were combined into one site analysis.   Last, we believe the cleaned data can be used to populate new surrogate conflict-based methods such as Movement Based Safety Performance Functions (MBSPFs) at the national level. The unique movements present at a CFI provide an opportunity to expand these conflict-based models.

8. REFERENCES

AASHTO. (2010). *The Highway Safety Manual,* American Association of State Highway Transportation Professionals, Washington, D.C.

Abdelrahman, A., Abdel Aty, M., Lee, J., Yue, L., Al-Omari, M. (2020) *Safety Analysis of Displaced Left Turn Intersections.* TRB 99th Annual Meeting, Washington D.C. (Paper No. 20-03379)

Ahmed, I.; Warchol, S.; Cunningham, C.M.; and N. Rouphail (2020). Integrated Implementation of Innovative Intersection Designs. Funded by University of Florida UTS "STRIDE".

Bared, J. G., Edara, P. K., and Jagannathan, R. (2006). *Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange*. Transportation Research Record: Journal of the Transportation Research Board, No. 1912, Washington D.C.

Carroll, D., and D. Lahusen. *Operational Effects of CFI Geometrics: A Deterministic Model for Continuous Flow Intersections.* Presented at 92nd Annual TRB Meeting. Transportation Research Board, National Research Council: Washington, DC, 2013.

Chase, T., Cunningham, C., Warchol, S., Vaughan, C., and Lee, T. (2020). *Reasonable Alternatives for Grade-Separated Intersections.* Report No. FHWA/NC/2018-20, North Carolina Department of Transportation, Raleigh, N.C.

Chen, Y. (2013). *Integrating Information from Prior Research into a Before-after Road Safety Evaluation*. PhD Thesis, Ryerson University.

Cook, M. *Continuous Flow Intersection Reduces Congestion, Increases Safety.* Transcript: The Ohio Department of Transportation Employee Newsletter. Ohio DOT: Columbus, OH, 2003.

Federal Highway Administration (FHWA) (2013). *Highway Functional Classification: Concepts, Criteria and Procedures* (Report No. FHWA-PL-13-026).

Federal Highway Administration (FHWA) (2019). *Guide for Pedestrian and Bicycle Safety at Alternative Intersections and Interchanges*: NCHRP Project 07-25.

Federal Highway Administration (FHWA) (2014). *Displaced Left Turn Intersection: Informational Guide*. Federal Highway Administration (FHWA).

Garcia, A. and L. Libreros (2007). *Safety Effect of the Skew Angle in Right Turn Maneuvers.* TRB Urban Street Symposium: Uptown, Downtown, or Small Town: Designing Urban Streets that Work, Seattle, WA.

Gross, F., Persaud, B. N., and Lyon, C. (2010). *A Guide to Developing Quality Crash Modification Factors* (No. FHWA-SA-10-032). United States. Federal Highway Administration. Office of Safety.

Haley, R., Ott, S, Hummer, J.E., Cunningham, C.M., Foyle, R., and B.J. Schroeder (2011). *Operational Effects of Signalized Superstreets in North Carolina,* Journal of the Transportation Research Board – TRR Issue 2223, TRB, Washington, D.C.

Haley, R., Ott, S., Hummer, J.E., Foyle, R., and C.M. Cunningham (2015). *Resident, Commuter, and Business Perceptions of New Superstreets*, Journal of Transportation Engineering, Volume 141, Issue 7. American Society of Civil Engineers.

Hauer, E. (1997). *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety.* Oxford, U.K.: Elsevier Science Ltd.

Holzem, A., Hummer, J.E., Cunningham, C.M., O'Brien, S., Schroeder, B., and K. Salamati (2015). *Pedestrian and Bicyclist Accommodations on Superstreets.* Submitted for Publication by the Transportation Research Record: Journal of the Transportation Research Board: TRR Issue 2486, TRB, Washington, D.C.

Jagannathan, R. and J.G. Bared. Design and Operational Performance of Crossover Displaced Left-turn Intersections. In Transportation Research Record 1881 (2004).

Lee, T., Thomas C., Christopher C., and Shannon W. (2020). *Movement-Based Safety Functions for Signalized Intersections.* 99th Annual Meeting of Transportation Research Board (in press), Washington, D.C.

Louisiana Department of Transportation and Development (LADOT) (2007). *Continuous Flow Intersection (CFI) US 61 (Airline Highway) @ LA 3246 (Siegen Lane) Report*.

Nightingale, E., Parvin, Nico, Seiberlich, C., and M. Savolainen (2017). *Investigation of Skew Angle and Other Factors Invluencing Crash Frequency at High-Speed Rural Intersections.* In Transportation Research Record 2636, Issue 1.

Ott, S., Haley, R., Hummer, J.E., Foyle, R., and C.M. Cunningham (2012). *Safety Effects of Unsignalized Superstreets in North Carolina*, Accident Analysis and Prevention, Volume 45.

Park, S. and Rakha, H. (2010). *Continuous Flow Intersections: A Safety and Environmental Perspective.* 13th International IEEE Annual Conference on Intelligent Transportation Systems, Portugal.

Persaud, B. and Lyon, C. (2007). *Empirical Bayes Before-After Safety Studies: Lessons Learned from Two Decades of Experience and Future Directions*. Accident Analysis and Prevention, Vol. 39 (3), pp. 546 – 555.

Reid, J., and J. Hummer (2001). *Travel Time Comparisons between Seven Unconventional Arterial Intersection Designs.* In Transportation Research Record 1751.

Schroeder, et al. *Guide for Pedestrian and Bicycle Safety at Alternative Intersections and Interchanges*. NCHRP Report 948, TRB, Washington, DC, 2021.

Wilbur Smiths Associates and HDR Thompson. (2008). *Innovative Intersections: Overview and Implementation Guidelines.* Prepared for Community Planning Association of Southwest Idaho (COMPASS).

Wolshon, B. (2004). *Toolbox on Intersection Safety and Design: Chapter 1 - Geometric Design.* Prepared for The Institute of Transportation Engineers and The Federal Highway Administration.

Yahl, M. E. (2013). *Safety Effects of Continuous Flow Intersections.* North Carolina State University, Thesis.

Zlatkovic, M. (2015). *Development of performance matrices for evaluating innovative intersections and interchanges* (No. UT-15.13). Utah. Dept. of Transportation. Research Division.

APPENDIX A. EMPIRICAL BAYES (EB) METHODOLOGY

In the EB approach, the estimated change in safety for a given crash type at a site is given by the equation in Exhibit A-1.

Exhibit A-1. Equation. Estimated Change in Safety

$$\Delta Safety = \lambda - \pi$$

Where:

λ = Expected number of crashes that would have occurred in the after without the treatment.

π = Number of reported crashes in the after period.

The sum of the annual SPF estimates for the before period (P) was combined with the count of crashes (x) in the before period at a treatment site to obtain an estimate of the expected number of crashes (m) before the treatment was applied.

Exhibit A-2. Equation. Empirical Bayes Estimates of Expected Crashes in the Before Period

$$m = w(P) + (1 - w)(x)$$

Where the EB weight, w, was estimated from the mean and variance of the SPF estimate using the equation in Figure A6-3.

Exhibit A-3. Equation. Empirical Bayes Weight

$$w = \frac{1}{1+kP}$$

Where:

k = Overdispersion parameter of the negative binomial distribution.

In high volume locations with long before periods, P would tend to be high leading to *w* being low and closer to zero (in these situations 1 – w is closer to 1, and m will be closer to *x* compared to P). The expected number of crashes in the after period, λ, was calculated by applying a factor to m as seen in the equation in Exhibit A-4Exhibit . This factor was the sum of the annual SPF estimates for the after period (A) divided by P.

Exhibit A-4. Equation. Empirical Bayes Estimates of Expected Crashes in the After Period

$$\lambda = m \times \left(\frac{A}{P}\right)$$

The estimate of λ and variance of λ, were then summed over all sites to obtain λ_{sum} and $Var(\lambda_{sum})$. λ_{sum} was then compared with the sum of count of crashes observed during the after period over all sites (π_{sum}) to obtain the CMF (θ). The safety effect θ was calculated using the equation in Exhibit A-5 and the standard error of θ was calculated using the equation in Exnibit A-6.

Exhibit A-5. Equation. CMF

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1 + \left(\frac{Var(\lambda_{sum})}{\lambda_{sum}^{2}}\right)}$$

Exhibit A-6. Equation. Standard Error of CMF

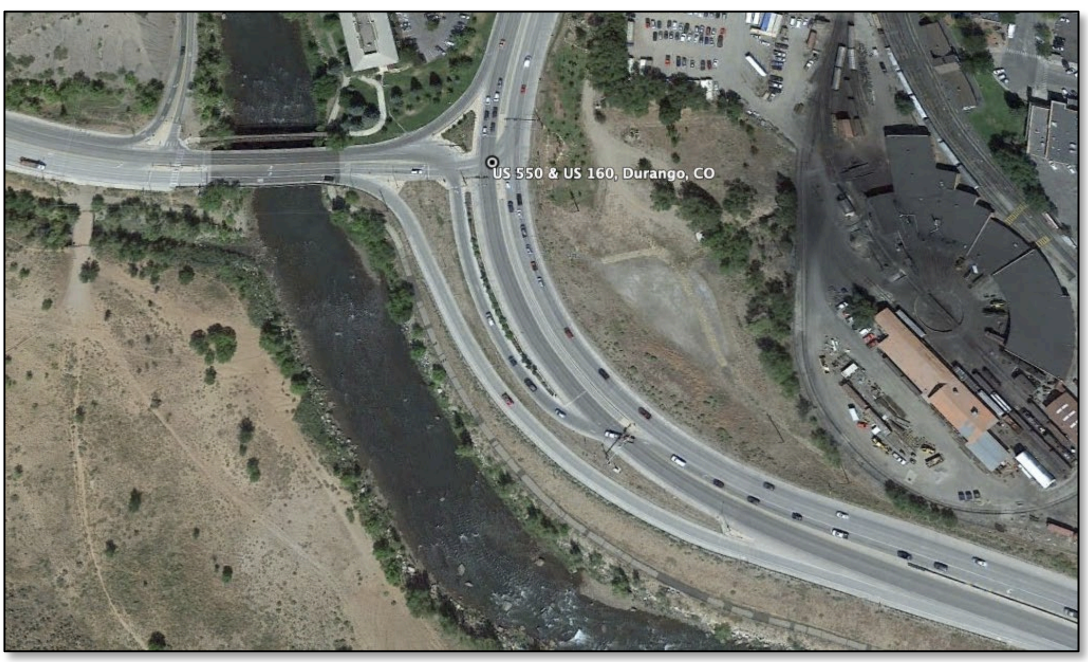
$$Standard\ Error\ of\ \theta = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^{2}} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^{2}}\right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^{2}}\right)^2}}$$

The percent change in crashes is calculated as $100(1 - \theta)$. Therefore, a value of $\theta = 0.9$ with a standard of error of 0.05 indicates a 10% reduction in crashes with a standard error of 5%. Conversely, a value of $\theta = 1.2$ with a standard of error of 0.1 indicates a 20% increase in crashes with a standard error of 10%.

APPENDIX B. CFI TREATMENT SITES (BEFORE & AFTER)

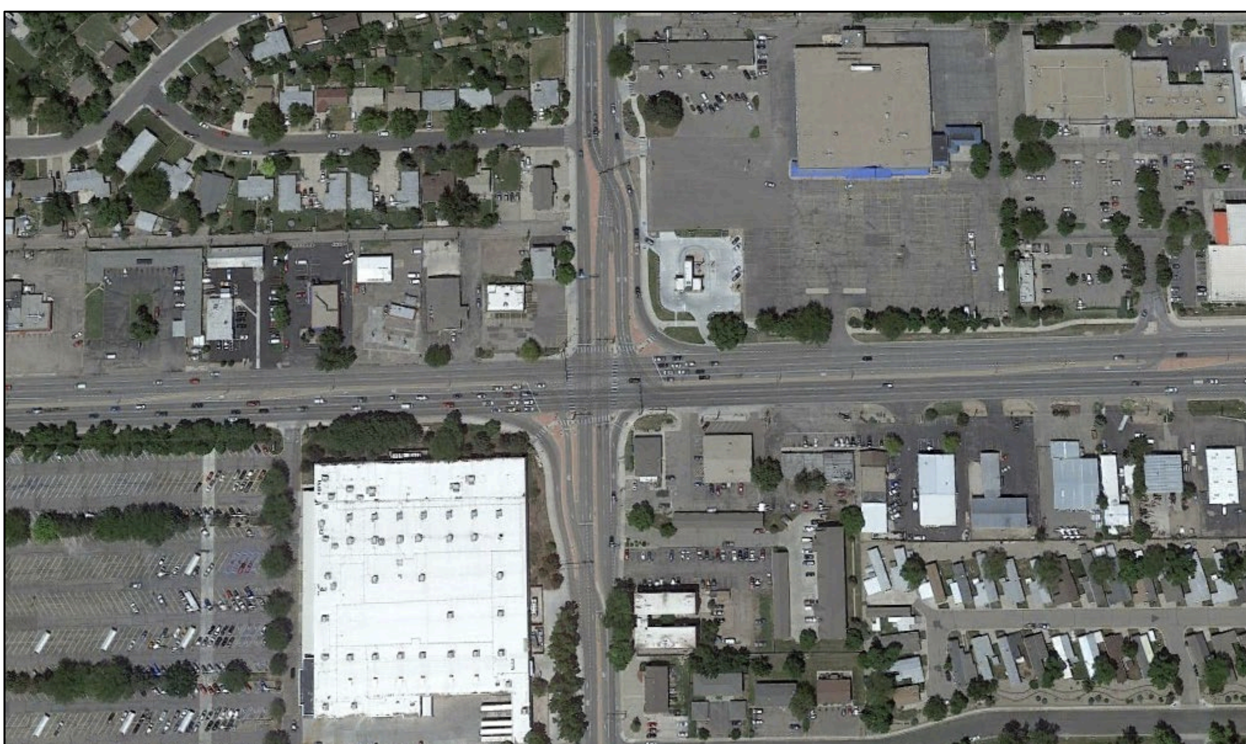
T1_US 550 & US 160_37.268548, -107.884906
BEFORE (Google Earth 2011)

AFTER

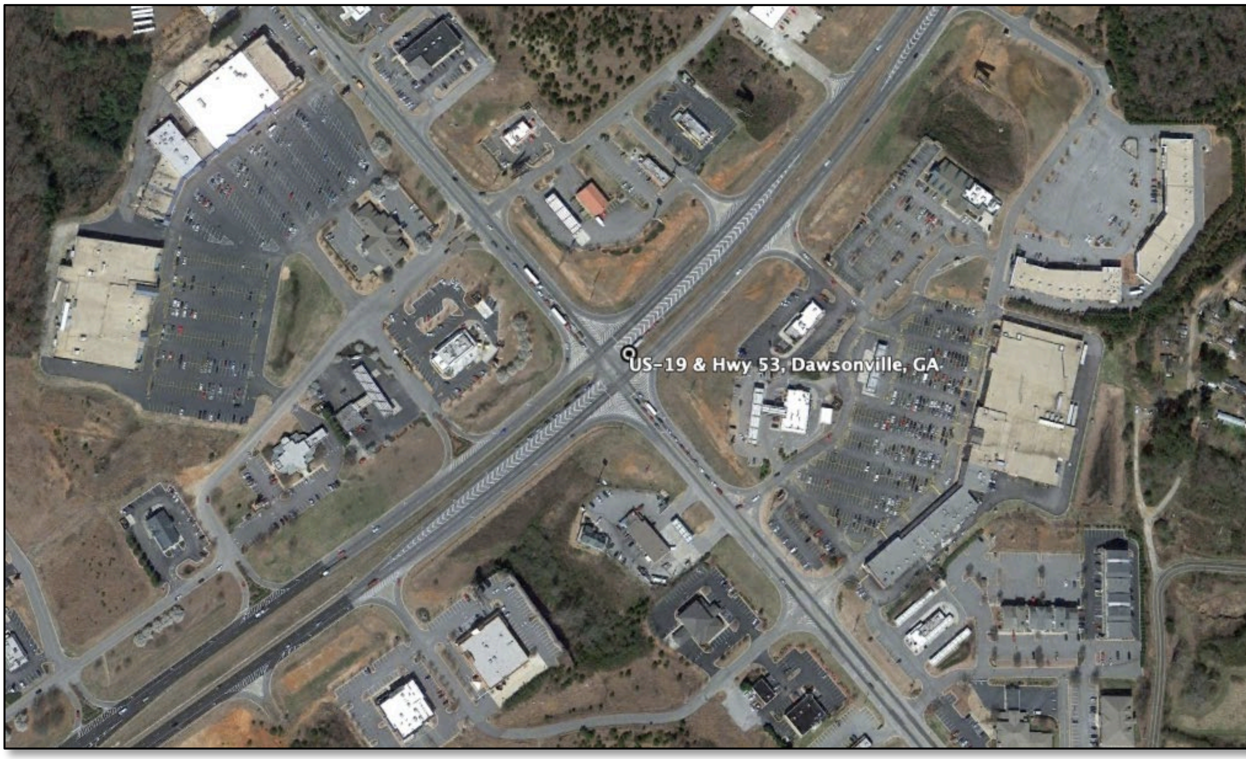


T2_US 34 & Madison Ave_40.407262, -105.058699
BEFORE (Google Earth 2007)

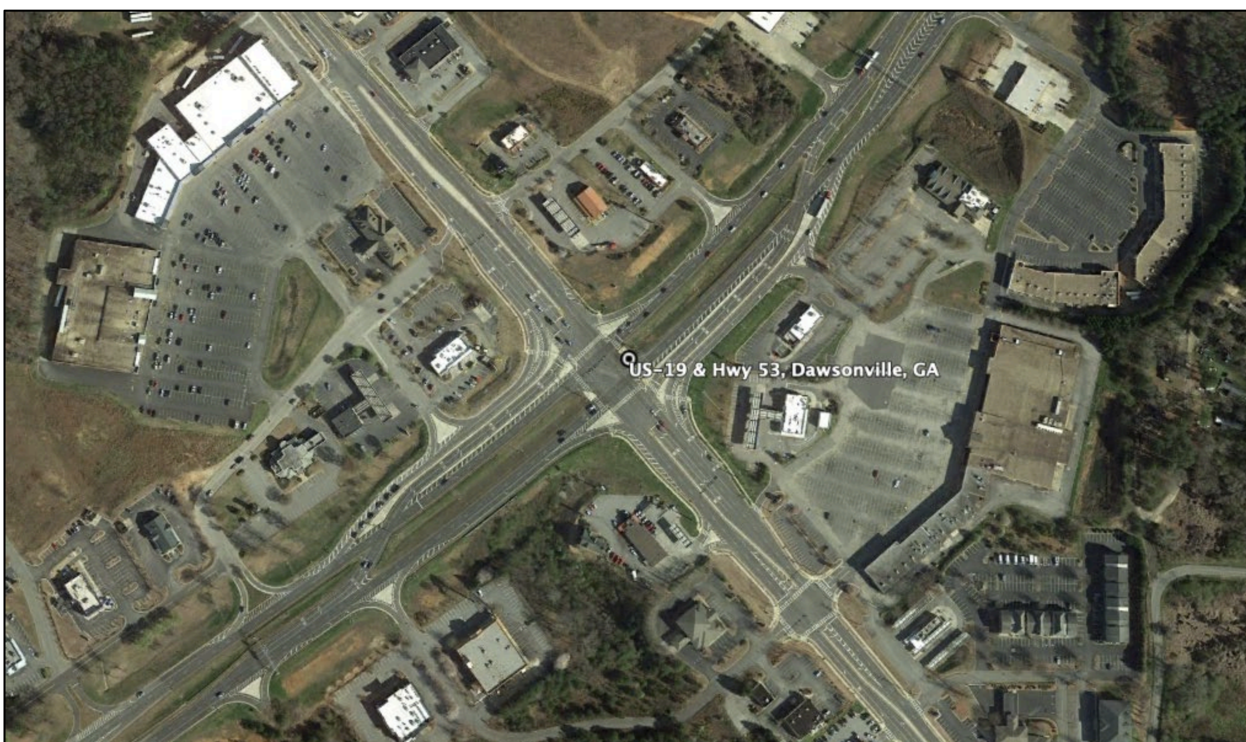
AFTER



T3_US-19 & Hwy 53_34.363472719, -84.0362967
BEFORE (Google Earth 2013)



AFTER



T4_Scenic Hwy S & Main St W_33.8575802, -84.0199935
BEFORE (Google Earth 2017)

AFTER

T5_US 61 & Sherwood Forest Blvd/Siegen Ln_30.398833, -91.0540653
***Removed due to frontage road impacts on NW and SE quadrants**
BEFORE (Google Earth 2002)

AFTER

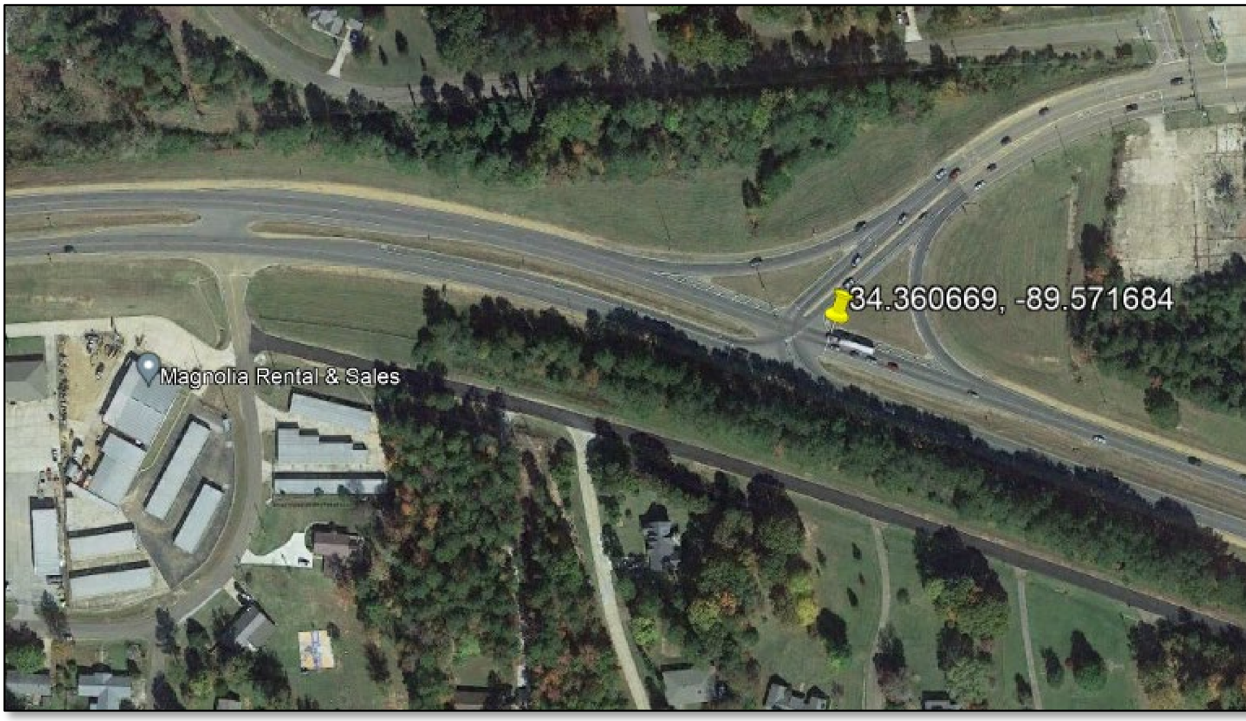
T6_MD 210 & MD 228_ 38.665012, -77.017558
***Removed due to lack of available crash data prior to 2002.**

BEFORE (Google Earth 2002)
No imagery able to be fond prior to 2002

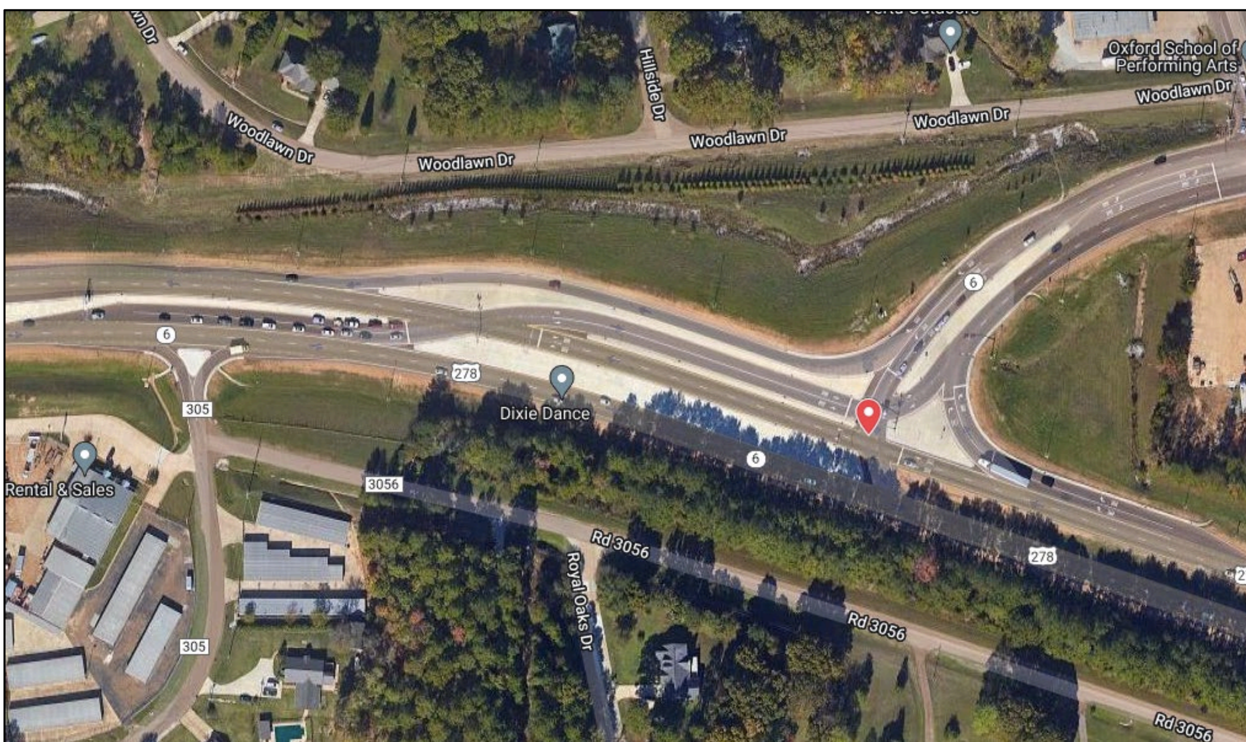
AFTER


MD-210 & MD-228
ory Chapel
Goog

T7_US 278 & Jackson Ave_34.360669, -89.571684
BEFORE (Google Earth 2012)

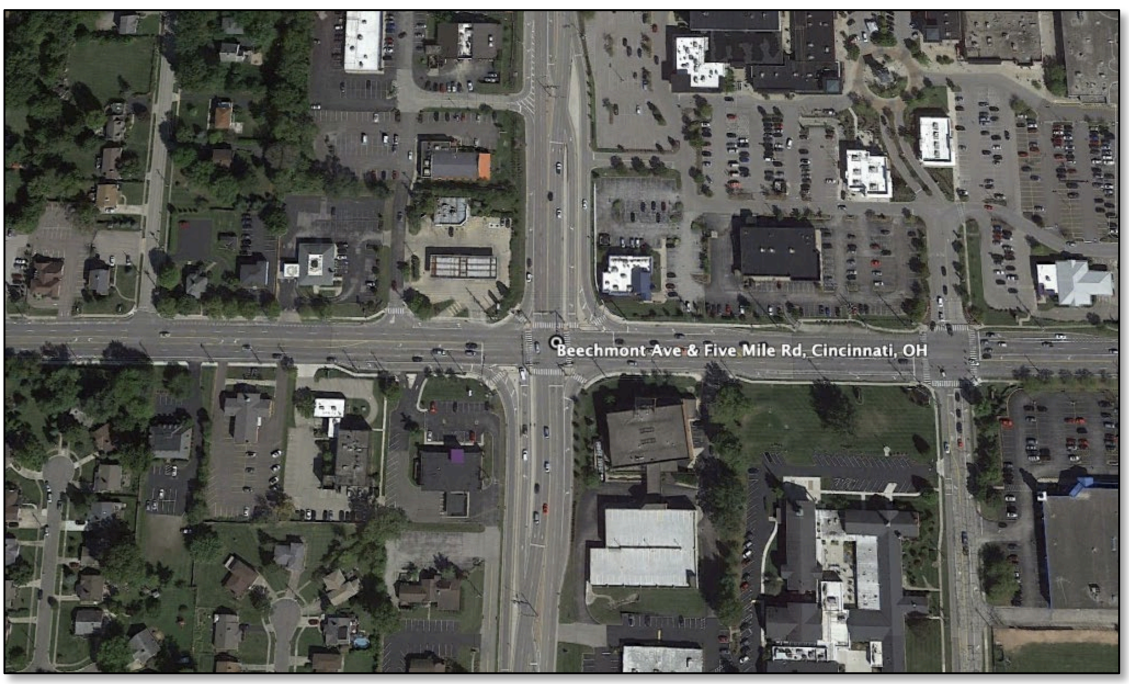


AFTER



T8_Beechmont Ave & Five Mile Rd_39.072856091, -84.351999
BEFORE (Google Earth 2014)

AFTER

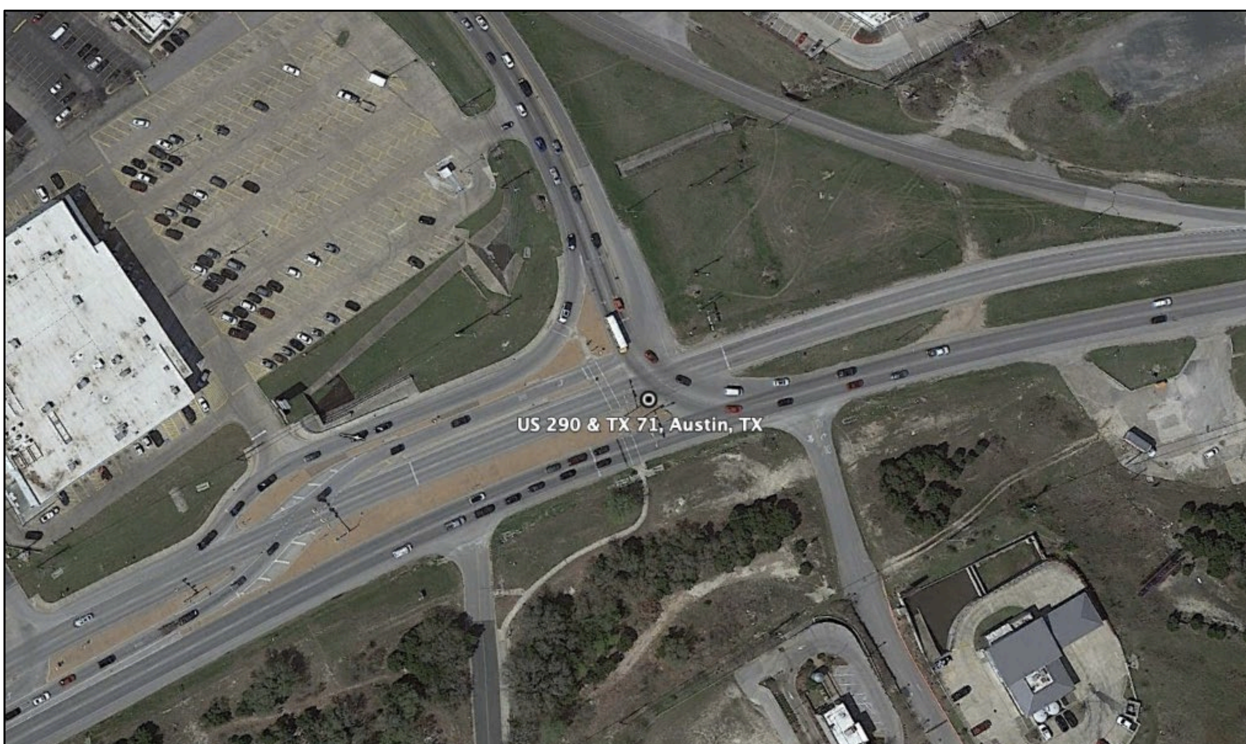


T9_US 290 & W William Cannon Dr_30.234020785, -97.864759
BEFORE (Google Earth 2013)

AFTER

T10_US 290 & TX 71_30.233323, -97.874727
BEFORE (Google Earth 2011)

AFTER

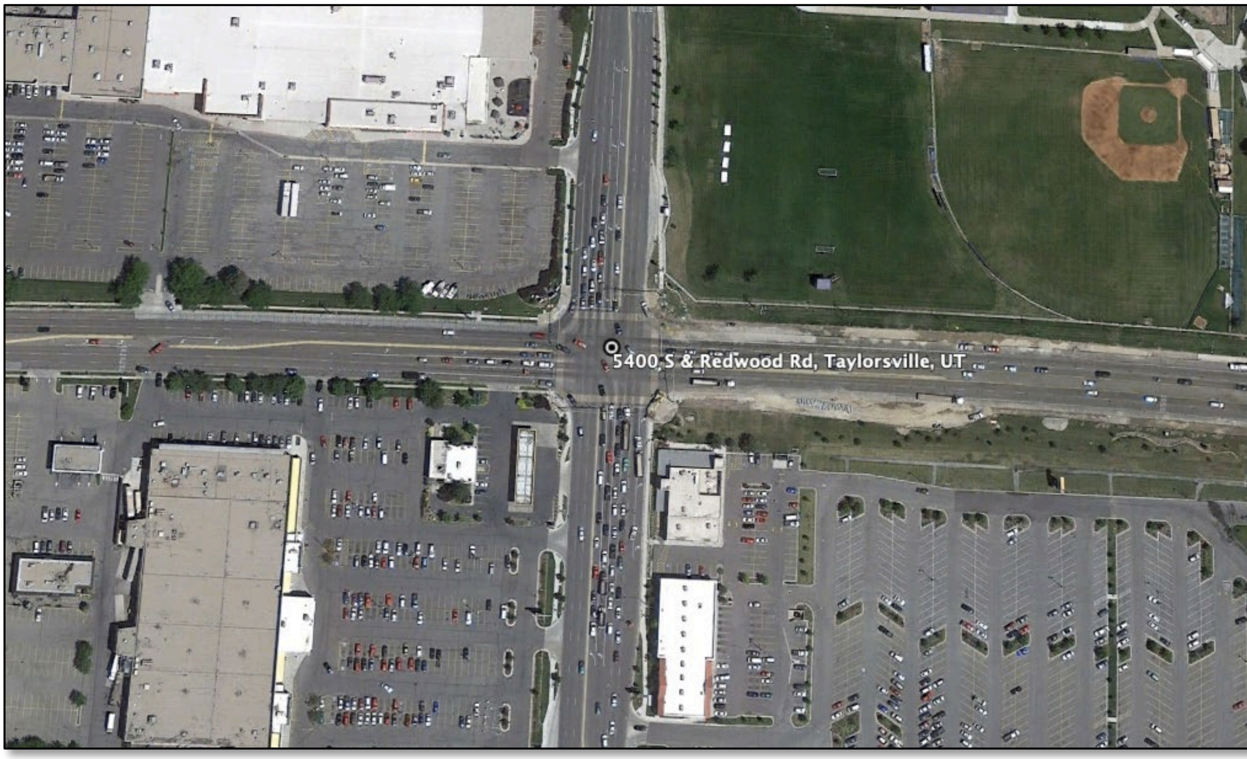


T11_Whitestone Blvd & Ronald Reagan Blvd_30.534647, -97.782662
BEFORE (Google Earth 2012)

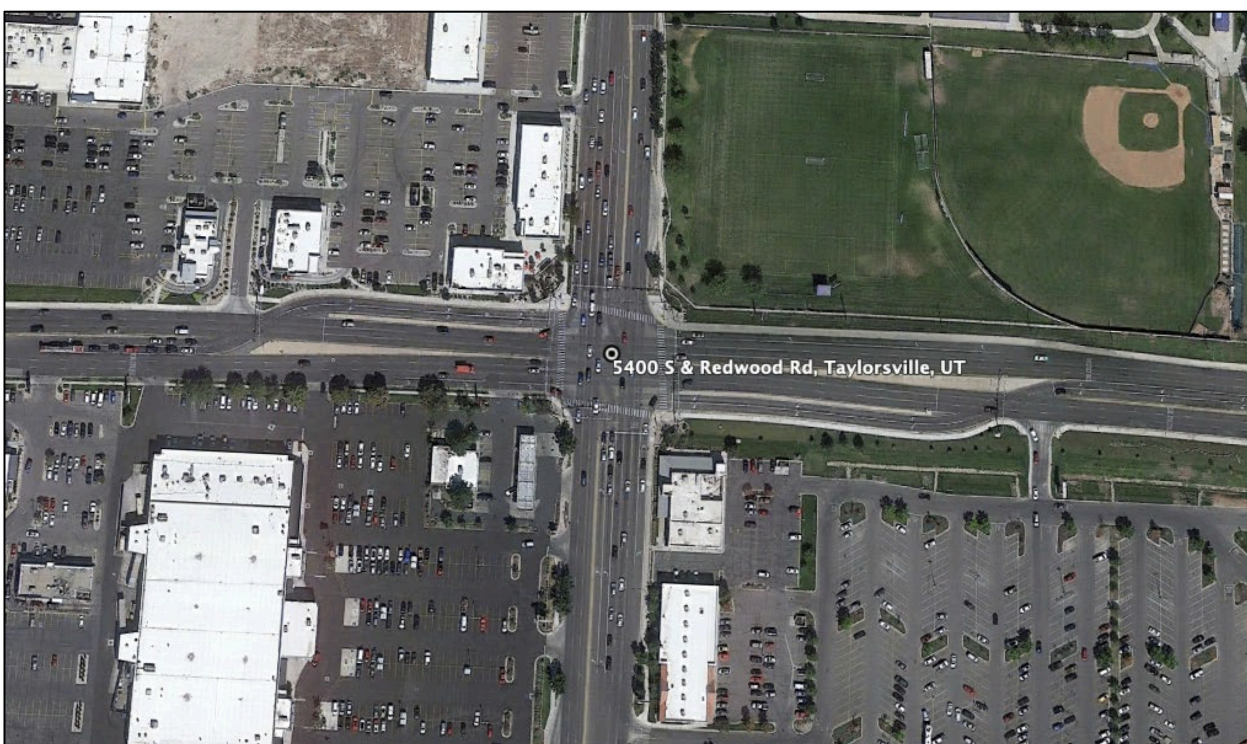
AFTER

T12_5400 S & Redwood Rd_40.653205, -111.9388229

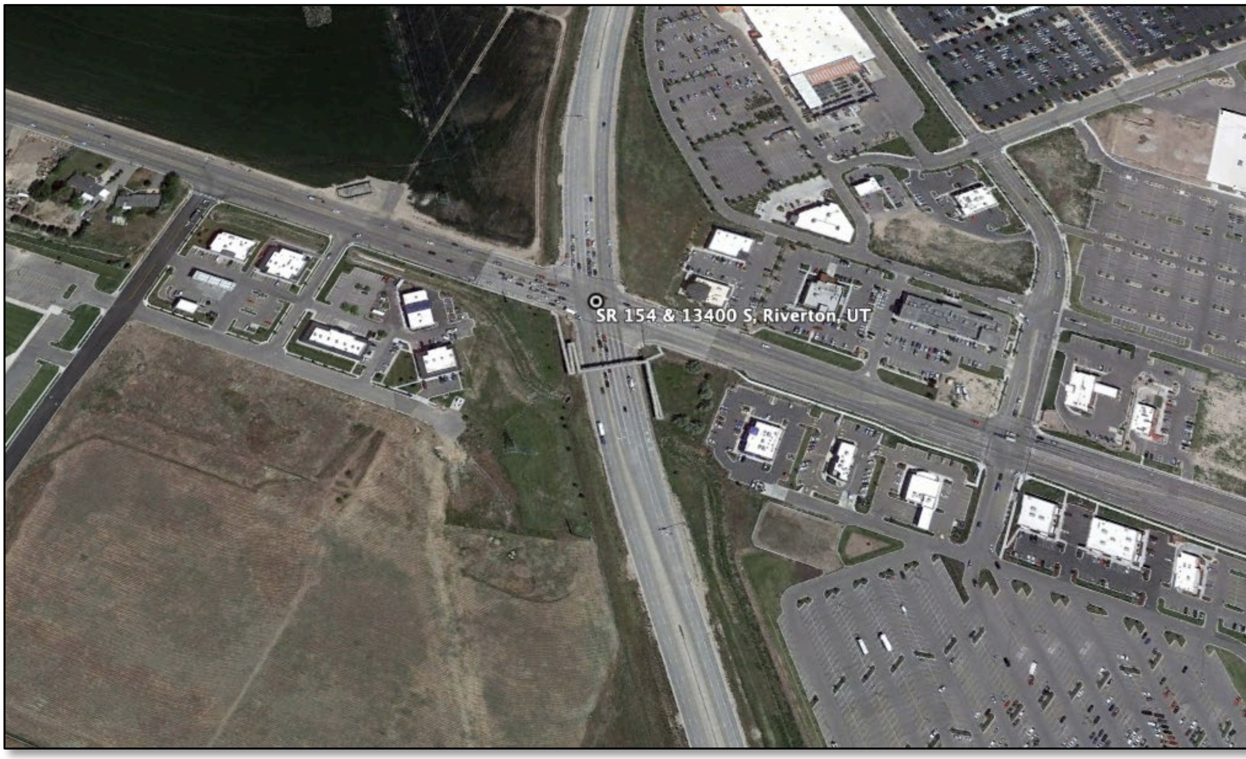
BEFORE (Google Earth 2010)



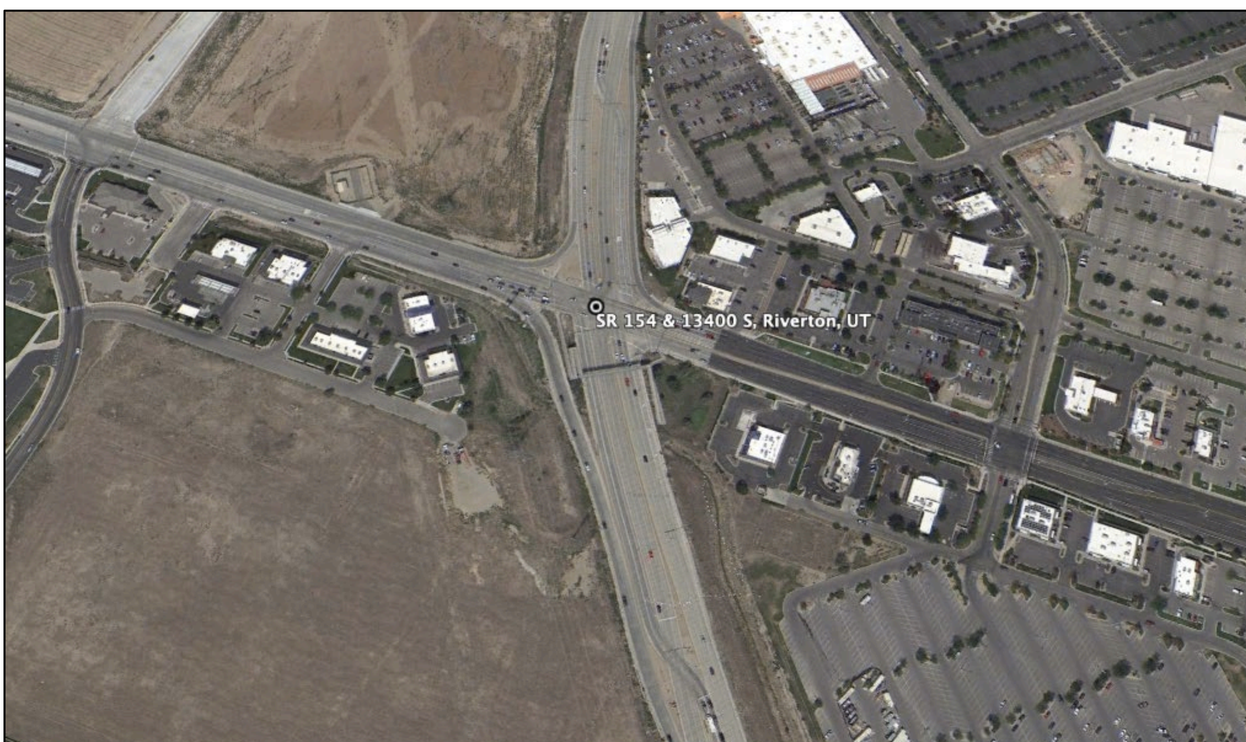
AFTER



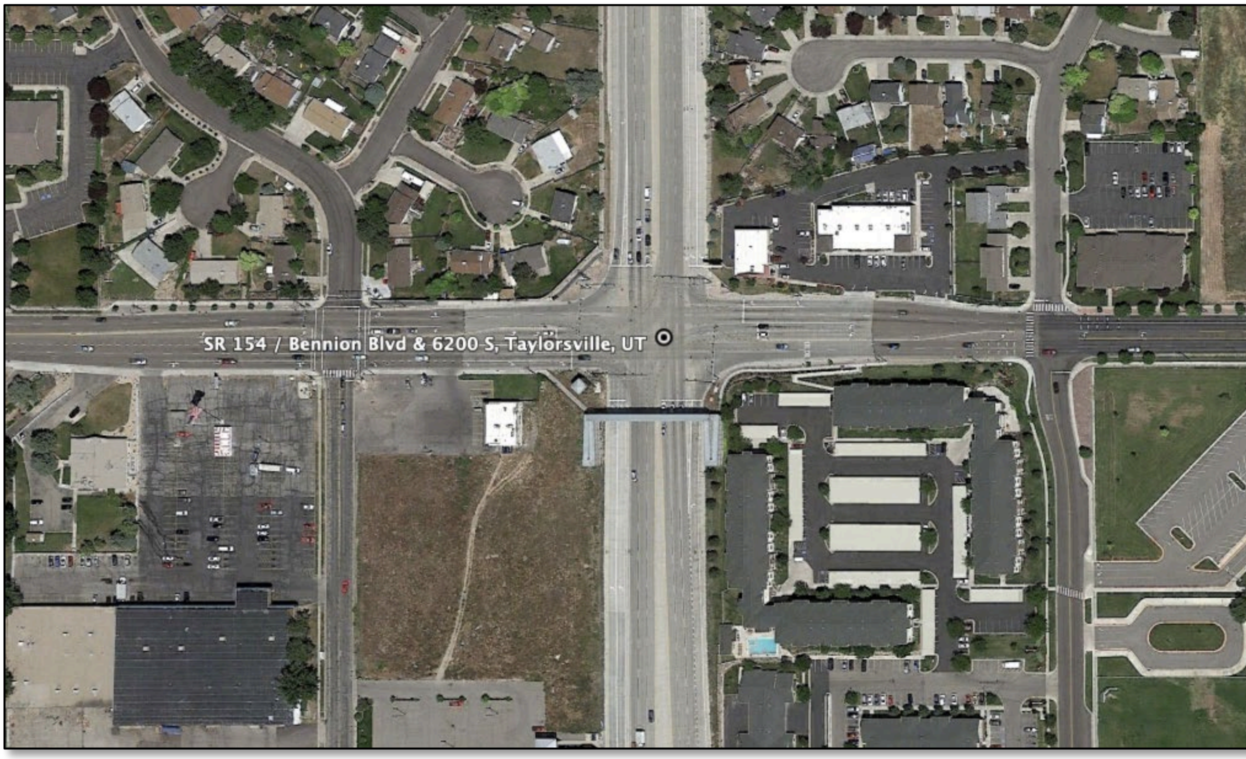
T13_SR 154 & 13400 S_40.507793, -111.982755
BEFORE (Google Earth 2010)



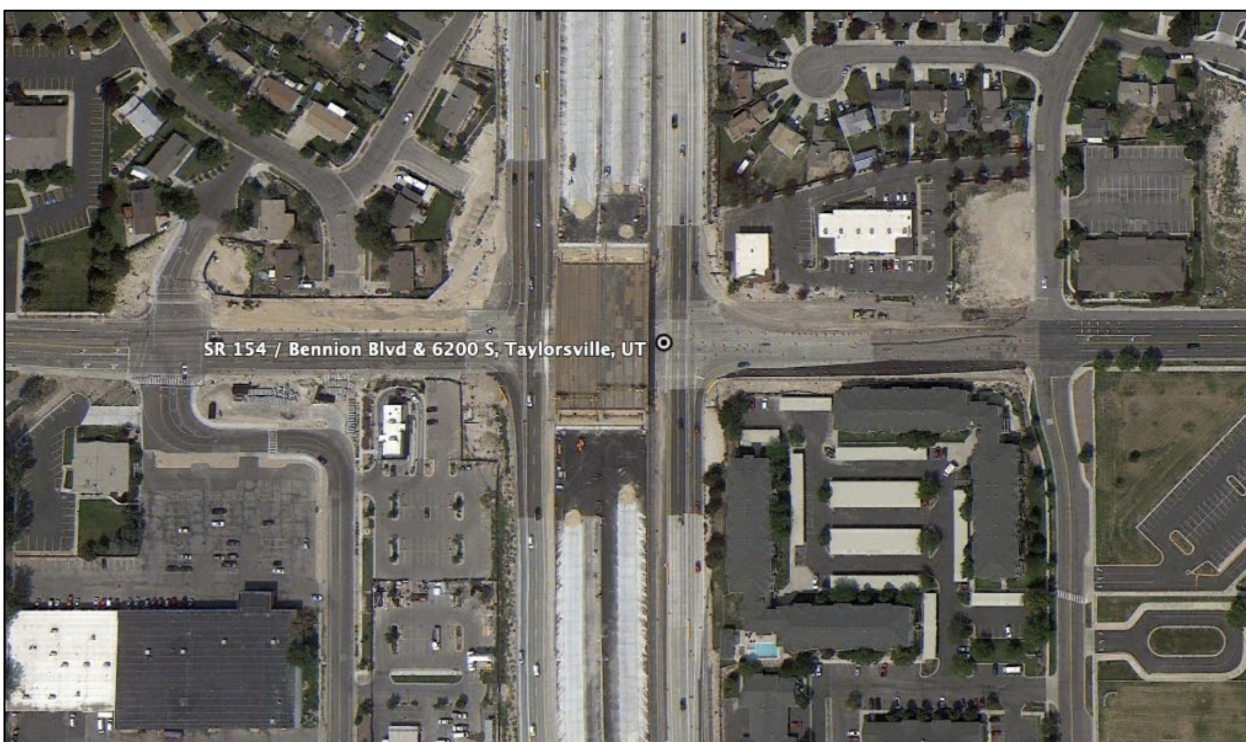
AFTER



T14_SR 154 / Bennion Blvd & 6200 S_40.638568, -111.976612
BEFORE (Google Earth 2015)

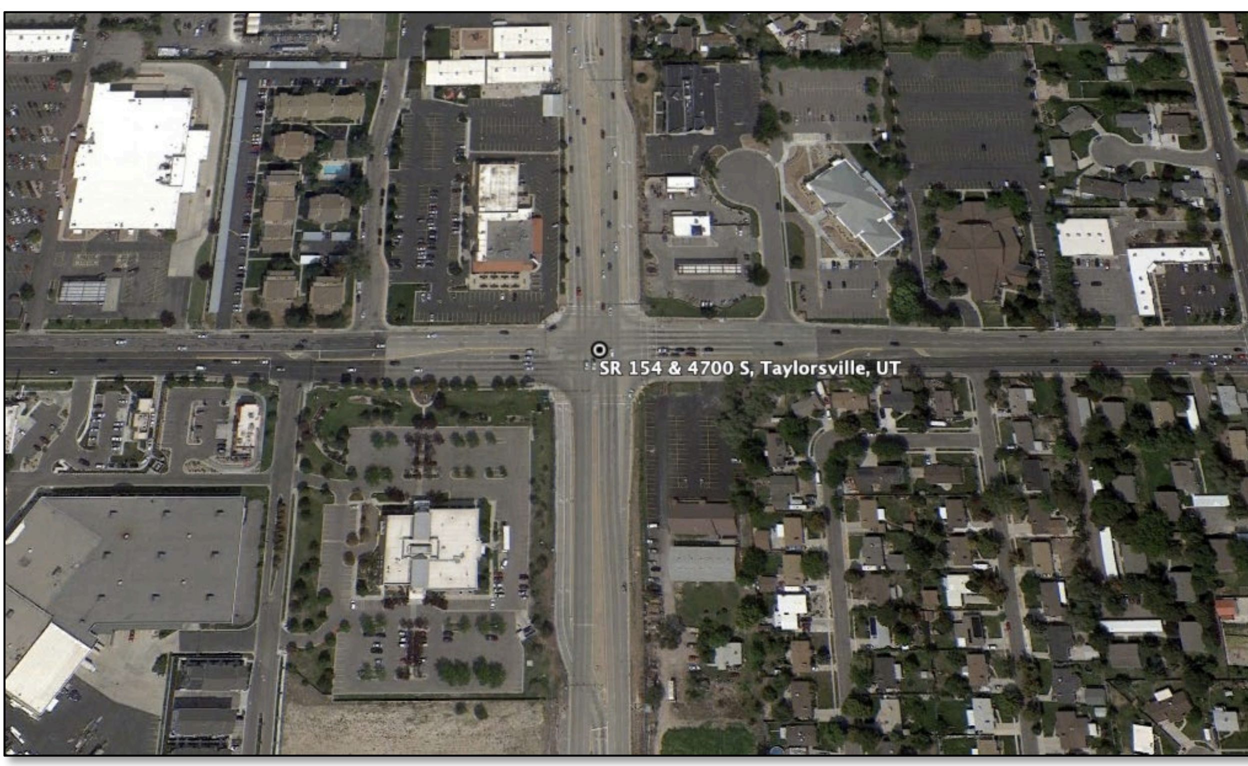


AFTER (August 2021 Bridge in Process)



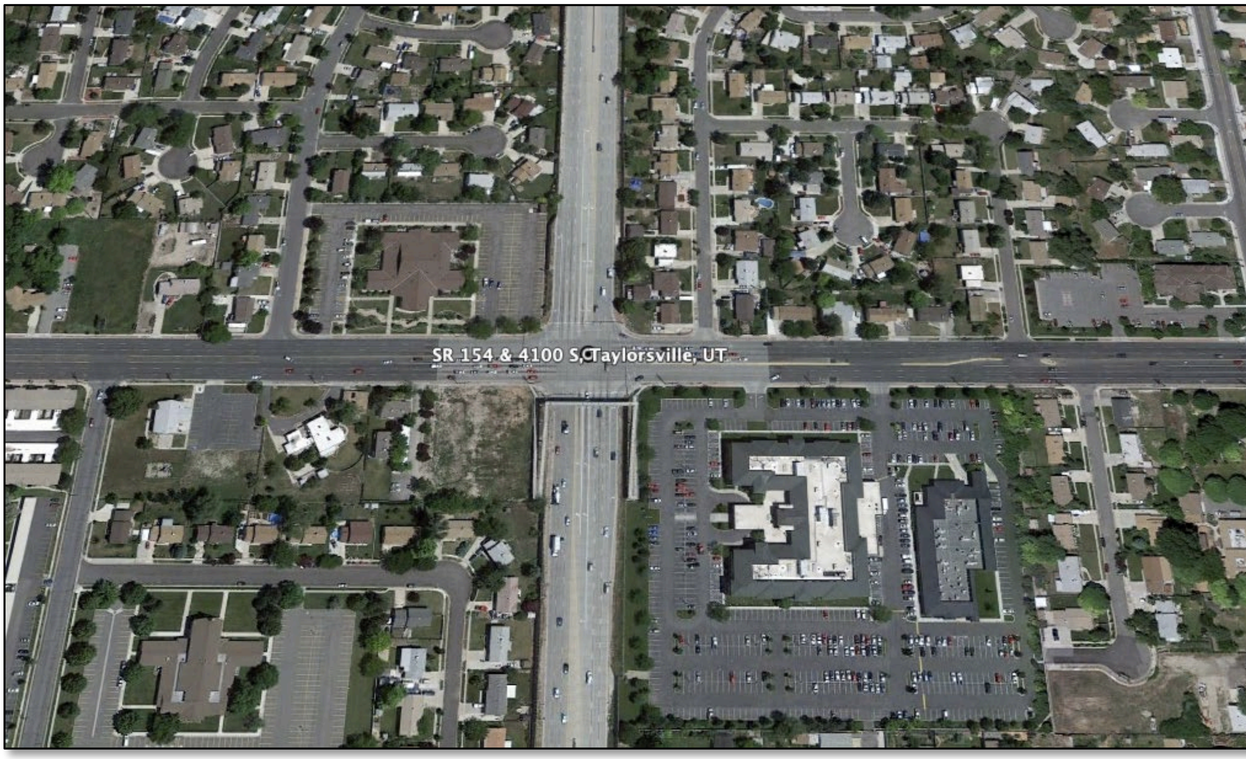
T15_SR 154 & 4700 S_40.667563, -111.981551
BEFORE (Google Earth 2010)

AFTER

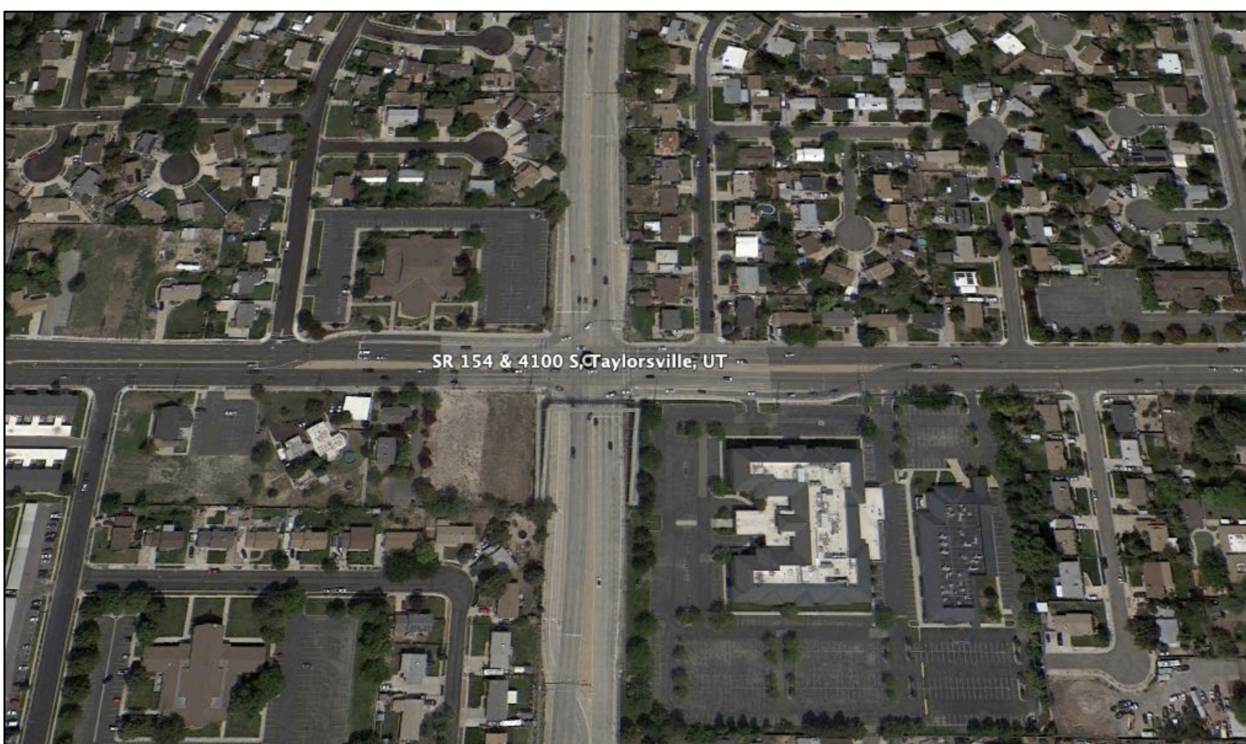


T16_SR 154 & 4100 S_40.682102, -111.981578

BEFORE (Google Earth 2010)



AFTER

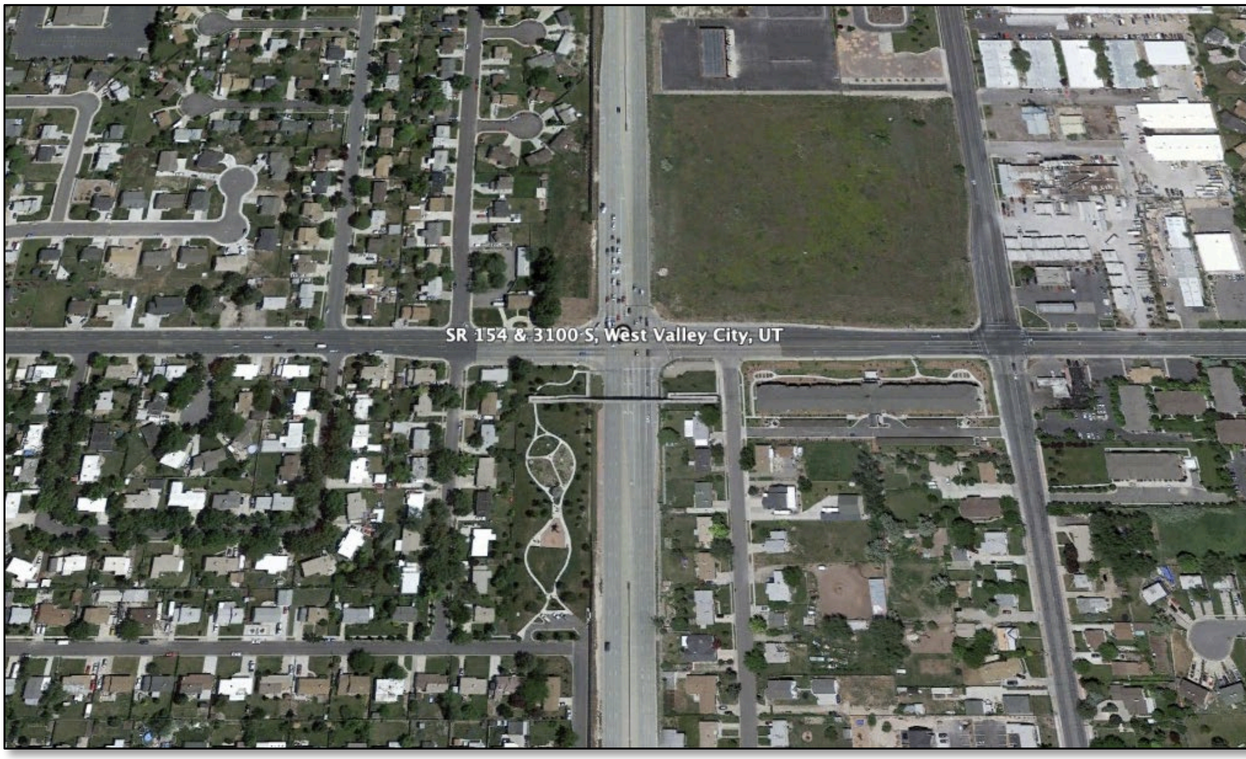


T17_ SR 154 & SR 171_ 40.696732, -111.980930
***Removed due to lack of available crash data prior to 2006 (database changeover).**
BEFORE (Google Earth 2006)

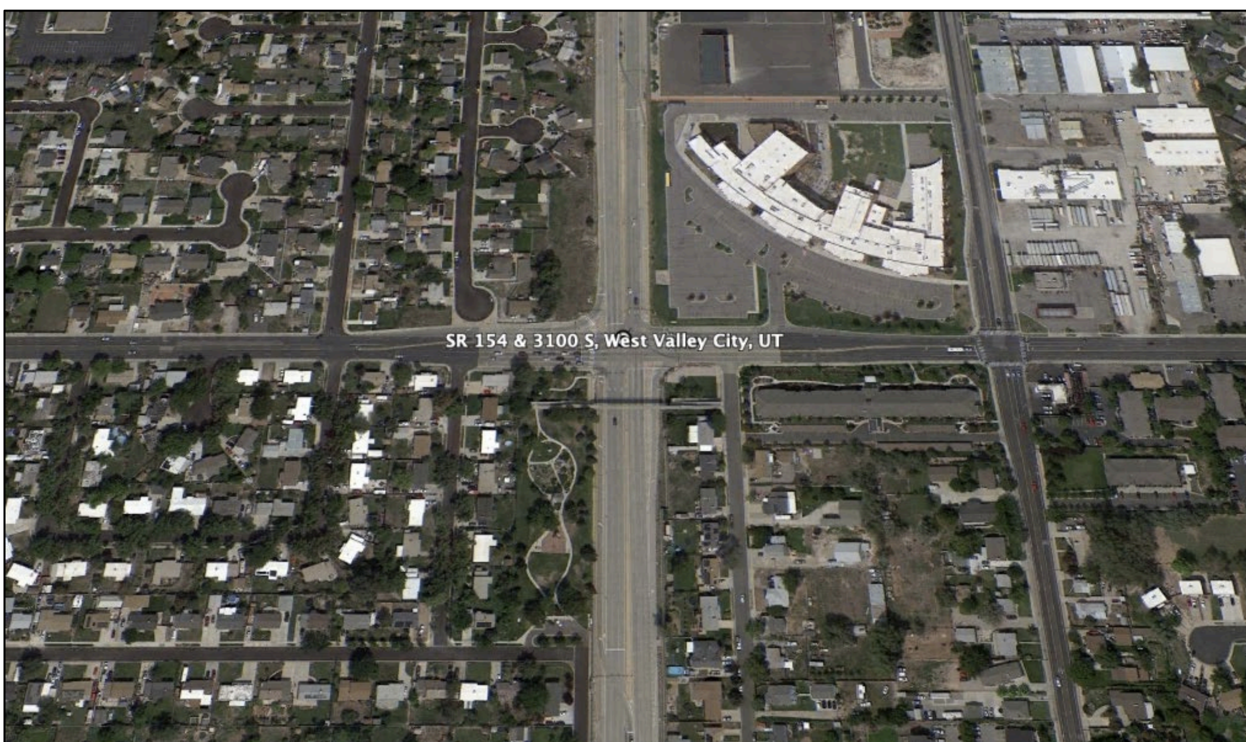
AFTER


6/2010
Jiffy Lube Oil Change & Multicare
Express Employment Professionals
Pets & Such
UT-154 & UT-171
Les Schwab Tire Center
Google

T18_SR 154 & 3100 S_40.703934, -111.980098
BEFORE (Google Earth 2010)



AFTER



T19_Redwood Rd & Bennion Blvd_40.6385603, -111.938796
BEFORE (Google Earth 2006)

AFTER