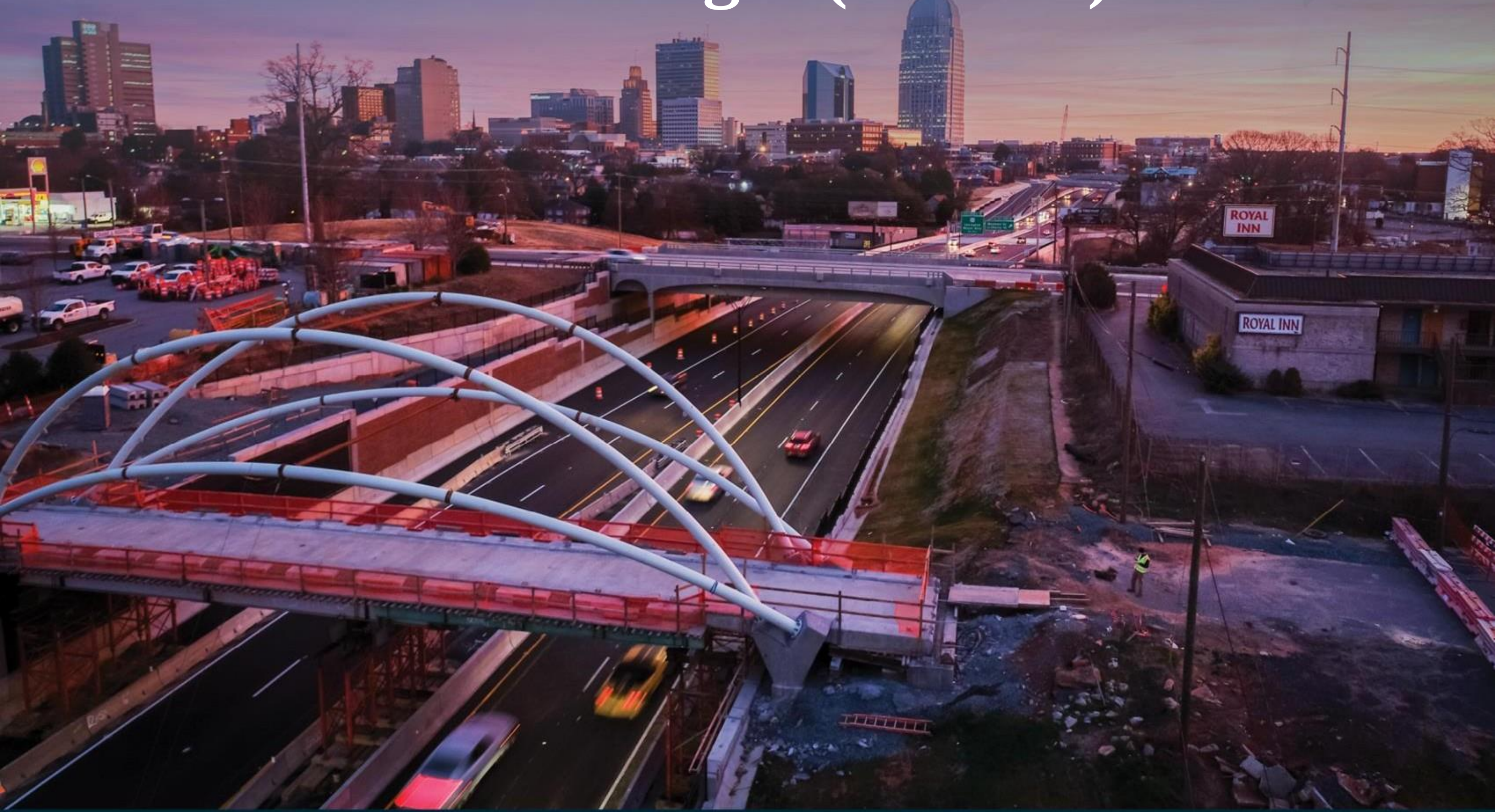
Guidelines to Enhance the Constructability of Diverse, Modern, and Unconventional Intersections and Interchanges (DMUII)



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William Rasdorf, Ph.D., P.E.
Minerva Bonilla, Ph.D. Candidate
Nagui Rouphail, Ph.D.
Rudolf Seracino, Ph.D.
Kevin Han, Ph.D.

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16. Abstract

The current focus on promoting sustainability in the United States transportation infrastructure has led to adopting Diverse, Modern, and Unconventional Intersections and Interchanges (DMUII) to improve traffic flow while ensuring safety. However, the adoption of DMUII designs presents challenges, including a learning curve for the public and contractors and additional time and cost compared to conventional Intersection and Interchange (CII) designs. This research aims to identify and mitigate the inhibitors that hinder DMUII design and construction while addressing critical questions related to constructability and cost-effectiveness. To achieve these goals, multiple studies were conducted to identify inhibitors and strategies to overcome them.

The identified inhibitors affecting DMUII projects were validated using four approaches that include the use of data from interviews, surveys, findings from field observations, and evaluation of claims and supplemental agreements. Additionally, a case study evaluating roadway congestion and detour operations resulting from Work Zone Traffic Control measures was undertaken, revealing the complexities of DMUII and CII projects and their implications on travel time, roadway congestion, and road user costs. Through this research, effective methods to enhance DMUII constructability were identified and these include constructability reviews, modularization, prefabrication for bridge construction, automation, staging, and 3D/4D modeling.

Findings were compiled in the form of lessons learned and best practices obtained which provide valuable insights for formulating construction strategies, facilitating the construction of DMUIIs, and addressing traffic volume challenges while ensuring safety. These findings can be implemented by transportation departments seeking to optimize DMUII performance and contribute to more sustainable transportation infrastructure.

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EXECUTIVE SUMMARY

The current transportation infrastructure in the United States focuses on promoting the use of projects that promote more sustainable practices. Diverse, Modern, and Unconventional Intersections and Interchanges (DMUII) can help to achieve this sustainability by providing ways to improve traffic flow while maintaining or improving traffic safety. However, DMUIIs present a learning curve for the public in terms of accepting DMUII designs and for contractors in terms of building DMUIIs. Also, DMUII construction involves additional time and cost compared to conventional intersection and interchange (CII) designs. Thus, the reasons for this additional time and costs need to be determined and mitigation strategies need to be identified to present constructible DMUII designs. To this end, the essential research questions are: (1) How can problems related to the construction of DMUIIs be solved without incurring cost increases, schedule delays, or traffic congestion? (2) What are the constructability inhibitors that hinder DMUII design?

This research aims to address these questions by assessing differences in construction performance between projects that have DMUII and CII designs. This research also aims to assess and identify strategies that can greatly improve the construction of DMUIIs. For this effort, interviews and surveys were conducted with stakeholders, including consultants, designers, and contractors with experience working on DMUII projects, and were designed to understand the inhibitors that hinder the selection and construction of DMUII projects. To reinforce the findings from the interviews and surveys, a field study was undertaken that monitored three projects under construction in North Carolina. The projects were monitored for ten months and the inhibitors that affected these projects were documented and recorded.

To validate the information related to the identification of inhibitors that affect projects with DMUII designs, this research utilized North Carolina Department of Transportation data (records of claims, supplemental agreements, costs, and schedules) for projects that already had been constructed or were currently under construction. These datasets allowed for the identification of inhibitors that affect the cost and schedules of projects with DMUII designs. The top five inhibitors identified are utilities, contract changes, signal and signage, traffic control, and material estimate change.

In addition, this research conducted a case study to evaluate roadway congestion and detour operations resulting from WZTC measures. The case study assessed the performance of DMUIIs and CII designs in terms of travel time, roadway congestion operations, and road users' costs, aiming to identify the impact of the construction process. The findings indicated that roadway congestion operations vary depending on the applied control measures. However, although the results obtained from the three approaches provide a reasonable comparison of the roadway congestion operations caused by WZTC on a DDI and CII, further studies are needed to determine their performance. The findings shed light on the complexities of WZTC in both CII and DDI projects, and their implications for travel time, roadway congestion operations, and RUC.

Effective methods to enhance the constructability of projects with DMUII designs were identified in this research and these include constructability reviews, modularization and prefabrication for bridge construction, automation, and 3D/4D modeling. The lessons learned and best practices obtained from the findings of this research have been documented and can be used to formulate construction strategies that will contribute to the improvement of DMUII construction. The findings can be implemented by any department of transportation that is seeking to facilitate the construction of DMUIIs to solve serious traffic volume problems while maintaining safety.

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INTRODUCTION

In 2017, the infrastructure report card published by the American Society of Civil Engineering (ASCE) indicated that America's transportation infrastructure was performing poorly, with a failing grade of D. At the time, restoration efforts to bring this grade up to a passing grade of C were estimated to require $1.5 trillion in funding (ASCE 2017). In the latest 2021 ASCE infrastructure report card, America's roadway infrastructure again received a failing grade of D, despite approximately $786 billion having been spent since 2017 on restoration efforts related to transportation infrastructure (ASCE 2021). In 2022, the United States Congress passed the Bipartisan Infrastructure Law, which will provide over $2.2 billion in funding to finance 166 transportation infrastructure initiatives in both rural and urban areas. Allocated funds were set aside to improve the condition of transportation infrastructure which includes roads, bridges, transit, rail, ports, and intermodal transportation (U.S. DOT 2022).

Despite these investments, failing grades continue to be received because departments of transportation (DOTs) are utilizing their resources (primarily public funds, which are typically limited) on restoration efforts that focus on solving immediate problems but in some cases fail to account for future needs. Both the restoration of current infrastructure and the creation of new sustainable infrastructure are needed to combat deterioration and accommodate population growth impacts. A possible solution to this problem is promoting the construction of diverse, modern, and unconventional intersections and interchanges (DMUII) that have the potential to improve traffic flow, capacity, and safety, especially in highly congested and spatially constrained areas.

DMUIIs offer numerous designs that include partial cloverleaf, single-point urban interchanges, diverging diamond interchanges, quadrant roadways, grade-separated quadrants, continuous flow intersections, reduced conflict intersections, echelons, roundabouts, and others. Although multiple benefits are associated with DMUIIs, their diversity presents unique design, construction, and constructability challenges to stakeholders (state transportation agencies, consultants, and contractors). Since DMUII designs are relatively new, they are also unfamiliar to the public who must navigate them and to contractors who must construct them. Shumaker et al. (2012) first documented that projects with DMUII designs often are perceived to require additional time and cost compared to conventional intersections and interchanges (CII) designs. The main reason for this perception is that DMUIIs often have unique construction challenges that require an understanding of best practices that evolve in an industry over time and are known only through experience. When projects with new designs are being built, experience is lacking and new best practices need to be developed. Therefore, this research aims to address shortcomings associated with DMUIIs and assess the impact of project costs and schedules on DMUII construction.

Background

Improving the transportation infrastructure in the United States can be achieved by promoting innovative design solutions that address current and unforeseen issues. However, research is lacking in ways to distinguish construction practices between DMUII and CII designs. Mistakes and omissions in design documents can lead to construction problems that cause delays and cost overruns. Similarly, but less commonly recognized, unfamiliar designs such as DMUIIs lead to projects that encounter obstacles due to their newness and their uniquely different construction characteristics. This research aims to address gaps in the body of knowledge by developing practical applications that enhance the construction of DMUII.

Alternative Intersections and Interchanges

Tables 1.1 and 1.2 present a full list of all DMUII design types found in the literature. Table 1.1 presents the list of alternative intersections and identifies the designs as being either at-grade or grade-separated. Table 1.2 presents the list of alternative interchanges, all of which are grade-separated. Although a variety of DMUII designs is available, this research focused on five DMUII designs. Two of these designs are at-grade intersections, one is a continuous flow intersection (CFI), and the other is a reduced conflict intersection (RCI). The remaining three designs are grade-separated DMUII designs: echelon intersection (EI), quadrant roadway (QR) intersection, and diverging diamond interchange (DDI). The five designs of interest are highlighted in gray on the tables. Also, because a naming system for DMUII has not yet been standardized and is currently inconsistent, both tables provide the most widely used name for each DMUII type and also list any additional names associated with each DMUII type.

Table 0.1 Type of Alternative Intersections

Type	Name	Abbreviation	Additional Name(s)
At grade	Continuous flow intersection	CFI	Displaced left turn; crossover displaced left turn; double crossover intersection; left turn bypass; crossover intersection; parallel flow intersection; synchronized split-phasing.
At grade	Reduced conflict intersection	RCI	Superstreet; J-turn; restricted crossing U-turn; reduced conflict U-turn; synchronized street; super street median; super street direct major street left turns; super street indirect major street left turns; and superstreet with direct super street left turns.
Grade separation	Echelon intersection	EI	-
At grade	Quadrant roadway	QR	Loop intersection; single loop.
Grade separation	Quadrant roadway	QR	Loop intersection; single loop.
At grade	Jughandle	JI	New Jersey jughandle and mini cloverleaf intersection
At grade	Continuous green-T	CGT	Continuous-T; turbo-T; high-T; Florida-T; Florida green-T; seagull intersection; and offset T-intersection.
At grade	Split intersection	SI	-
At grade	Median U-turn	MUT	Michigan left; thru-turn; median U-turn crossover; boulevard turnaround; boulevard left.
At grade	Roundabout	RI	Mini roundabout.
Grade separation	Roundabout	RI	Mini roundabout.
At grade	Bowtie	BI	-
At grade	Tandem intersection	TAI	-
At grade	Directional Y	DY	-
At grade	Alternative design -4 left	AD-4L	-

Table 1.1 Type of Alternative Intersections

Type	Name	Abbreviation	Additional Name(s)
Grade separation	Flyover	FI	-
At grade	Directional left	DL	-
Grade separation	Two levels signalized	TLS	-
Grade separation	Double crossover intersection	DXI	-
Grade separation	Parallel flow intersection	PFI	-
At grade	Continuous green-T	CGT	Continuous-T; turbo-T; high-T; Florida-T; Florida green-T.
Grade separation	Center turns overpass	CTO	-
At grade	Double wide	DW	-
At grade	Paired intersection	PI	-

Table 0.2 Types of Alternative Interchanges

Name	Abbreviation	Additional Name(s)
Diverging diamond interchange	DDI	Double crossover diamond interchange; split diamond; compressed diamond interchange; tight urban diamond interchange; half diverging diamond interchange; simple diamond; three-level diamond interchange; volleyball interchange; upstream signalized crossover; and tight urban diamond interchange.
Roundabout interchange	RI	Single raindrop interchange; bridged rotary; frontage road interchange; single roundabout interchange; frontage road interchange; double raindrop interchange; and two-way frontage road interchange.
Upstream signalized crossover	USC	Signalized crossover; direct left-downstream; and direct left-upstream.
Turbine interchange	TI	-
Contraflow left	CL	-
Median U-turn Interchange	MUT	Michigan urban.
Single point urban interchange	SPUI	Single point interchange (SPI); single point diamond interchange (SPDI); and single point left (SPL).
Trumpet	TRI	-
Left flyover	LF	-

At-Grade Intersections

At-grade designs are characterized by their ability to improve capacity at bottleneck intersections (He et al. 2016). This Section 1.1.1.1 provides the geometric design characteristics and locations of operational, under construction, and under consideration intersections for at-grade designs of CFIs and RCIs.

Continuous Flow Intersection

A CFI is an alternative intersection design that aims to reduce the number of conflicts at the main intersection. Instead of dealing with both left turning traffic and traffic in the opposite direction, the conflict is eliminated in a CFI by directing the left turn traffic to the left side of the roadway. Figure 1.1 presents a CFI conceptual design. The crossing from the right side to the left side is accomplished at a midblock signalized intersection for each approach that includes continuous flow lanes (NCDOT 2018). CFIs are ideal for intersections with high through and left turn volumes because they allow the traffic to move through the intersection without causing delays. CFIs are also beneficial for minimizing U-turn movements (NCDOT 2018). This design is extremely flexible and can be implemented from only a single leg to all four legs of the intersection depending on the traffic volume.

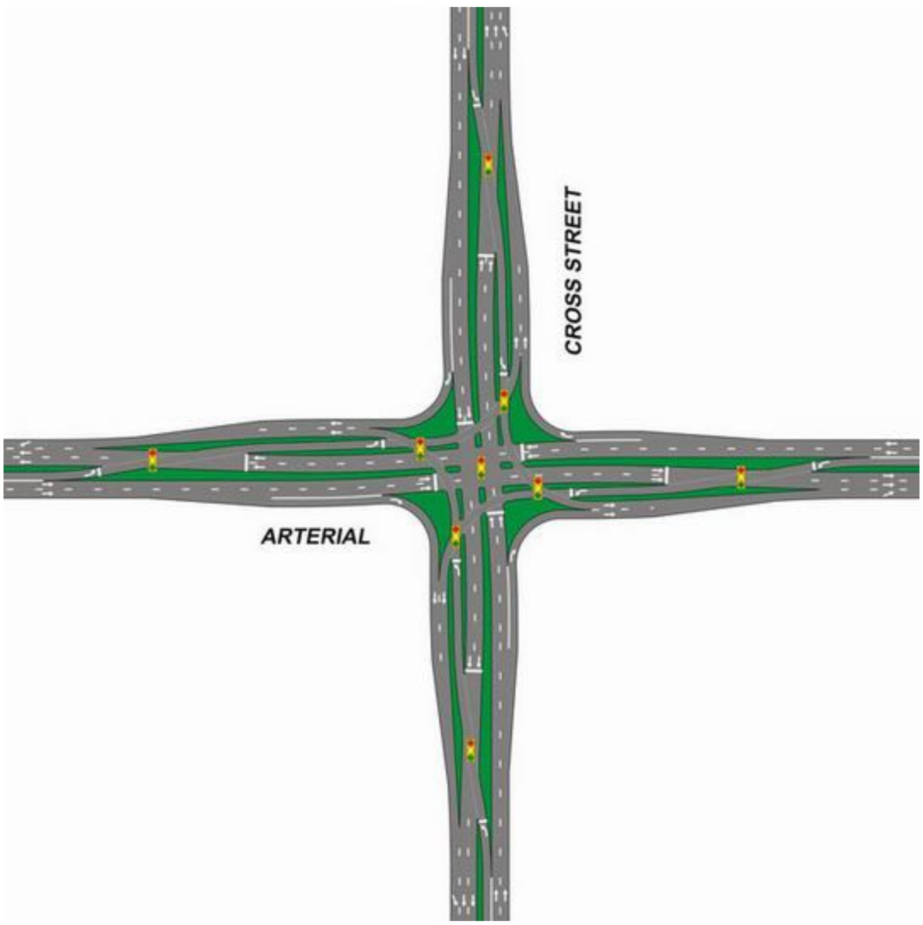

Figure 0.1 Conceptual Design of Continuous Flow Intersection (Reid 2004)

The first CFI in the United States was built in New York in 1995 (Hummer 2020; Hummer 2019). Since then, more than 13 have been constructed around the world: 1 in Germany; 1 in the United Kingdom; 10 in Mexico; and 1 planned for construction in Australia. The United States has about 40 CFIs. Figure 1.2 shows the locations for planned and constructed CFI projects in the United

States. These location data were obtained from the Alternative Intersections and Interchanges database (Institute for Transportation Research and Education 2013), the Alternative Intersections report (Institute for Transportation Research and Education 2013), and information provided by the North Carolina Department of Transportation (NCDOT). Note that these databases are not up to date and the information presented in these maps is limited to the data available.

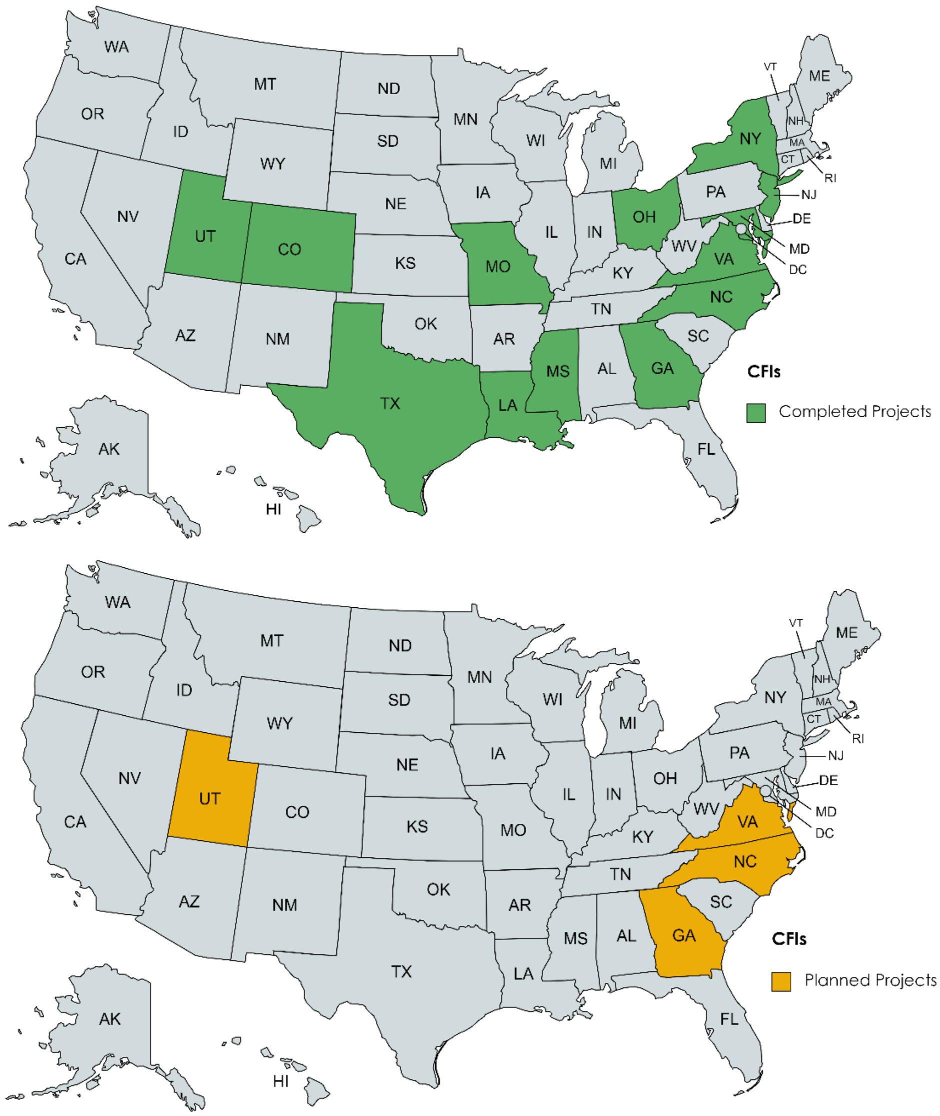

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Figure 0.2 Locations of Completed and Planned Continuous Flow Intersections in the United States

Reduced Conflict Intersection

RCIs redirect left turn and through movements from the minor street. Figure 1.3 presents an example of this design configuration. As shown, the RCI accommodates side street traffic movements by adding a U-turn. It requires drivers to turn right on the main road and then incorporate a U-turn maneuver (Hughes et al. 2010). The movement of traffic in an RCI is considered to be ideal for arterials that have a dominant flow on major roads. This design has the potential to improve arterials with high volumes of traffic because it moves more vehicles efficiently with minimal disruptions to adjacent development. Note that RCIs are different from median U-turns (MUTs), which re-route all four left turn movements at the intersection, whereas RCIs re-route the left turns and through movements of minor streets (Hummer 2019; Hummer 2020).

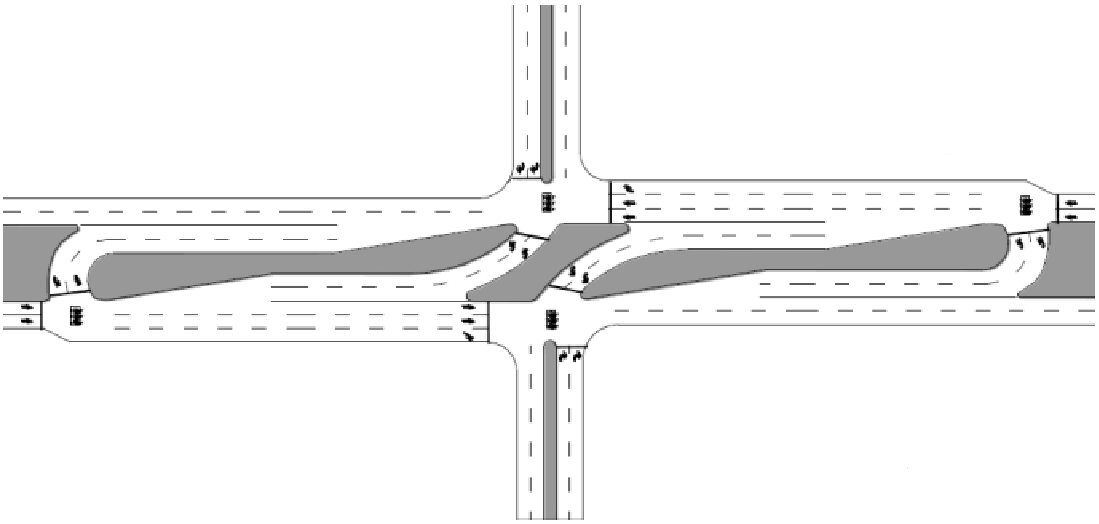

Figure 0.3 Conceptual Design of Reduced Conflict Intersection (Hummer et al. 2014)

RCIs were first developed in the 1980s (McClure 2023). Currently, North Carolina has over 100 unsignalized intersections and over 10 signalized corridors (Hummer 2019; Hummer 2020). Currently, no information is available regarding the total number of RCIs worldwide. Data collected from the Alternative Intersections and Interchanges database (Institute for Transportation Research and Education 2013), the Alternative Intersections (Metro Analytics 2021), and information provided by the NCDOT yielded a total of 158 RCIs in the United States, with North Carolina having the largest number of RCIs in the country. Figure 1.4 shows states with RCIs, but does not distinguish among locations with RCIs constructed, under construction, or planned. Because information obtained from the data sources is limited, the information retrieved for states with RCIs might not be accurate.

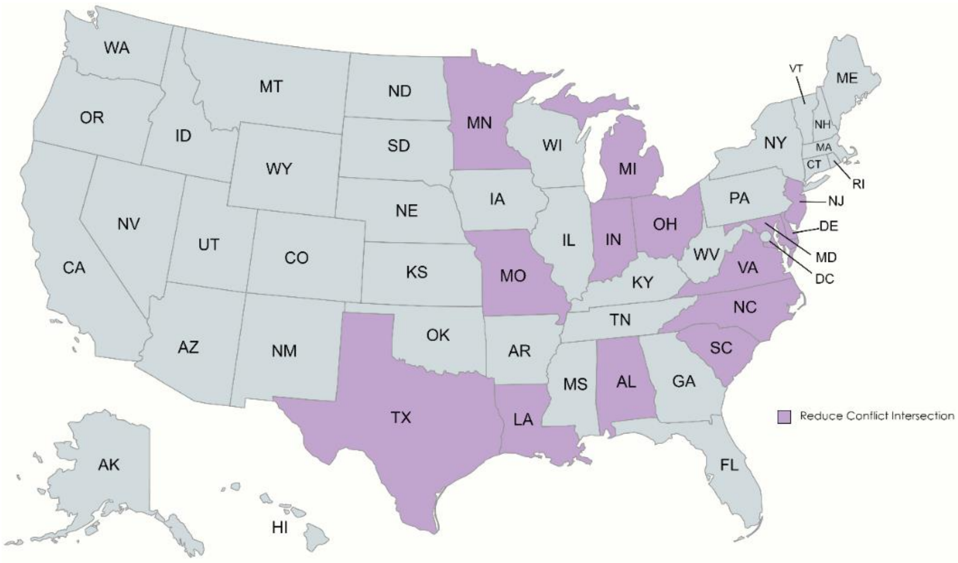

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Figure 0.4 Location of Reduced Conflict Intersections in the United States

Grade Separated Intersections

Intersections that experience high volumes of both vehicular and pedestrian traffic are prone to suffer capacity issues (He et al. 2016). When conventional measures are not feasible or are no longer adequate to address this concern, grade separation may be a feasible countermeasure to improve traffic conditions (Almoshaogeh 2020). Grade separation reduces the number of conflict points by separating them and allowing uninterrupted traffic flow while eliminating the safety threat to pedestrians or other vehicles (He et al. 2016). Section 1.1.1.3 provides the geometric design characteristics and locations of operational, under construction, and under consideration intersections of grade-separated intersection designs that use EI, DDI, and QR types.

Echelon Intersection

An EI divides traffic movements by separating the traffic direction into two levels, which allows having a signal system with two two-phase one-way pairs (one elevated above the other) (Shin et al. 2008). Figure 1.5 presents a configuration of an EI design. Each intersection operates independently and operates similarly to CII one-way streets, which allows for fewer overall turns compared to a standard four-leg intersection. Thus, an EI design allows intersections to operate at lower cycle lengths (less waiting time at intersections) and is ideal for locations with heavy traffic on both the main and side streets and for locations with a limited right-of-way for expansion (Virginia DOT 2021). EIs have a level of service (how well an intersection meets the demand in terms of mobility, safety, and comfort) that is better than other interchange alternatives (Miller Consulting 1999). However, EIs are not flexible enough to respond to varying directions of traffic flow and can respond only to predetermined routes of flow. Due to the design characteristics of an EI, retaining walls are needed to elevate half of the roadway while the other half is at grade (Virginia DOT 2021). The EI accommodates pedestrians at grade by providing sidewalks and crosswalks. Overall, EIs are intended to increase efficiency and reduce wait times by reducing signal phases and thus is a design that could potentially save construction costs. They also can have a narrower cross-section, which is less expensive to construct than a traditional diamond interchange (Virginia DOT 2021).

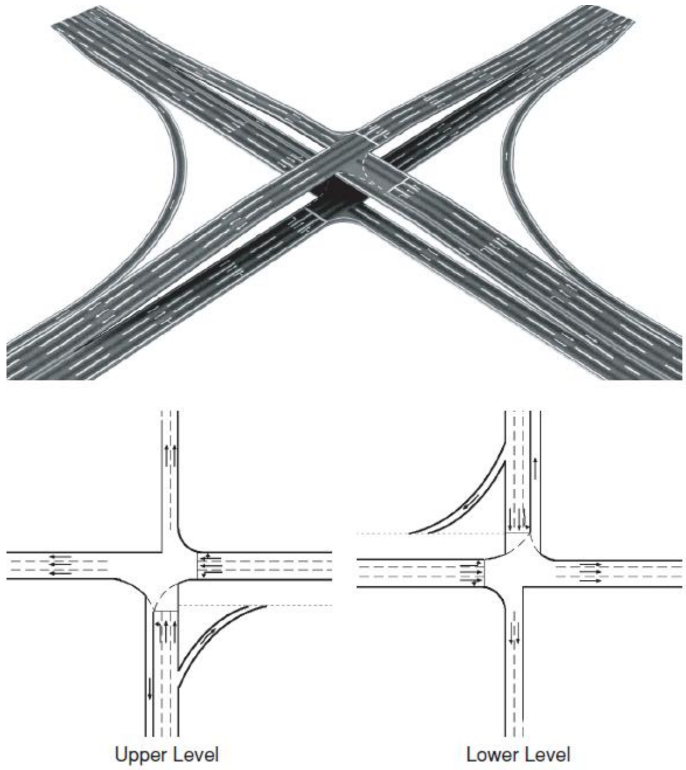

Figure 0.5 Conceptual Design of Echelon Intersection (Shin et al. 2008)

The first EI was built in 2000 for a single intersection improvement project in Aventura, Florida. The design was named ‘echelon’ by Don Beccasio, a Florida Department of Transportation Planning Division employee who worked on the initial design application (Reid 2004). Currently, this EI in Aventura, Florida is the only EI in the world. However, a new project in Florida is expected to be constructed at Apopka in Orlando (Florida DOT 2021). As of 2023, the Apopka project is the only one at the design phase and construction was planned to begin when funds became available. Due to the lack of Echelon projects, it was not possible to provide any guidance on the constructability of Echelon. If ay future Echelon are built, it is recommended to assess their constructability.

Grade-Separated Quadrant Roadway

The grade-separated QR is a variation of the at-grade QR which was first published in 2000 (Reid 2000; FHWA 2009). This design adds an overpass at the main intersection, which substantially improves the operations of the intersection (NCDOT 2018). This QR configuration eliminates all left turns at the intersection by building an additional roadway section in one intersection quadrant (Hughes et al. 2010). Figure 1.6 shows an example of a single QR with grade separation. One of the main design concerns for QRs is the right-of-way and properly identifying the characteristics of the site. Multiple factors are important for site selection, such as choosing a quadrant in which to locate the connecting roadway, determining the number of connecting roadways, and designing the main intersection, the secondary intersections, horizontal alignment, and the cross-section of the connecting road (Hughes et al. 2010).

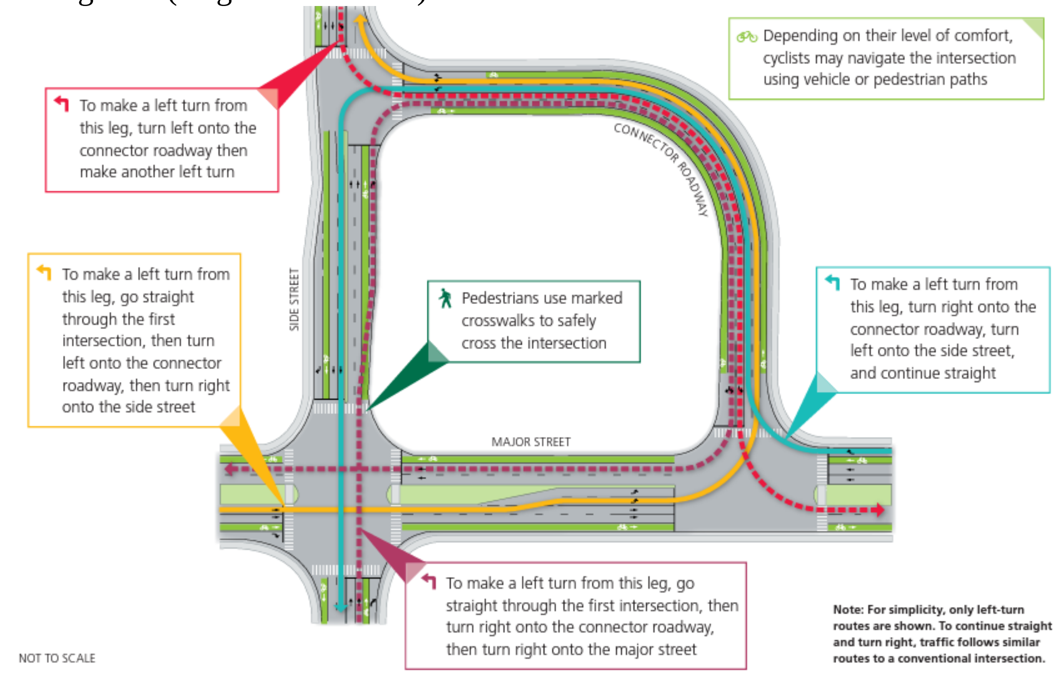

Figure 0.6 Conceptual Grade-Separated Quadrant Roadway Design (Virginia DOT 2021)

The national and worldwide databases that list the locations of QRs include do not make a distinction of at-grade and grade-separated QRs (Institute for Transportation Research and Education 2013; Metro Analytics 2021). In addition to QRs in the United States, four proposed projects were found for Canada and one has been constructed in Australia. Figure 1.7 shows the locations of the QRs in the United States. Note that Figure 1.7 includes only projects that have been completed or are in the planning phase, as no information related to projects currently under construction was found.

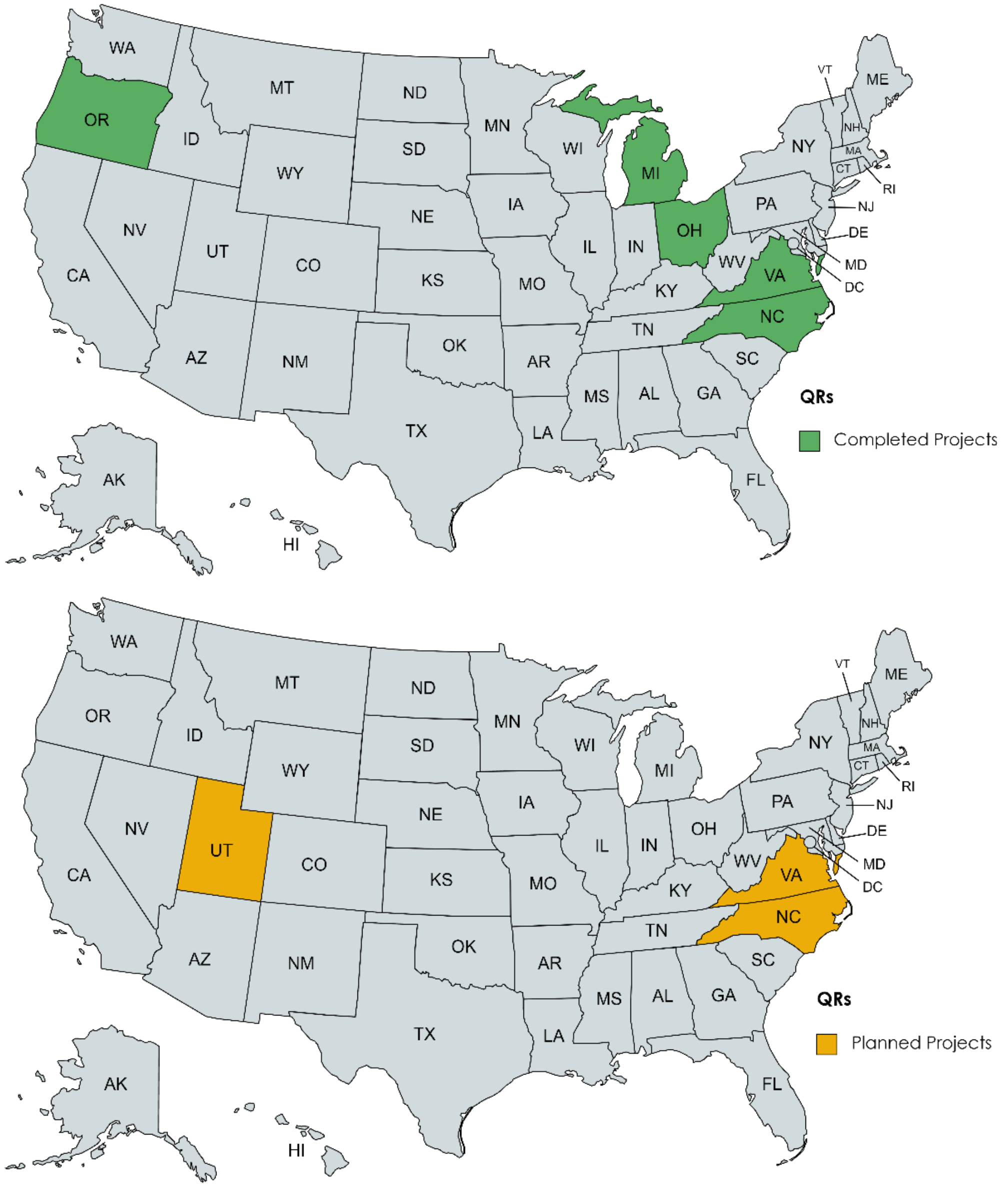

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Figure 0.7 Constructed and Planned Quadrant Roadways in the United States

Diverging Diamond Interchange

A DDI accommodates left turn movements and limits access from the main road while eliminating the need for a left turn signal phase at signalized ramp terminals. Figure 1.8 presents a conceptual design and traffic movement of a DDI. This new design can improve traffic flow and reduce congestion, especially for traffic with high left turn volumes on freeways. A significant design characteristic of DDIs is the redirection of traffic to better accommodate incoming volumes (Shaw and Chlewicki 2016). The main road is connected to the cross street by two on-ramps and two off-ramps, which is similar to a conventional diamond interchange. However, for a DDI, the traffic on the cross street moves to the left side of the roadway between the ramp terminals, which allows the vehicles that need to turn left onto the ramps to continue to the on-ramp without conflicting with the oncoming through traffic (Hughes et al. 2010). As in a conventional diamond design, the right turn movements from the cross street to the ramps occur at the ramp terminal intersections.

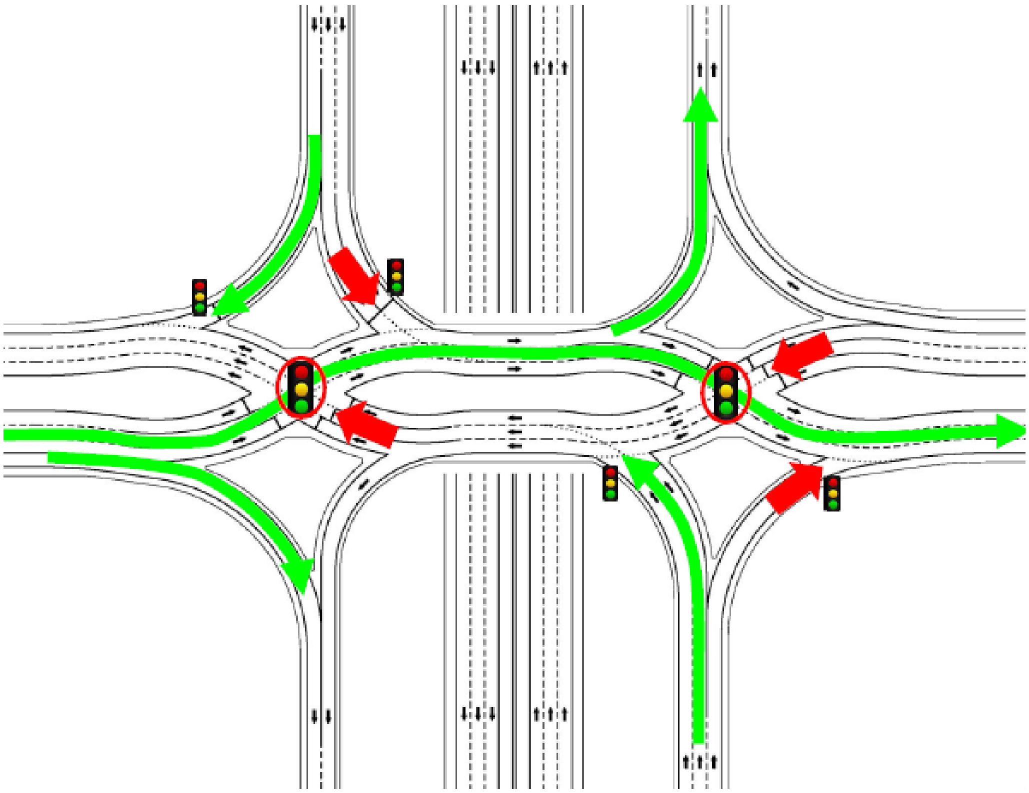


Figure 0.8 Conceptual Design of Diverging Diamond Interchange (Wisconsin DOT 2013)

The first DDI in the United States was built in Missouri in 2009 (Hughes et al. 2010). Currently, two DDIs are in operation in France, one in the United Arab Emirates, two are proposed, and one is under construction in Australia, and five are proposed and two are in operation in Canada. The majority of DDIs are constructed in the United States. Figure 1.9 shows that only three states (North Dakota, Connecticut, and New Jersey) do not have plans to incorporate DDIs, 31 states have operational DDIs, around 7 states are in the advanced design stage, and 8 states are in the study phase. North Carolina has 13 operational DDIs, 6 under construction, and 6 proposed or in the planning stage.

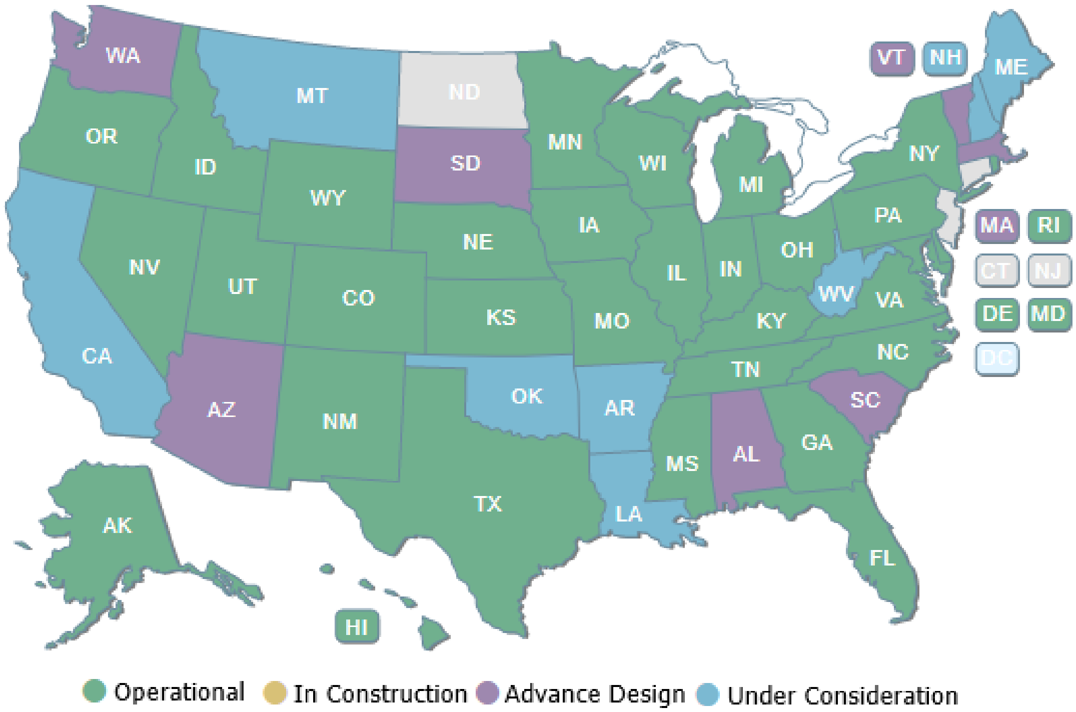


Figure 0.9 Status of Diverging Diamond Interchanges in the United States (ATS/American 2021)

Literature Findings

An extensive literature review was conducted to investigate the current state of research into DMUII designs and their unique characteristics as well as to identify the need for future work related to strategies for improving the construction of DMUIIs. This information has been submitted to the NCDOT and is attached as a separate file. The important findings obtained from the literature review are summarized in the remainder below.

Some general literature findings indicate that DMUII provides benefits such as improved safety, increased mobility, higher cost benefits, and reduced traffic signal phases. In the United States, North Carolina has the most DMUIIs being constructed and the largest number of RCIs under construction. Limited resources are available that specifically address construction practice assessment for DMUIIs. Therefore, the use of lessons learned is critical for improving constructability practices. Lessons learned can be incorporated into projects through constructability review (CR) programs. CR programs are not standardized nationally, so each DOT has its approach to assessment. The NCDOT uses CRs to address constructability issues but does not mandate a CR for all projects, and no protocols are currently available for all types of designs. An effective CR program could be useful for ensuring the success of projects with DMUII designs because it could provide several benefits, including better communication between design and construction engineers, potential cost savings, risk reduction, and schedule acceleration. For example, utility conflicts are a major challenge when trying to enhance constructability practices in the design phase and for bridge construction in urban and rural areas. A CR program could help to address this problem.

At the time of this research, Building Information Modeling (BIM) and 3D modeling were being used by only 19 DOTs for visualization, detailing, design, and analysis of transportation projects. The NCDOT is currently implementing 3D modeling for its projects but is still in the early stages. 3D modeling has the potential to identify construction interference and sequencing problems before projects are built; however, there is no consistency in ways to produce the 3D models, which leads to the models not being useful. However, when 3D modeling overcomes this inconsistency problem and DOTs implement a more standardized method to create models, the technology will have a positive impact on project performance because contractors will have an alternative method to improve their efficiency. For example, utility companies can use 3D-engineered models for accurate mapping and subsurface utility engineering. Further, clash detection, a 3D modeling feature, can detect utility conflicts early in the design process, avoiding additional time and costs.

Another important enhancement technique is the use of modularization and prefabrication (M&P). Best practices include accelerated bridge construction, which can minimize construction impact and reduce delays. However, accelerated bridge construction presents issues related to work zone traffic control (WZTC), mobility, cost, seasonal constraints, project schedule, technical feasibility, risk, site, and structural considerations. To ensure the maximum benefits of M&P, these inhibitors need to be addressed during design. Automation is beneficial for transportation projects and can enhance productivity. The construction industry is experiencing a labor shortage, and therefore, making use of automation technologies can be useful. However, tasks that require precise control (i.e., activities such as excavation and trenching) may not be suitable for automation.

Efficient staging and sequencing of activities are important for project success. Benefits include having more buildable, cost-effective, and maintainable projects. Projects that involve innovative practices such as DMUII designs require special attention to staging considerations to enhance construction. Another important consideration is the use of performance metrics, which are essential for evaluating the success of an activity and can simplify complex tasks while improving consistency. However, at the moment, no performance metrics are available for tracking the impact of certain processes, such as CRs, modularization, prefabrication, automation, 3D modeling, and staging.

When evaluating construction inhibitors of DMUIIs, the literature findings indicate that, in general, DMUII designs tend to be more expensive than CII designs, but the long-term benefits in terms of capacity and efficiency justify the additional cost. Of all the DMUIIs evaluated for this research, the DDI is the only DMUII design that does not require additional right-of-way compared to CIIs, which could indicate that the DDI is the only cost-effective design. For WZTC considerations, limited information was found regarding planning strategies for DMUIIs. Adequate planning for staging is also important. Another significant finding is that the actual construction activities for DMUIIs are not significantly different from those of CII; however, during construction, guidance for navigation through the new designs, which require different driving patterns, is critical.

Strategies to improve project performance were identified throughout the literature. These strategies include changing the structure for awarding projects to consider contractor performance, low bids, and project attributes such as quality and time. Another strategy suggests consistently documenting inhibitors that are related to constructability and assessing them throughout the project to learn from them for future projects. Gaps in the literature include:

- A lack of guidelines for the construction of DMUII designs. Specific areas that require attention must be identified and ways to implement these guidelines must be explored to ensure enhanced designs.
- A notable absence of records that document lessons learned from best practices in DMUII construction projects at both the national and state levels. This gap must be addressed to capture valuable insights that can be utilized for future projects.
- Information about inhibitors and enhancers for DMUII construction. Constructability inhibitors and constructability enhancers that have the potential to impact the construction of DMUII projects negatively or positively must be identified. Once enhancement techniques are identified, a thorough assessment of their respective impacts on DMUIIs needs to be conducted.

Research Objectives

Although some efforts to improve constructability in transportation projects have been made, little research has been conducted that targets the implementation of these efforts for DMUII designs specifically. To address this shortcoming, this research aims to identify constructability problems that hinder DOTs from widely and successfully adopting DMUIIs. To achieve this goal, the following objectives will be addressed:

1. Identify construction inhibitors for the DMUII designs of interest.
2. Assess the differences and effectiveness of construction performance between projects with DMUII and CII design.
3. Assess the impact of WZTC measures on DMUII and CII projects in terms of handling congestion.
4. Identify the most promising construction enhancement approaches that can aid in the mitigation or reduction of inhibitors affecting projects with DMUII design.

Significance of the Research

Little information is currently available about ways to improve the construction of DMUII projects. No studies have applied constructability practices or CR concepts to DMUII projects. This research helps advance the state of knowledge by identifying and providing a better understanding of the constructability inhibitors that affect DMUIIs and identifying enhancers to address the inhibitors in a cost-efficient manner. The results can be used as part of a set of new consensus guidelines to enhance the constructability of DMUIIs and to provide an analytical approach to help transportation infrastructure personnel (in the United States and globally) identify constructability problems during design and construction phases so that corrections can be made quickly to mitigate cost and schedule overruns. The results from this research also can be applied to other types of infrastructure construction projects (buildings, bridges, dams, etc.) and eventually, help promote the construction of more sustainable infrastructure, save lives, save money, and reduce congestion.

Research Scope and Limitations

The data for this research were obtained from the NCDOT and pertained only to retrofit projects with design bid build contracts. A retrofit project modifies or improves existing infrastructure to enhance the performance and sustainability of that existing structure. In North Carolina, most DMUIIs have been designed as retrofit projects, and therefore, the focus is limited to this type of project. This research is limited to its use of NCDOT data. Nonetheless, the findings are summarized in a manner that can lead to the implementation of recommendations that are applicable beyond North Carolina. Some of the proposed strategies are expected to be relevant for the long term, whereas other recommendations, such as those that apply to the top inhibitors that affect specific designs, may require periodic revision as additional data become available for analysis.

Report Organization

This report is organized into chapters that respectively discuss the analyses performed in this research.

- Chapter 1 presents the introduction to this research, objectives, significance, scope, limitations, a list of abbreviations, and definitions.
- Chapter 2 presents the findings derived from interviews, surveys, and field study projects, which effectively identify inhibitors that significantly impact DMUIIs.
- Chapter 3 presents significant findings that identify construction inhibitors that impact DMUIIs, as evidenced by claims and supplemental agreement data. These inhibitors are then compared to the inhibitors that affect CII projects, to gain a comprehensive understanding of the distinctions between DMUII and CII projects.
- Chapter 4 provides findings based on an evaluation of DMUII and CII project performance, with a focus on cost and schedule data.
- Chapter 5 describes a case study that evaluates roadway congestion that is due to WZTC measures implemented for a DMUII and a CII project.
- Chapter 6 discusses the identified construction enhancers for the improved construction of DMUII projects.
- Chapter 7 offers a conclusion that identifies the contributions, limitations, and future work derived from this research.

List of Abbreviations

The following abbreviations are utilized in this document:

- 3D: Three-dimensional
- 4D: Four-dimensional
- AADT: Average annual daily traffic
- AAA: American Automobile Association
- AASHTO: American Association of State Highway and Transportation Officials
- DMUII: diverse, modern, and unconventional intersection and interchange
- ATRI: American Transportation Research Institute
- ATC: Alternative technical concepts
- AVO: Average vehicle occupancy
- BIM: Building Information Modeling
- CII: Conventional intersection and interchange
- CFI: Continuous flow intersection
- CLEAR: Communicate Lessons, Exchange Advice, Record

- CM/GC: Construction manager/General contractor
- CR: Constructability review
- DB: Design build
- DBB: Design bid build
- DDI: Diverging diamond interchange
- DOT: Department of Transportation
- EI: Echelon Intersections
- FHWA: Federal Highway Administration
- GIS: Geographic information system
- M&P: Modularization and prefabrication
- NCDOT: North Carolina Department of Transportation
- NCHRP: National Cooperative Highway Research Program
- ORD: Open Road Designers
- QR: Quadrant roadway
- RCI: Reduced conflict intersection
- ROW: Right-of-way
- RUC: Road user cost
- TDC: Travel delay cost
- TTI: Travel time index
- VMO: Value Management Office
- VOC: Vehicle operating cost
- VOT: Value of time
- WZTC: Work zone traffic control

Definitions

1. **Diverse, Modern, and Unconventional Intersections and Interchanges (DMUII):** An intersection or interchange where one or more traffic movements are strategically rerouted from a conventional signalized intersection to remove or reduce major conflict points. DMUIIs also are referred to as alternative, nontraditional, novel, or innovative intersections.
2. **Actual project cost:** The total project cost at project completion.
3. **Actual project duration:** The total days required to complete the work for the project, also referred to as 'revised calendar days' in HiCAMS.
4. **At grade intersection:** When two or more surface streets intersect at grade level.
5. **BIM:** (Building Information Modeling) is a digital representation of the physical and functional characteristics of a project.
6. **Constructability:** The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives.
7. **Contract bid:** The winning bid is accepted by the NCDOT.
8. **Constructability review:** A process that utilizes extensive construction knowledge from contractors, designers, and construction experts early in the design stages of a project to ensure that the projects are buildable while also being cost-effective, biddable, and maintainable.

9. **Claims:** Requests (from contractors) to the NCDOT to perform contract modifications in terms of time or money to solve an issue found during construction. Claims can be submitted throughout the construction phase of a project.
10. **Cost difference:** The result of the comparison of the estimated project cost and the actual cost required to perform the work. These values are also referred to as 'overrun/underrun values.
11. **Estimated project cost:** The values of NCDOT's estimated project cost.
12. **Enhancers:** Promising construction concepts such as emerging technologies that have the potential to positively affect the construction of DMUII projects.
13. **Estimated project duration**: The estimated days needed to complete the work for the project, also referred to as 'project calendar days' in HiCAMS.
14. **Grade-separated intersection:** When two or more non-freeway streets intersect with a grade separation (requires a bridge).
15. **Inhibitors:** The factors that have the potential to negatively affect the construction of projects with DMUII designs.
16. **Interchange**: The intersection of a freeway and surface streets.
17. **Retrofit:** The process of modifying the layout/geometric design of an existing intersection or interchange.
18. **Supplemental agreement (**also known as a change order): An agreement between NCDOT and the contractor for a specific project. The contractor requests an amendment to the contract in terms of monetary compensation, time, or scope of the work as necessary to satisfactorily complete additional construction work that was not in the initial contract. The supplemental agreement process begins once a project has been awarded to a contractor. The contractor then reviews the contract and requests amendments.
19. **Schedule difference**: The result of the comparison of the estimated project duration and the final project duration that is required to perform the work.

The 19 definitions are the ones utilized in this research. Other terms that can lead to possible confusion include:

- Estimated project cost = original estimates, engineering estimates
- Inhibitors = factors, drawbacks, problems, etc.
- Supplemental agreements = change orders
- Cost differences = overrun/underrun values
- Estimated project duration = project calendar days

IDENTIFICATION OF INHIBITORS FOR CONSTRUCTION OF ALTERNATIVE INTERSECTIONS AND INTERCHANGES: INSIGHTS FROM STAKEHOLDERS' PERSPECTIVE AND FIELD STUDIES

This chapter focuses on the identification of inhibitors to the construction of diverse, modern, and unconventional intersections and interchanges (DMUII) designs. To do so, an online survey was distributed and virtual interviews were conducted to gather knowledge from stakeholders (consultants, designers, and contractors) with experience building projects with DMUII designs. The results were compiled and assessed to better understand the inhibitors that prevent DMUIIs from being selected and constructed. The results are promising and help Departments of Transportation (DOTs), contractors, and consultants to focus their resources on minimizing inhibitors to improve project performance. The results show that utilities and right-of-way are the most prevalent inhibitors that prevent DMUIIs from being selected and constructed.

Introduction

The United States had a particularly strong investment in transportation infrastructure (roadways) prior to WWII. This investment influenced the economic growth of the country and positioned the United States as an economic leader (Council on Foreign Relations 2021). However, since WWII, except for the interstate highway system, national infrastructure has not been optimally maintained. To address the effects of the aging and underperforming infrastructure, it is necessary to restore the existing infrastructure to optimal performance levels and to promote sustainable design, construction, and rehabilitation practices for new infrastructure. Doing so is more important due to the emergence of practices that promote more transportation networks, smart mobility, connectivity, and resilient systems (Raza et al. 2022).

DMUIIs are cost-effective, safe, sustainable, and efficient alternatives to the existing aging intersections and interchanges (Almoshaogeh et al. 2020). DMUIIs have the potential to improve traffic flow, capacity, and safety, especially in highly congested and spatially constrained areas (Almoshaogeh et al. 2020; Shaw and Chlewicki 2016). A reduction in vehicle emissions can be achieved by increasing capacity and improving traffic flow, which is a critical and sustainable step toward reducing negative climate impacts (Raza et al. 2022; Sabory et al. 2021). The benefits associated with DMUIIs often get overlooked due to their unique design, construction, and constructability challenges for the stakeholders (DOTs, consultants, and contractors). Similarly, since most DMUII designs are relatively new (around 10 years old), they are also unfamiliar to drivers. As a result, projects using DMUII designs are frequently perceived to require additional time and cost to build compared to conventional intersection and interchange (CII) designs.

Shumaker et al. (2012) first documented this shortcoming by noting that few DMUIIs see widespread use because they require unique construction approaches that mandate a deep understanding of best practices. However, these best practices are acquired gradually through experience. Without such experience, contractors face challenges when they design and construct DMUII projects. This chapter aims to address these issues by identifying construction inhibitors that could affect DMUII construction costs and schedules. It also aims to establish a framework for understanding why many DMUIIs are not widely and readily adopted for use, especially given their promise to improve both traffic flow and safety and generate more sustainable infrastructure. To do so, an online survey and virtual interviews were conducted with the stakeholders (consultants, designers, and contractors) involved in projects that had a DMUII design to identify the inhibitors associated with the design and construction process of the DMUIIs.

Literature Review

To enhance infrastructure sustainability, the building industry has developed sustainable building rating systems such as LEED, BREEM, Green Globes, and many more (Fantana 2013) to integrate design and construction to incorporate sustainability and green construction practices (Sabory et al. 2021). Such practices have been lacking in the transportation industry. This can be attributed to the fact that achieving sustainability in existing transportation facilities is not an easy task that can be achieved with a rating system or through the use of CII designs (Humble and Furtado 2010). However, sustainability can still be achieved with the promotion of sustainable designs such as DMUIIs. DMUIIs can improve operational performance, safety, and environmental performance (Sabory et al. 2021; OECD 2001).

DMUIIs have a large number of designs but not much information or detail is widely available for contractors on the unique differences between DMUIIs and CII and interchanges or on how to construct DMUIIs. This lack of information makes them appear to be complex for construction. There are multiple factors affecting project success that are highly dependent on the project type, size, and complexity (Shumaker et al. 2012; Wisconsin DOT 2013). For example, DMUII designs may appear to be more challenging and riskier due to the introduction of new products and technologies as well as the combined efforts of multiple contractors.

Alternative Intersection and Interchanges

Table 2.1 identifies some of the most relevant benefits of DMUIIs and their respective inhibitors. Findings from Wisconsin DOT (2013) indicated that an advantage of Continuous flow intersection (CFI) and quadrant roadway (QR) is that these projects have lower costs compared to the cost of building a full conventional interchange. The reduced conflict intersection (RCI) and diverging diamonds (DDI) are considered to be one of the safer designs for rural and urban locations. In addition, findings in Table 2.1 also indicate that the DDI design is the only one that typically does not require the acquisition of right-of-way (ROW).

Just like the benefits of DMUII, the inhibitors associated with the construction of each DMUII design are specific. The acquisition of ROW to construct the DMUII is a common disadvantage among CFI, RCI, and QR designs. Driver and pedestrian confusion are another inhibitor affecting CFI, DDI, and EI during construction and initial use. Additional maintenance costs due to special operations or the need for additional structures are inhibitors that are often associated with CFI, EI, and QR.

Table 0.1 Benefits and Limitations of Alternative Intersections and Interchanges

Design	Benefits	Limitations	Sources
CFI	• Ideal for locations with significant ROW. • Lower cost compared to a CII.	• Additional ROW for ramps. • Driver and pedestrian confusion. • Additional construction, maintenance, and operation costs.	Wisconsin DOT 2013; Furtado et al. 2003; Fitzpatrick et al. 2005
RCI	• Good safety performance in rural and urban areas.	• Additional ROW along the arterial roadway.	Furtado et al. 2003; Fitzpatrick et al. 2005; Hiddlebrand 2007; Hughes et al. 2010
QR	• Less expensive than a full CII. • Reduces total intersection system delay and reduces queuing.	• Bridge cost for pedestrians crossing. • High structure cost. • Driver and pedestrian confusion. • Additional structure maintenance.	Wisconsin DOT 2013; Fitzpatrick et al. 2005; Hughes et al. 2010
EI	• Increase efficiency. • Improve safety.	• Structure cost and maintenance. • Additional advance signing requirements. • Additional ROW is required for the QR.	Wisconsin DOT 2013; Fitzpatrick et al. 2005; Hughes et al. 2010; Virginia DOT 2021
DDI	• Minimizes ROW impacts. • Improve safety.	• Require additional pedestrian crossings. • Drivers' confusion due to the crossover.	Wisconsin DOT 2013; Hughes et al. 2010; Virginia DOT 2021

CFI: continuous flow intersection. **RCI**: reduced conflict intersection. **QR**: quadrant roadway. **EI:** echelon intersection. **DDI**: diverging diamond interchange.

In general, most DMUIIs designs have evoked strong resistance from the public due to their unfamiliar design and routing complexities. Public perception is considered the biggest obstacle preventing the wider implementation of DMUIIs. Unfortunately, few efforts have been made to address and improve the public perception of DMUIIs. A recent study by Brown et al. (2020) noted that public perception can be relatively negative before the projects are built, but it improves once the design is completed and the public becomes familiar with the design and its use, especially when they see the resulting improvements in traffic flow.

Another problem with DMUIIs is the contractors' lack of familiarity with (and negative perception of) their cost and time requirements (compared to CII designs). This perception is often rooted in the DMUII requirements for unique construction approaches to meet the specific challenges resulting from unique site characteristics (Shumaker et al. 2012). Therefore, when a new design is proposed, and there is limited prior construction experience with it, bid costs are high since contractors need to compensate for the risk associated with the new and unique unknowns of DMUII projects.

A common perception is that some DMUIIs are more expensive to build than CII designs, therefore these are not feasible for economic reasons (Olarte 2011). The difference in cost is typically associated with the additional ROW, additional signals and signs, the construction of grade separation, and in some cases, the cost of staging. The complexity of projects that have a DMUII design does incur high levels of organization and construction; therefore, the cost increases.

Table 2.2 identifies the construction cost requirements for each of the DMUIIs of interest. The first column identifies the design, the second column describes the findings related to the construction cost of that respective design, and column three identifies the source. Notice that only information about the cost of CFI, QR, RCI, and DDIs was found in the literature. Notice that from the DMUIIs of interest presented in this research, the cost associated with EI can be assessed as the cost associated with a grade-separated intersection, which is known for being costly compared to at-grade intersections (Shin et al. 2008).

Table 0.2 Alternative Intersections and Interchanges Construction Cost

Design	Construction Cost	Source
CFI	• Design cost is approximately 50% higher than CII. • Primarily due to increased footprint and associated additional ROW requirements. • The costs for ROW and new signal control will increase the cost. • More cost-effective and produce similar operational benefits compare to grade-separated designs.	Hughes et al. 2010; Steyn et al. 2014
RCI	• Cost 24% more than the CII designs. • More expensive to construct than a CII. This requires more ROW, extra signals and controllers, extra pavement, higher costs for traffic signal control, and construction staging. • Planning and design costs may initially be higher for the first few RCI intersections compared to a CII, in part because of extra public outreach, digital renderings, and traffic operation microsimulation video clips. • As RCIs become more common in an area, special efforts and costs will likely be reduced. • Actual project costs will vary depending on each project's location and unique contextual design environment.	Hughes et al. 2010; Hummer et al. 2014
QR	• The construction costs are likely higher than at a CII. • The incurred cost is attributed to the connector roadway, extra signals, and extra overhead signs.	Hughes et al. 2010
DDI	• The actual costs of designing and constructing are highly variable based on site-specific elements, particularly if a design is newly constructed versus a retrofit. • Extra cost is minimal compared to a CII design. • Additional costs are attributed to mobilization, overhead lighting, pavement markings, and drainage costs.	Hughes et al. 2010; Schroeder et al. 2014

CFI: continuous flow intersection. **RCI**: reduced conflict intersection. **QR**: quadrant roadway. **DDI**: diverging diamond interchange.

However, despite its cost, extensive research has been conducted on the benefits of DMUIIs and these benefits include improvements in traffic flow, capacity, and safety portion of it. Meng and Weng (2013) assessed the traffic delay of DMUIIs by utilizing queuing models and single or multiple sub-work-zone strategies. Sub-work-zone strategies are those that can be adopted to mitigate queue length and travel delays. In this same study, the researchers evaluated multiple approaches to evaluate how traffic affects capacity due to work-zone control measures.

Additionally, DMUIIs with at-grade designs are characterized by improving capacity at bottleneck intersections, and intersections experiencing a high volume of traffic and high volumes of pedestrians are prone to suffer capacity issues (He et al. 2016). Therefore, the ideal solution will be to opt for DMUII designs. For example, one of these designs is the DDI. In their study, Schroeder et al. (2014) mentioned that DDI projects are ideal for constraint areas since this design generally fits within the existing interchange ROW and bridge structure.

In another study performed by Brown et al. (2016), space constraints, phasing, and safety considerations were evaluated. The findings indicated that detouring traffic away from construction is ideal for safety and operations; however, if maintaining the existing intersection operation with all movements as long as possible at the main intersection is needed, consideration of factors that affect construction timing should be made. Some of these activities that can be monitored to address safety with phasing are construction work related to drainage, utility movements, and other situations that can affect projects. Depending on the specific location, multimodal accommodations for pedestrians, bicycles, and disability accommodations can also be considered.

Table 2.3 summarizes how safety is enhanced based on the number of conflict points, collision rates/crashes, human factors, signal progression, and sight distance. From the conflict point perspective, if compared to a CII signalized intersection, all DMUII designs have a better performance. A similar trend can be observed in the collision rate reduction, with all DMUIIs reporting a decrease in fatal/injury collisions. Nonetheless, the results oscillate greatly from study to study and the analysis type being performed. It can also be noted that even though the majority of DMUII designs improve safety considerations for pedestrians and bicyclists, there is a great deal of confusion from drivers and pedestrians about how to navigate through these designs. Concerning signal progression, DMUII designs improve signal timing by separating movements.

Table 0.3 Alternative Intersections and Interchanges Safety Performance

Design Type	Conflict Points	Collision Rates/Crash Reduction	Human Factor	Signal Progression	Sight Distance	Sources
CII	32	-	Standard configuration, well understood by drivers. Drivers' confusion is prone to unsignalized intersections	• Inefficient operation due to many movements • Sight distance concerns	-	Hughes et al. 2010; Brown et al. 2020
RCI	12-20	Injury crash reduction of -42% up to -54%	Potential driver, pedestrian, and bicyclist confusion	Signal controllers for one direction of the arterial roadway operate independently from the opposite direction	Limitations at crossovers	Hughes et al. 2010; Brown et al. 2020; Hummer et al. 2014; Hummer and Jagannathan 2008
QR	16-28	-	Potential for illegal left turn, driver, and bicyclist confusion	Two-phase signal at the main intersection and a three-phase signal at a connecting road	-	Hughes et al. 2010; Brown et al. 2020
DDI	8-12	Fatal/injury crash reductions of -41% up to -68%	Driver and pedestrian confusion	Two-phase signals	-	Hughes et al. 2010; Brown et al. 2020; Schroeder et al. 2014; FHWA 2017
CFI	28	Fatality and injury crash reductions of -18.9%	Potential driver, pedestrian, and bicyclist confusion	Shorter cycle lengths	-	Hughes et al. 2010; Brown et al. 2020; Steyn et al. 2014

CII: Conventional intersection and interchange. **RCI**: reduced conflict intersection. **QR**: quadrant roadway. **DDI**: diverging diamond interchange. **CFI**: continuous flow intersection.

Construction Inhibitors

The success of a project that has a DMUII design is dependent on factors that have the potential to negatively affect its construction. These factors are referred to in this research as construction inhibitors. Table 2.4 identifies construction inhibitors that are typically associated with transportation infrastructure projects. Each inhibitor is associated with the literature source where they were found. The majority of the literature identified fabrication and assembly, foundations and soil conditions, safety, and construction/installation specifications as constructability inhibitors in their projects.

Table 0.4 Alternative Intersections and Interchanges Construction Inhibitors

Inhibitors	Source															Total
	Brown 2010	Goodrum et al. 2008	Terzioglu et al. 2016	Zhan and El Diraby 2006	Arzamendi et al. 2020	Bradshaw 2005	Furtado et al. 2003	Cadenazzi et al. 2020	Michelle et al. 2019	Sanchez and White 2012	Yang 2017	Concrete Opening 2020	Maves and Furrer 2020	Aktan and Attanayake 2015	Shafieifar et al. 2017	
Fabrication and assembly	X	-	X	-	-	-	-	X	X	-	-	X	-	X	X	7
Foundation and soil issues	-	-	-	X	-	X	X	-	X	-	X	-	-	X	-	6
Safety	-	-	X	-	-	-	-	-	X	-	-	X	X	X	-	5
Construction/Installation specifications	X	-	-	X	-	-	-	-	-	X	-	-	X	-	X	5
Design errors	-	X	X	-	X	-	-	-	-	X	-	-	-	-	-	4
Installation errors	-	-	X	-	-	-	-	-	X	-	-	X	-	-	X	4
Space constraints	-	-	-	-	-	-	-	-	X	-	-	X	X	-	-	3
Excavation slope	-	-	-	-	-	X	-	-	X	-	X	-	-	-	-	3
Cost	-	-	X	-	-	-	-	-	-	-	-	-	-	X	-	2
Workforce experience	-	-	-	-	-	-	-	X	-	-	-	-	-	X	-	2
Utility conflict	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	1

Gaps in Literature

The information provided in this literature section presents robust information about the state of practice. It was found that there is currently no information related to DMUII construction inhibitors. This chapter focuses on identifying the inhibitors to DMUII construction based on findings from interviews and surveys.

Methodology

Sample Size

To understand how engineers perceive projects with DMUII design, a study using surveys and interviews was performed. A group of 221 participants from multiple disciplines with previous experience in the construction, planning, and design of DMUII projects was compiled. The participants' backgrounds included roadway engineers, traffic engineers, geotechnical engineers, construction engineers, structural engineers, work-zone traffic-control engineers, and congestion managers. Participants were contacted to complete an online survey or schedule a virtual interview. The response rate was 34.8% (77 participants of the 221 contacted) and the participation was as follows:

- 29 participants (20 North Carolina Department of Transportation (NCDOT) personnel, 4 contractors, and 5 consultants) were interviewed.
- 28 additional responses were received from the North Carolina stakeholder survey (12 NCDOT personnel, and 16 contractors).
- 20 responses were received from multiple stakeholders in other DOTs. The participating DOTs include California, Colorado, Connecticut, Georgia (n = 3), Illinois, Indiana, Kansas, Kentucky, Maine, Minnesota, New Hampshire, New York, Rhode Island (n = 2), South Carolina, Tennessee, Utah, and Vermont.

A total of 32 were received responses from NCDOT personnel, 21 from consultants, 4 from contractors, and 20 from other DOTs, which is a sample size greater than the minimum needed (68 participants) to have a confidence level of 95% with a real value within ±10% of the measured/surveyed value.

Questionnaire

Two sets of questionnaires were developed to capture participants' responses. The first questionnaire included a total of 24 questions that were used to guide the conversation during the interviews (see a sample questionnaire in Appendix A). This questionnaire was used as a guide to direct the flow of the conversational data collection effort, but deviations in the questioning during the interviews allowed the research team to have greater latitude and to identify unanticipated responses. This was one of the advantages of the interview process.

The questionnaire, developed for the online survey, only contained 11 questions (see questionnaire in Appendix B). The questions asked in the survey were similar to those developed for the interview. However, the research team opted to shorten the online survey to capture the most relevant information from participants in a time-efficient manner for the participants.

Field Studies

Field studies were performed for three projects that were under construction in North Carolina at the time of this research. The purpose of field studies is to document construction in progress and gather data that enables the identification of construction inhibitors and document best practices. Table 2.5 presents the information for these three NCDOT DDI projects.

Table 0.5 Field Study Projects' Information

Design Type	TIP #	Division	Route	Across
DDI	U-2719	5	I-440	Western Boulevard
DDI	I-5700	5	I-40	Airport Boulevard
DDI	I-5111	5	I-40	NC-42
				Jones Sausage Road

DDI: diverging diamond interchange

Site visits to the projects were made at a frequency of approximately one per month for each of the field study projects for 10 months from June 9, 2022, to May 30, 2023. During the site visits, project engineers provided updates regarding any delay or identification of constructability inhibitors that were affecting the project.

Data Analysis

The surveys focused on details related to the identification of construction inhibitors, the identification of unique construction practices for DMUIIs, and the identification of sustainable practices that have the potential to enhance projects. The interview and survey participants were asked to identify their level of experience with DMUII projects.

The results from this inquiry are displayed in Table 2.6. Out of the 77 participants, 61 of them were familiar with the construction or design process of a DDI. Among these participants, RCI was the second most commonly mentioned design, with 39 responses. Following RCI, participants indicated familiarity with QR (n = 34), CFI (n = 26), and EI (n = 2). Furthermore, several additional DMUII designs were identified but classified as "Others" as they fell outside the scope of this research. The "Other" category encompasses roundabouts, single-point urban interchanges, and turbines.

Table 0.6 Participants' Familiarity with Alternative Intersections and Interchanges

Design	Total
Diverging Diamond Interchange	61
Reduced Conflict Interchange	39
Quadrant Roadway	34
Continuous Flow Intersection	26
Echelon Intersection	2
Other Alternative Intersections and Interchanges	15

The general findings from the interviews and surveys are presented below. In addition to general findings, the discussion session of this report presents lessons learned and documents best practices identified by interview and survey participants.

Participant's Familiarity with Alternative Intersections and Interchanges

During the interviews, participants were questioned about their familiarity with DMUII designs. The findings were tabulated based on the participants' job functions. First, note that contractors are left out of Figures 2.1 and 2.2 because contractors do not directly respond to this question. When contractors were asked about their familiarity with DMUII designs, they emphasized that while they may not be well-versed in the geometric and design aspects specific to DMUII projects, the construction process for these projects is similar to that of conventional designs they have previously worked on. Consequently, from the contractors' perspective, it is believed that DMUII designs do not require any specialized construction knowledge.

Figure 2.1 presents a side-by-side bar plot comparing job function and job familiarity. The results indicate that managers and consultants exhibit significantly higher levels of knowledge and familiarity with their respective roles compared to other job functions. Construction engineers appear to have the least familiarity with DMUII designs, suggesting the need to prioritize their training to ensure they become familiar with DMUIIs. Additionally, a substantial number of construction engineers and designers responded with “No Response,” highlighting the importance of further investigating their familiarity with the job function.

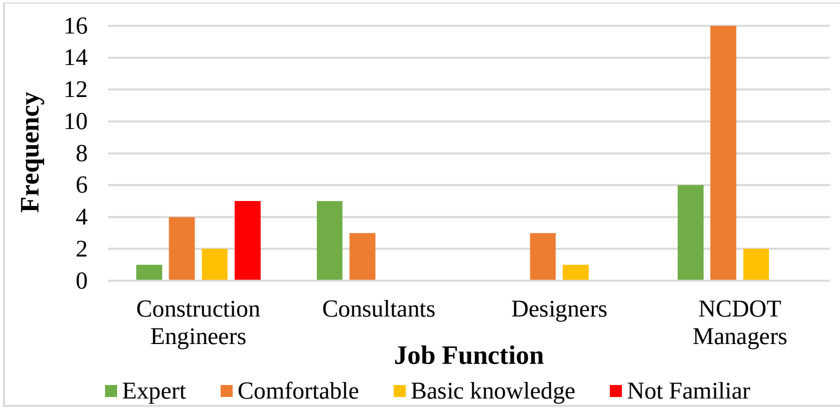
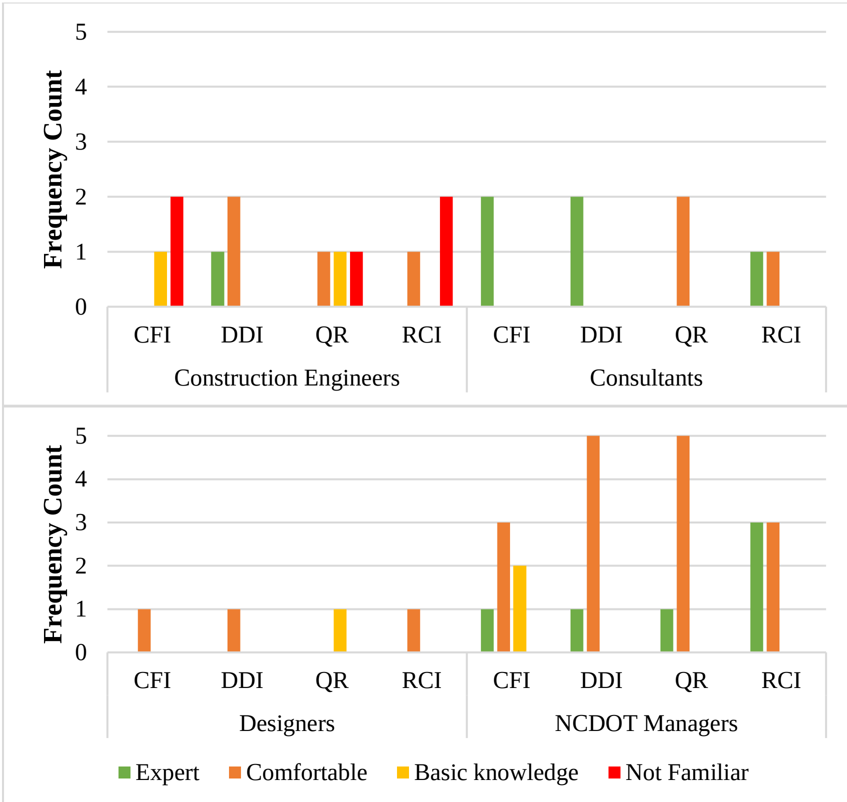


Figure 0.1 Participant’s Familiarity with Alternative Intersections and Interchanges Based on Job Function

To further analyze the findings in Figure 2.1, a side-by-side bar plot was created to investigate the participant’s role familiarity with CFI, DDI, QR, and RCI designs and this is results are reported in Figure 2.2. The results indicated that managers are the most comfortable with DMUII designs, as they reported a high level of familiarity ranging from comfortable to expert. The only design where managers showed lower familiarity was with CFI, indicating basic knowledge and a comfortable familiarity level. These results align logically with the fact that a few (around 2-4) CFI are at the project development stage and only one CFI project has been constructed in North Carolina. On the other hand, construction engineers displayed the lowest familiarity with DMUIIs, particularly with CFI, RCI, and QR designs. Consultants reported a comfortable to expert level of familiarity, while designers generally exhibited a relatively comfortable level of familiarity with DMUIIs, except for QR designs, where they indicated having only basic knowledge.



CFI: continuous flow intersection. **DDI**: diverging diamond interchange.
QR: quadrant roadway. **RCI**: reduced conflict intersection.

Figure 0.2 Participant's Job Function and Familiarity with Alternative Intersections and Interchanges Design Types

Identification of Construction Inhibitors

After identifying the participants' familiarity with DMUIIs, they were then asked to identify the specific construction inhibitors that they saw as most significantly affecting projects that have a DMUII design. The participants were encouraged to identify multiple inhibitors for a project, if appropriate. In total, the participants identified 19 inhibitors affecting projects that have DMUII designs. The results from their identification of inhibitors and their percentage frequency are displayed in Table 2.7.

Table 2.7 associate the inhibitors identified by participants in surveys and interviews with the design type that participants were discussing. Notice that conditional formatting was utilized to determine which inhibitors have the largest percentage for each design type. It can be observed that the most common inhibitor among all DMUIIs was utilities (n = 9%). The second-largest inhibitor was the business impact (n = 9%), followed by public acceptance (n = 9%), multimodal transit accommodation (n = 7%), and ROW (n = 7%). By focusing on the top inhibitors specific to each design type, we can observe certain overlaps (e.g., the business impact has 14% QR and 12% RCI) between designs. However, it is noteworthy that the top 5 inhibitors affecting each project that have a DMUII design differ. This finding suggests that no general assumptions can be made about the inhibitors affecting projects.

Table 0.7 Construction Inhibitors Associated with Alternative Intersections and Interchanges Projects

Inhibitors	CFI	DDI	QR	RCI	Total
Utilities	21%	9%	7%	9%	**9%**
Business Impact	0%	6%	14%	12%	**9%**
Public acceptance	0%	8%	12%	8%	**9%**
Multimodal transit accommodation	0%	6%	9%	9%	**7%**
Right of way	7%	5%	8%	11%	**7%**
Safety for workers	7%	10%	3%	7%	**7%**
Space constraints	0%	8%	7%	8%	**7%**
Safety for drivers	7%	9%	4%	5%	**7%**
Site access	7%	5%	9%	7%	**6%**
Work zone traffic control	7%	9%	3%	5%	**6%**
Construction sequencing	7%	7%	4%	1%	**5%**
Wall construction	14%	4%	3%	3%	**4%**
Bridge construction	0%	4%	5%	1%	**3%**
Geotechnical issues	14%	3%	3%	3%	**3%**
Water drainage during construction	7%	3%	1%	4%	**3%**
Environmental concerns	0%	1%	3%	3%	**2%**
High bids	0%	1%	3%	3%	**2%**
Signals and signage	0%	2%	3%	0%	**2%**
Total	**100%**	**100%**	**100%**	**100%**	**100%**

CFI: continuous flow intersection. **DDI**: diverging diamond interchange. **QR**: quadrant roadway. **RCI**: reduced conflict intersection.

Through the conversations held with participants during the interviews, it became clear that participants feel these inhibitors are not limited to projects that have DMUII design, nor are they entirely due to DMUII project characteristics. Instead, they are more likely to be presented based on the unique characteristics of each project site. However, DMUIIs result in an added complexity to a number of the inhibitors identified in Table 2.7. The next section further addresses this point.

Unique Construction Characteristics of Alternative Intersections and Interchanges

This research sought to identify the differences in the process of constructing a project with a DMUII vs CII design. The interview participants noted six main areas in which DMUII and CII projects differ: sequencing and phasing, WZTC, contractor's perception, complexity and site characteristics, relocation of utilities, and driver's perception (see Figure 2.3).

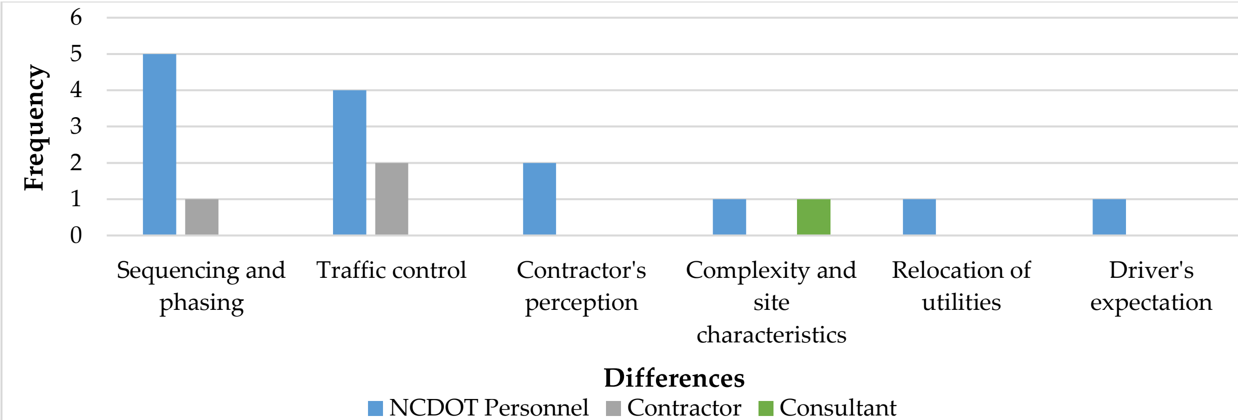


Figure 0.3 Unique Construction Characteristics of Alternative Intersections and Interchanges

The results indicated that sequencing/phasing and WZTC are two of the most notable differences. This and the remaining results agree with the findings in prior research (Reeder and Nelson 2015; Hancher 2003; Wong 2006; United States Army Corps of Engineers 2013; Zhan and El Diraby 2006). Since the geometry of DMUIIs is new and unique, guidelines or manuals are not available to address sequencing or WZTC. Stakeholders experienced difficulties in these areas, mainly because the total phasing and WZTC required for a particular design varies drastically depending on its geometric constraints. Therefore, these two factors were identified as the most predominant differences in this study.

In addition, contractors perceive projects that have DMUII design to be more challenging than projects that have CII design. This is in part due to the greater complexity of DMUIIs, resulting in increased costs. Therefore, the construction of DMUIIs is considered to be riskier. Additionally, participants indicated that the complexity of DMUII projects, combined with unusual site characteristics, make construction more challenging. Because DMUII designs are ideal for addressing capacity problems, they are typically implemented in congested and complex areas.

The relocation of utilities and driver's expectations were also identified as differences in the process of constructing a project with a DMUII vs a CII design. Participants indicated that in some cases, due to the unique geometry of DMUIIs, some projects are built within the existing ROW. In such cases, utilities are already located outside of the construction footprint; therefore, utility impact is lower. In other cases, DMUII designs require a larger ROW, and therefore, utility relocations are more significantly impacted. For driver perception, participants indicated that DMUII projects have unconventional geometry, and therefore, drivers perceive them to be complicated, unfamiliar, and uncomfortable.

<u>Projects Under Construction</u>

Over a period of ten months, three projects that have DMUII design in North Carolina were closely monitored to determine the construction inhibitors that were affecting them. The first project monitored was project U-2719, located at the intersection of Western Boulevard and I-440 in Wake County, as shown in Figure 2.4. Project U-2719 involves the construction of a DDI design and is expected to be completed in October 2024. The construction progress was 65% completed at the time of the field observations.

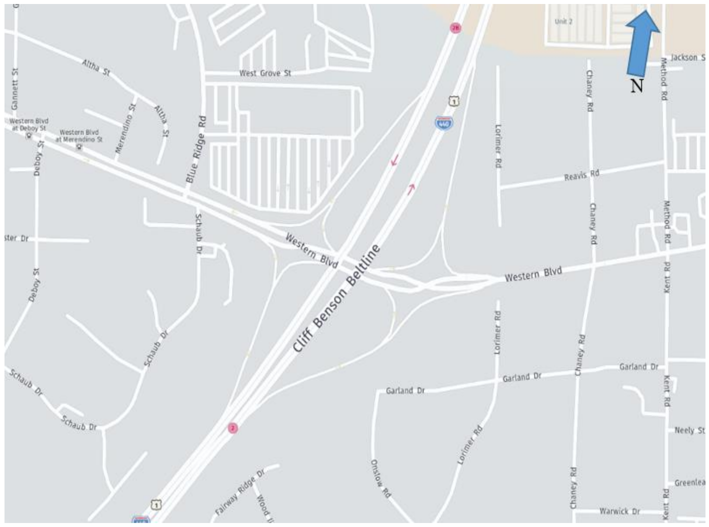


Figure 0.4 Location of Project U-2719

The second project monitored was I-5700, also a DDI design, located at the intersection of Airport Boulevard and I-40 in Wake County, as shown in Figure 2.5. I-5700 is projected to be completed by December 2024, and the construction progress was 40% completed at the time of the field observations.

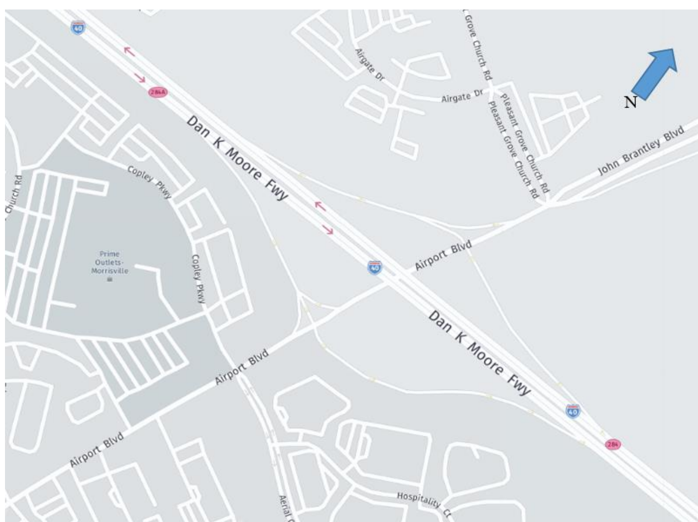
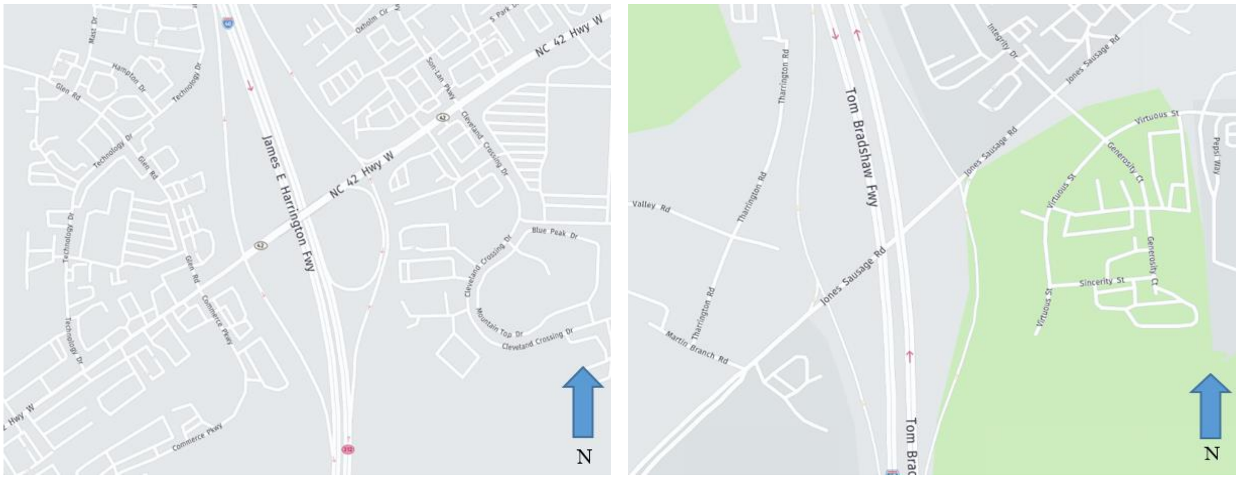


Figure 0.5 Location of Project I-5700

The third project that was monitored is I-5111 in Wake County which involves the construction of two DDIs. Figure 2.6 (a) shows that the first DDI is being constructed at the intersection of I-40 and NC-42 and Figure 2.6 (b) shows that the second DDI will be constructed at I-40 and Jones Sausage Road. This project is expected to be completed in August 2024. Only 20% of the first DDI project had been completed at the time of the field observations and construction on the second DDI had not yet started.



(a) I-40 and NC-42 (b) I-40 and Jones Sausage Road

Figure 0.6 Location of Project I-5111

Table 2.8 provides a breakdown of the inhibitors that were identified in this field of study. The most frequent inhibitors are shown to be material delivery issues, space constraints, and utility problems. Material delivery proved to be a significant problem for all three projects and was due to labor shortages and the inability to get material shipped to contractors on time. To address this issue, contractors opted to request materials in advance and secure on-site storage areas. Another prominent issue observed at the sites was space constraints. For instance, for the I-5111 project, the clearance area that separates the construction site from live traffic was six to eight feet. This limited space posed significant risks to both construction activities and traffic in the area. In terms of utilities, project I-5111 has experienced a delay of two years due to the relocation of gas lines. Similarly, in project I-5700, the relocation of utility poles is impacting the scheduling of construction activities in that location, causing further delays to the project.

Table 0.8 Total Inhibitors per NCDOT Field Study Project

Inhibitors	U-2719 Western Boulevard and I-440	I-5700 Airport Boulevard & I40	I-5111 I-40 and NC-42	Total	Frequency
Material delivery	1	1	1	3	21%
Space constraints	1		1	2	14%
Utilities	0	1	1	2	14%
Design errors	0	1	0	1	7%
Design specifications	0	1	0	1	7%
Multimodal transit accommodation	0	1	0	1	7%
ROW	0	0	1	1	7%
Safety	0	1		1	7%
Water drainage	0	0	1	1	7%
Work zone traffic control	1	0	0	1	7%
Total	**3**	**6**	**5**	**14**	**100%**

The field study projects also identified a benefit associated with their construction. Specifically, in the case of the I-5700 DDI project, construction personnel reported higher productivity due to the construction phasing at Airport Boulevard, which allowed them to work more efficiently away from traffic. This project required the construction of two bridges for the DDI. Figure 2.7 shows the construction and bridge locations. Note that I-40 and Airport Boulevard experience heavy traffic and are considered high-priority areas; therefore, closing lanes and reducing capacity could potentially cause significant problems and traffic delays. The current alignment of the I-5700 project is along Bridge B. Therefore, the construction phasing strategy facilitated the separation of construction activities at Bridge A from the existing traffic flow, eliminating the need for WZTC measures. Once Bridge A was completed, traffic was diverted to Bridge A, which allowed reconstruction activities to begin on Bridge B.

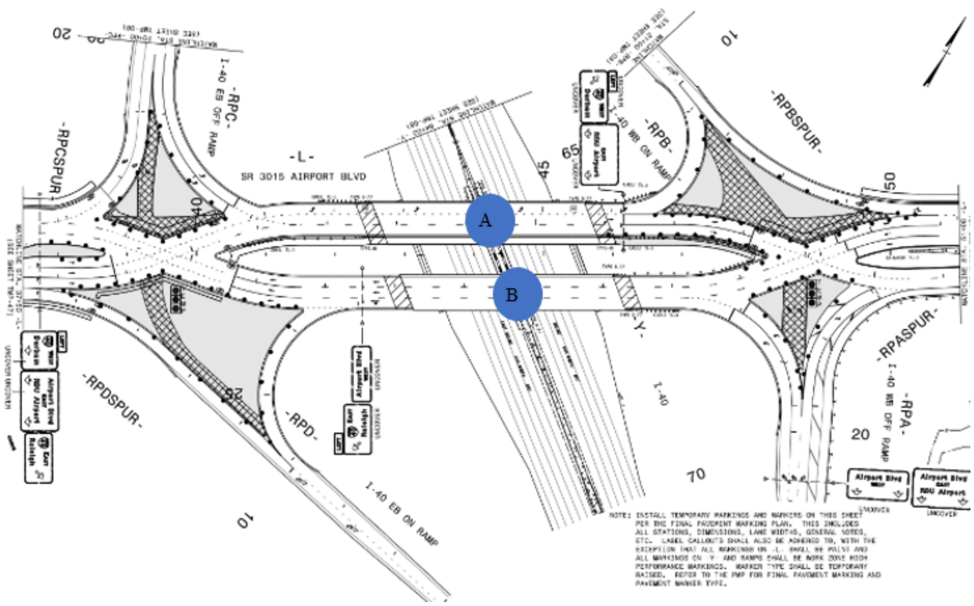


Figure 0.7 I-5700 Project: Location of Bridge Structures

Lessons Learned and Best Practices

DMUII projects support sustainability in multiple ways (Almoshaogeh et al. 2020), and therefore, documenting solutions that can lead to improving the construction of DMUII projects is essential. Findings from the interview process are documented in the form of lessons learned and best practices. Lessons learned describe the knowledge gained from industry experts about the process of conducting a project (Project Management Institute 2009) and best practices are the processes or methods that, when executed effectively, lead to enhanced project performance (Construction Industry Institute 2022).

Based on the survey and interview results, a set of lessons learned was compiled to identify the main construction inhibitors. The two most frequently identified inhibitors on projects that have DMUII design are utilities and ROW. The factor that most affect DMUIIs is the contractor's perception of the complexity and risks involved in the project, not the design. Lastly, creating consistent documentation to identify inhibitors related to constructability and assessing those inhibitors throughout the project's life is essential to meet the unique challenges and construction practices of projects that have DMUII design. In addition, planning was identified as the key to a successful project. Therefore, it is important to focus on the early identification and relocation of utilities by performing a utility assessment early in the planning stages of a project.

One of the best practices identified by participants is to make regular visits to the construction site to check the placement of temporary signs and to assess turning movements and overall performance during construction. Ideally, WZTC designers and safety officers should perform these inspections.

Construction personnel were found to have less familiarity with DMUII designs than conventional designs. To address this issue, workshops or 'lunch and learns' would be useful for construction personnel as well as other NCDOT employees to share knowledge gained. Similarly, designers and structural personnel should visit construction sites periodically to improve their understanding of construction-related activities. This exposure to the field will enable designers to address common construction concerns more effectively during the design phase and gain a clearer understanding of the project scope and characteristics.

Conclusions

To gain a deeper understanding of ways to build DMUIIs successfully and sustainably, interviews and online surveys were conducted to record information from industry experts regarding the construction inhibitors that impact projects that have DMUII design as well as to identify inhibitors through field observations. This study represents the first investigation of construction inhibitors for projects that have DMUII design, and its results provide valuable insights into inhibitors that negatively impact such projects. Stakeholders identified 18 inhibitors that affect the construction of DMUII projects: utilities, business impacts, public acceptance, multimodal transit accommodation, safety for workers, ROW, space constraints, safety for drivers, site access, WZTC, construction sequencing, wall construction, bridge construction, geotechnical issues, water drainage during construction, environmental concerns, high bids, and signals and signage. Additional relevant findings were also identified from the stakeholder's feedback. From the contractors' perspective, it is believed that DMUII designs do not require any specialized construction knowledge.

The 10-month field study of three projects with DDI design in North Carolina revealed construction inhibitors that affected them. A total of 10 inhibitors were identified across the evaluated projects, with material delivery issues, space constraints, and utility problems being the most frequent inhibitors. The field study also highlighted the benefits associated with DMUII projects. Construction personnel reported higher productivity due to the construction phasing of DDI project I-5700 at Airport Boulevard. The strategic construction phasing of the two bridges facilitated the separation of construction activities from the existing traffic flow, eliminating the need for additional WZTC measures.

The findings from the field study also emphasize the importance of proactive measures to address construction inhibitors, such as early material planning, efficient space utilization, and strategic phasing of construction activities. By identifying and mitigating these inhibitors, DMUII projects can experience enhanced productivity, minimized delays, and optimized safety for both construction activities and the driving public. In general, the findings reported in this chapter hold significant implications, primarily the identification of lessons learned and best practices. These findings can be used by DOTs and other transportation agencies in allocating their resources effectively to identify and mitigate inhibitors before they adversely affect projects that have DMUII design. Furthermore, these insights will enable DOTs and agencies to adopt enhancement strategies that promote more efficient construction of DMUII projects.

The results of this research are qualitative in nature and serve to establish an initial understanding of the inhibitors that impact projects that have DMUII design. However, to enhance the significance and reliability of these results, efforts were made to quantify the impact of each inhibitor on the performance of the projects that have DMUII design, as presented in Chapter 3.

CONSTRUCTION INHIBITORS: INSIGHTS FROM CLAIMS AND SUPPLEMENTAL AGREEMENT DATA

Transportation projects require a significant economic effort from departments of transportation (DOTs) (Lee et al. 2018; Lee and Alleman 2018). The failure of such projects can have serious consequences for national and regional economies (Love et al. 2016). Ensuring that projects are completed within the allocated budget and schedule is crucial for determining their success, particularly in transportation projects where public funding is involved (Shrestha 2022). For this reason, DOTs have recognized the critical role of completing transportation infrastructure projects within the estimated budget, specified timeframe, and original scope of work (FHWA 2007). However, due to the complex nature of transportation infrastructure projects, accurately predicting their outcomes is challenging (Rehak et al. 2018; Useche et al. 2018; Song et al. 2018).

To address this shortcoming, extensive research has been conducted to evaluate transportation project performance, providing valuable insights into potential inhibitors that can impact project success (Aziz and Abdel-hakam 2016; Parikh et al. 2019). Inhibitors are defined in this research as the factors that have the potential to negatively affect the construction of diverse, modern, and unconventional intersections and interchanges (DMUII) projects. A reliable technique for assessing project performance is to analyze claims and supplemental agreements (Shrestha 2022). Claims and supplemental agreements are critical aspects of construction projects that can significantly impact project performance. Even though the definitions of claims and supplemental agreements vary among researchers (Ndekugri and Russell 2006; Reid and Ellis 2007; Project Management Institute 2009), utilizing these data sources is an efficient way to evaluate project performance. Evaluating the causes of claims is important to gain a better understanding of the factors that affect project performance. In this research, ‘claims’ refers to a request for more time or money to compensate for losses due to changes. Additionally, supplemental agreements are inevitable in construction projects due to factors such as limited time, resources, and the budget that is allocated during the planning stage as well as the unique characteristics of construction projects (Hanna et al. 2002; Assbeihat and Sweis 2015). Supplemental agreements are defined in this research as a request to amend the contract in terms of monetary compensation, time, or scope of work to complete additional construction work that was not included in the initial contract.

Although extensive research has been conducted into project performance and the identification of inhibitors that affect transportation projects, limited literature is available that is specifically related to project design types. Evaluating the inhibitors that affect transportation projects based on design type is important because DMUIIs often require construction approaches that may be unfamiliar to professionals in the industry. This research aims to address this gap in the literature by focusing on the evaluation of claims and supplemental agreements. By examining this dataset, a deeper understanding of the performance of DMUIIs compared to conventional intersection and interchange (CII) designs is gained. The evaluation of these data also allows the identification of inhibitors that affect DMUIIs, which has the potential to shed light on the unique challenges and opportunities associated with DMUII projects. By understanding the causes, effects, and inhibitors associated with claims and supplemental agreements, construction can be enhanced to promote successful project delivery.

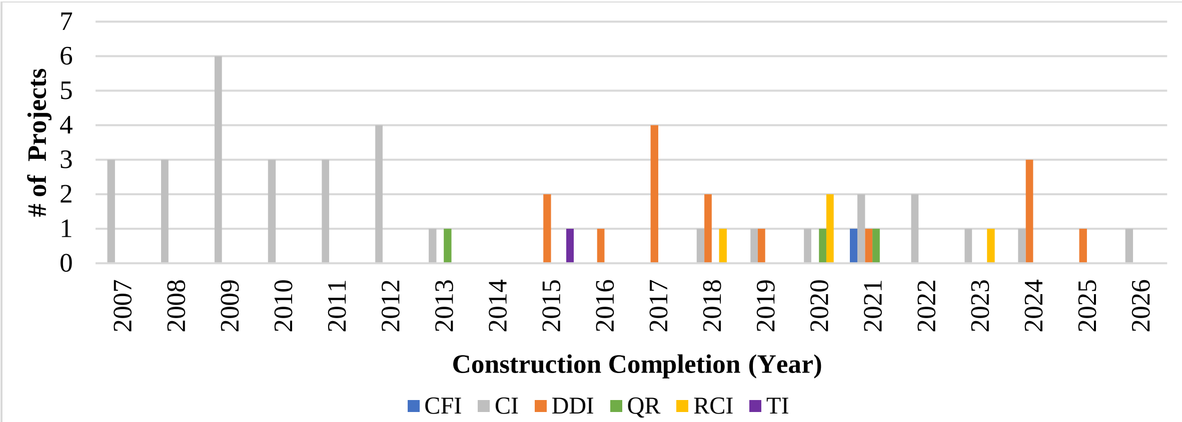
Data Sample

A list of 77 potential North Carolina Department of Transportation (NCDOT) projects was compiled based on input from interview participants and a Google Map database for DDIs and RCIs in NC. The database was shared by NCDOT personnel. Out of the 77 projects identified, 42 were DMUII designs and the remaining 35 projects had CII designs only. These projects were selected based on project characteristics and project status. Table 3.1 presents the list of projects that were in the following project delivery phases at the time of this study: planning, design, under construction, completed, unfunded (projects ready for construction but not begun due to lack of funding), under the process of right-of-way (ROW) acquisition, and currently receiving bids. Claims and supplemental agreement data from NCDOT Highway Construction and Materials System (HiCAMS) was not available for all the projects since the claims and supplemental agreements are only generated during construction. Therefore, the NCDOT projects with available claims and supplemental agreement data were those under construction or completed. Out of the 77 projects, claims information for 54 projects and supplemental agreement information for 57 projects were received from the NCDOT.

Table 0.1 Status of NCDOT Projects of Interest and Data Received

Project Status	Total Project Requested	Claims	Supplemental Agreements
Planning	3	0	0
In design	9	0	0
Construction	10	7	9
Completed	50	47	48
Unfunded	3	0	0
Right-of-way acquisition	1	0	0
Bidding	1	0	0
Total Projects	**77**	**54**	**57**

The dataset includes projects constructed from 2007 to 2026. Figure 3.1 shows the distribution of the project completion dates per design type. Note that nine projects are designated as currently under construction; out of these projects, one is expected to be completed in 2025 and another in 2026. Also, the figure indicates that the construction of DMUII projects started in 2013 and has maintained a steady rate of construction progress.



CFI: Continuous flow intersection. **CII:** Conventional intersections and interchanges. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway. **RCI**: Reduced conflict intersection. **TI:** Turbine intersection.

Figure 0.1 Construction Completion Year of NCDOT Projects

<u>Claims</u>

Claims data for 54 projects were obtained from the NCDOT. The NCDOT divides claims data into two types: Active and Final. Active claims are submitted during the life of the contract, and the authority to approve or decline those claims rests with the NCDOT Divisions. Active claims can become 'Final' or 'Void.' Final claims are submitted to the NCDOT Construction Unit and usually are the last to be resolved to close out a project. Therefore, for calculation purposes and to capture and include the entire scope of claims, this study considers only those claims classified as Final. The second column in Table 3.2 shows the total number of projects per design type, and the third column shows the percentage of the projects that were analyzed after data cleaning for Final claims. In total, 45 projects, which represent 85% of the claims data, were used for analysis.

Table 0.2 Claims Data after Data Cleaning

Design Type	Total Projects Requested	Total Projects Utilized	% Project Used
Continuous Flow Intersection (CFI)	1	1	100%
Diverging Diamond Interchange(DDI)	15	12	80%
Quadrant Roadway(QR)	3	2	67%
Reduce Conflict Intersection (RCI)	4	3	75%
Turbine Interchange(TI)	1	1	100%
Conventional Intersection and Interchange(CII)	30	26	87%
Total	**54**	**45**	**85%**

<u>Supplemental Agreements</u>

Supplemental agreements for a total of 57 projects were received from the NCDOT. Each supplemental agreement has a different approval authority level: resident engineer, division engineer/division construction engineer, state construction engineer/assistant construction engineer/area construction engineer, and state construction engineer/assistant state construction engineer. An approved supplemental agreement has been reviewed and approved by all required NCDOT personnel. When a supplemental agreement requires more than 30 days or more than

$100,000, the Resident Engineer cannot provide sole approval. The Resident Engineer will recommend approval, which places the supplemental agreement in the queue for the Area Construction Engineer/Assistant State Construction Engineer to review. Once it is approved, the supplemental agreement is sent to the contractor for their signature, after which the supplemental agreement has the status of Contractor Concurrence.

Based on the supplemental agreement process and for calculation purposes, only those supplemental agreements labeled as Approved or Contractor Concurrence were used for this study. Table 3.3 presents the total number of projects requested per design type and the total number of projects that could be used after cleaning the dataset for Approved or Contractor Concurrence. In total, 56 projects, which represent 99% of the supplemental agreement data, were used for analysis.

Table 0.3 Supplemental Agreements by Project Type

Design Type	Total Projects Requested	Total Projects Utilized	% Project Used
Continuous Flow Intersection (CFI)	1	1	100%
Diverging Diamond Interchange(DDI)	15	15	100%
Quadrant Roadway(QR)	3	3	100%
Reduce Conflict Intersection (RCI)	4	4	100%
Turbine Interchange(TI)	1	1	100%
Conventional Intersection and Interchange(CII)	33	32	97%
Total	**57**	**56**	**99%**

Upon identifying the projects with records of claims and supplemental agreements, an analysis is conducted to determine the extent of the impact of a DMUII on each project. This analysis becomes necessary due to the substantial variations in the scope of the evaluated projects. For instance, in project I-5700, the DDI involves only 0.798 miles of construction, limited to one intersection. In contrast, project I-3803B covers 6.8 miles of construction, incorporating three intersections, with the DDI design implemented in only one of these intersections. Consequently, assessing the scope of each project becomes crucial in determining the actual impact in terms of added project schedule and cost. Table 3.4 provides a comprehensive list of DMUII projects along with their respective impact on the overall project scope, which is determined based on the project length and the number of intersections or interchanges encompassed. It is also worth noting that this assessment does not apply to CII projects, as all intersections and interchanges fall under CII design.

Table 0.4 Impact of DMUII on Overall Project Scope

#	Design Type	TIP Number	Contract Type	Project Length (mile)	Total of Intersections/ Interchanges	Total of DMUIIs	Impact of DMUII on Total Project	Equivalent Affected Length (miles)
1	CFI	U-6084	DBB	0.632	1	1	100%	0.632
2	DDI	I-3803B	DB	6.8	3	1	33%	2.267
3	DDI	I-3819A	DBB	3.36	15	1	7%	0.224
4	DDI	I-4413	DBB	0.586	1	1	100%	0.586
5	DDI	I-4733	DBB	0.385	1	1	100%	0.385
6	DDI	I-5501	DBB	0.492	1	1	100%	0.492
7	DDI	I-5700	DBB	0.798	1	1	100%	0.798
8	DDI	U-2719/ U-4437	DB	6.5	39	1	3%	0.167
9	DDI	U-4909	DBB	4.163	24	1	4%	0.173
10	DDI	I-5714/ U-5114	DBB	1.163	4	1	25%	0.291
11	DDI	R-2248E	DB	5.1	13	1	8%	0.392
12	DDI	R-3601	DB	1.676	1	1	100%	1.676
13	DDI	U-2412B/ U-2524AE	DBB	4.836	4	1	25%	1.209
14	DDI	I-5111	DB	12.8	8	2	25%	3.200
15	DDI	U-2925	DB	1.094	8	1	13%	0.137
16	DDI	U-3109A	DBB	3.457	14	1	7%	0.247
17	QR	B-5121/ B-5317	DBB	0.82	2	1	50%	0.410
18	QR	R-2632AA	DB	1.8	5	1	20%	0.360
19	QR	U-2524D	DBB	1.873	8	1	13%	0.234
20	RCI	W-5514	DBB	2.956	8	1	13%	0.370
21	RCI	U-3330	DBB	2.044	9	2	22%	0.454
22	RCI	U-5713	DB	5.1	4	2	50%	2.550
23	RCI	W-5520	DBB	2.471	4	4	100%	2.471
24	TI	R-2123CE	DB	1.44	1	1	100%	1.440

Methodology

The data sample described in Section 3.1 was utilized to evaluate project performance and identify inhibitors. Figure 3.2 describes the methodology. The strategies to perform the analysis include descriptive frequency analysis and chi-square statistical testing. Descriptive frequency analysis is a statistical technique commonly used to summarize and describe the distribution of categorical variables or sets of discrete data (Agresti 2007). It involves analyzing the frequency or count of each category or value in the dataset and presenting the findings clearly and concisely. Valuable insights into the composition and distribution of data can be obtained by examining patterns, frequencies, and distributions via this method. Descriptive frequency analysis was conducted in this study to examine the results using tabulation and visualization to explain variations in the parameters.

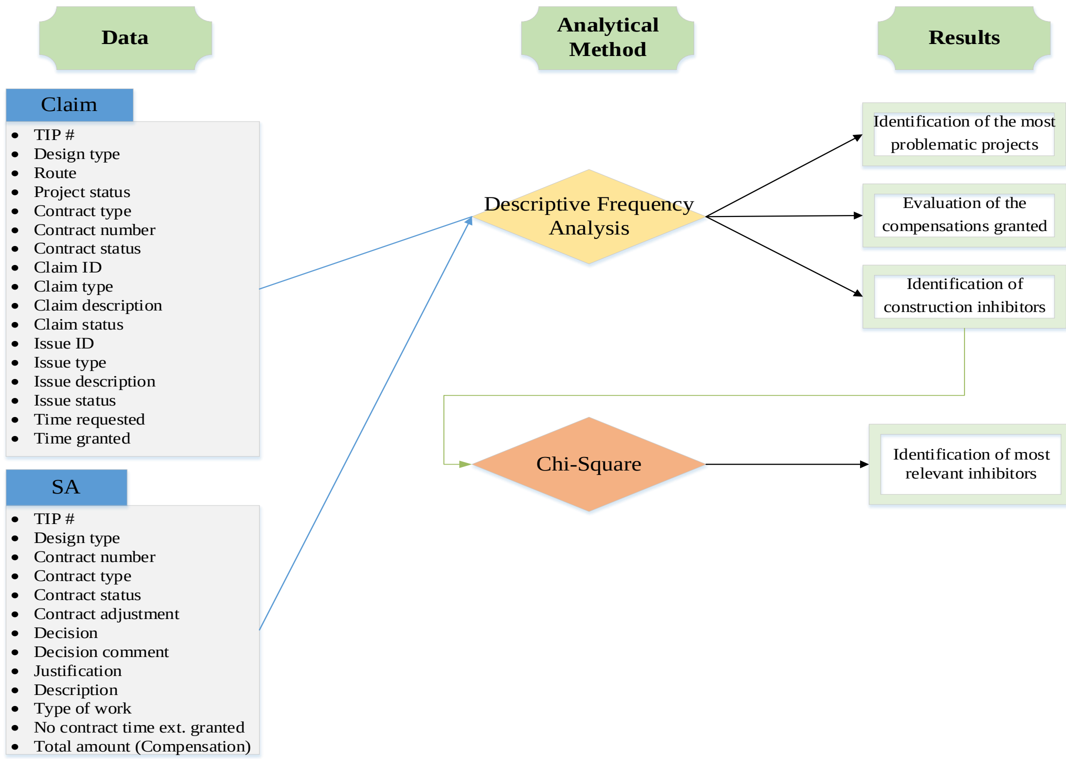


Figure 0.2 Methodology for Identification of Construction Inhibitors

The first part of this analysis involved claims data such as the Transportation Improvement Program number (TIP #), design type, contract number, claim ID, claim type, claim description, claim status, issue ID, issue type, issue description, issue status, time requested, and time granted. The supplemental agreement data included the TIP #, design type, contract number, contract type, contract status, contract adjustment, decision, decision comment, justification, description, type of work, no contract time extension granted, and the total amount (compensation) to evaluate project performance and help identify the designs that led to poor performance. A descriptive frequency analysis was also conducted to evaluate the compensations granted and their effect on project costs and schedules. The last outcome that resulted from the descriptive frequency analysis was the identification of the construction inhibitors associated with DMUII and CII projects.

Chi-square (X^2) tests of independence (also known as Pearson Chi-square tests) is similar to ANOVA factorial (Terrell 2012) and is useful for testing hypothesis when variables are normal (McHugh 2013) and the analysis of categorical data have been used (Bishop et al. 1975; Hosmane 1986). In this study, the Chi-square tests were performed to determine if any association was present among the inhibitors identified from the findings of the interviews and surveys (Chapter 2) and claims and supplemental agreement data. A higher value of the chi-square test statistic of independence indicates a stronger correlation between data sources (interviews and surveys, claims, and supplemental agreements). Upon identifying the chi-square value, the *p*-value was calculated to determine if it is associated with the chi-square value. A p-value less than 0.05 indicates a significant association between the obtained results.

$$X^2 = \sum_{i=1}^{c} \sum_{j=1}^{r} \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}} \tag{1}$$

where

X^2 = chi-square test statistic,
c = total number of attribute categories that are part of the first variable of interest,
r = total number of attribute categories that are part of the second variable of interest,
O_{ij} = observed count or frequency that corresponds to a particular inhibitor in category combination ij,
E_{ij} = expected count or frequency of inhibitors in category combination ij, and
N = total number of inhibitors.

The expected count or frequency is calculated using Equation 2.

$$E_{ij} = \frac{N_i * N_j}{\sum N_{ij}} \tag{2}$$

where

E_{ij} = expected count or frequency of inhibitors in category combination ij,
N = total number of inhibitors,
N_i = marginal frequency or count of inhibitors that corresponds to interviews and surveys, claims, or supplemental agreement for the first variable of interest, and
N_j = marginal frequency or count of inhibitors that corresponds to interviews and surveys, claims, or supplemental agreement for the second variable of interest.
ΣN_{ij} = sum of the marginal frequency or count of inhibitors that corresponds to the first and second variable of interest.

Standardized residuals also were calculated to identify attribute category combinations that are overrepresented or likely to relate to the expected count. The calculation of standardized residuals (Ɛ) follows Equation 3 for each attribute category. A positive computed standardized residual for a specific attribute category suggests that it is associated with a larger proportion of inhibitors than expected, indicating overrepresentation. This outcome provides robust evidence of a relationship, according to Agresti (2007). A standardized residual greater than 3 indicates a significant contribution of the particular attribute category combination to a larger chi-square value.

$$\varepsilon_{ij} = \frac{O_{ij} - E_{ij}}{\sqrt{E_{ij} * \left(1 - \frac{N_i}{N}\right) * \left(1 - \frac{N_j}{N}\right)}} \tag{3}$$

where

ε_{ij} = standardized residual from the chi-square test of independence,
O_{ij} = observed count or frequency that corresponds to a particular inhibitor in combination with ij,
E_{ij} = expected count or frequency of inhibitors in combination ij,
N_i = marginal frequency or count of inhibitors that corresponds to interviews and surveys, claims, or supplemental agreement with the first variable of interest,

N_j = marginal frequency or count of inhibitors that corresponds to interviews and surveys, claims, or supplemental agreement with the second variable of interest, and

N = total number of inhibitors.

Cramer's V ranges are widely used with the chi-square test of independence (Kvålseth, T. 2018; IBIM Documentation 2023; Cramer and Howitt 2004) to compute the strength of the relationship between data sources. Equation 4 was used to determine the Cramer's V range in this study. Cramer's V ranges from 0 (no association) to 1 (complete association). To interpret the magnitude of the relationship, the criteria suggested by Cohen (2016) were used whereby a range between 0.1 and 0.3 indicates a small tolerance, between 0.3 and 0.5 is considered moderate, and over 0.5 is considered large.

$$V = \frac{\frac{X^2}{N}}{min(c-1,\ r-1)} \tag{4}$$

where

χ^2 = chi-square test statistic computed using Equation 1,

N = total number of inhibitors in the database,

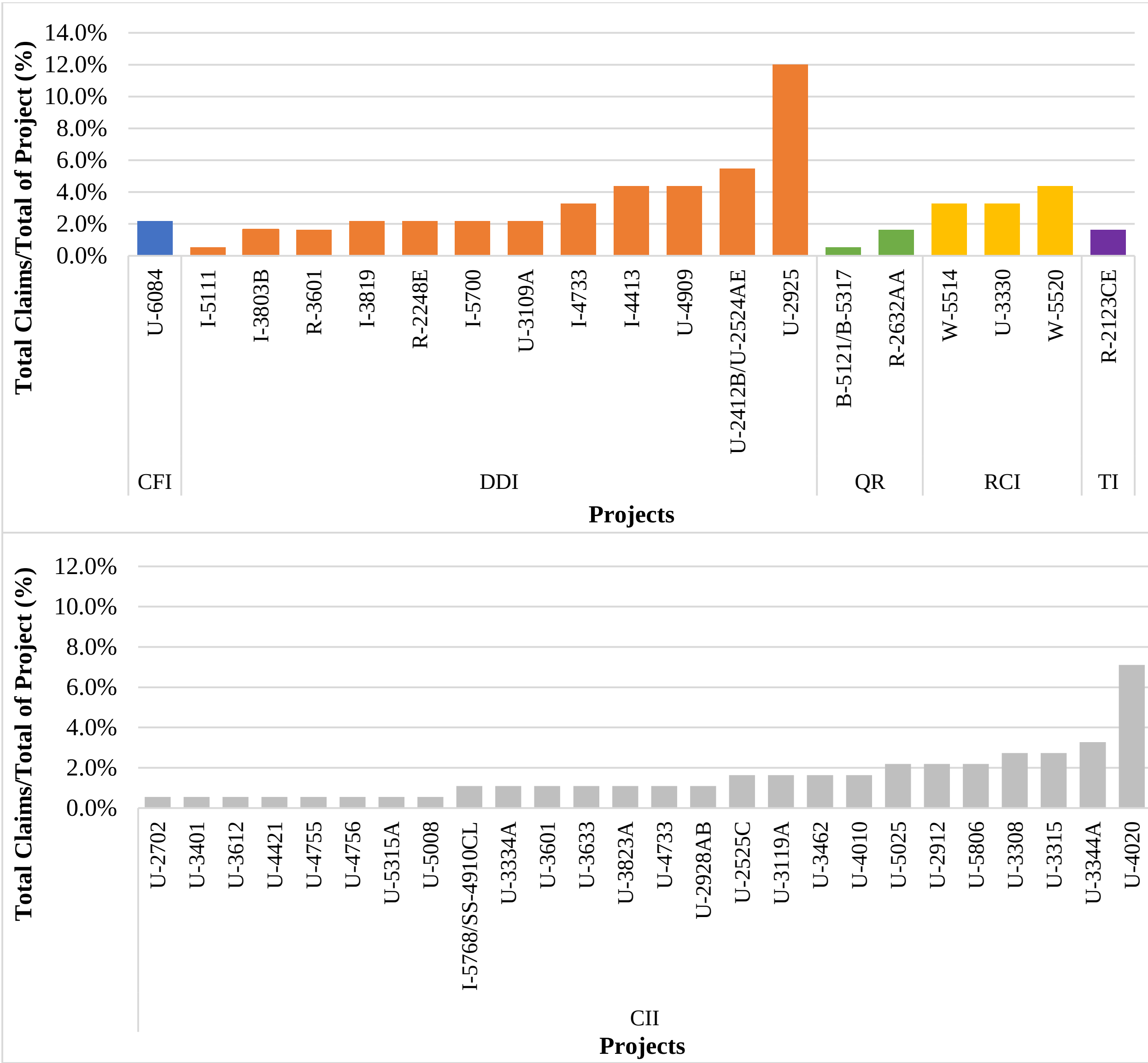
c = total number of attribute categories, represented as columns, and

r = total number of attribute categories, represented as rows.

Analysis

Identification of Most Affected Projects

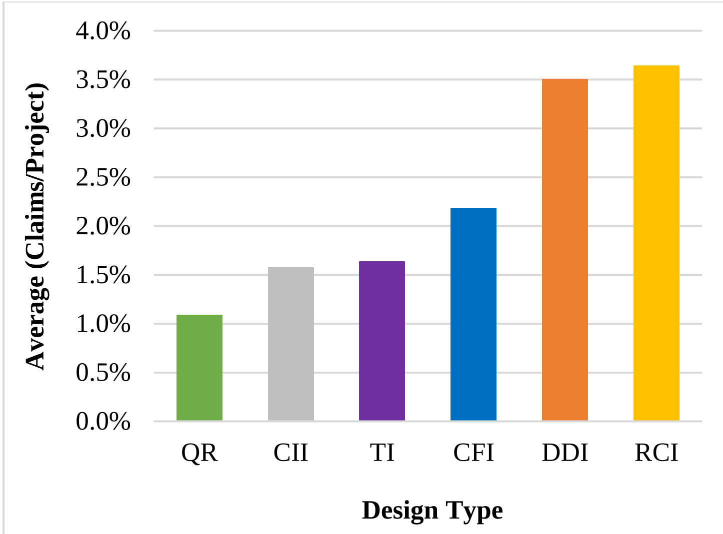
Descriptive statistical analysis was performed to identify the project designs with the highest number of claims. Because the majority of the data sample consisted of DDI and CII design types, multiple analyses were performed to normalize the data and identify the most affected projects. Figure 3.3 shows the total number of claims per project design type. To perform this analysis, the total claims per project were divided by the overall number of claims. For instance, CFI project U-6084 had a total of four claims. Dividing this number by 193 (the total number of identified claims) yielded a percentage of 2%, indicating that the CFI project contributed 2% of the total claims that affected the projects. Most of the projects have fewer than 4% claims. Out of the 45 projects evaluated, four have more than 4% claims and are considered the most affected project.



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

Figure 0.3 Claims per Project

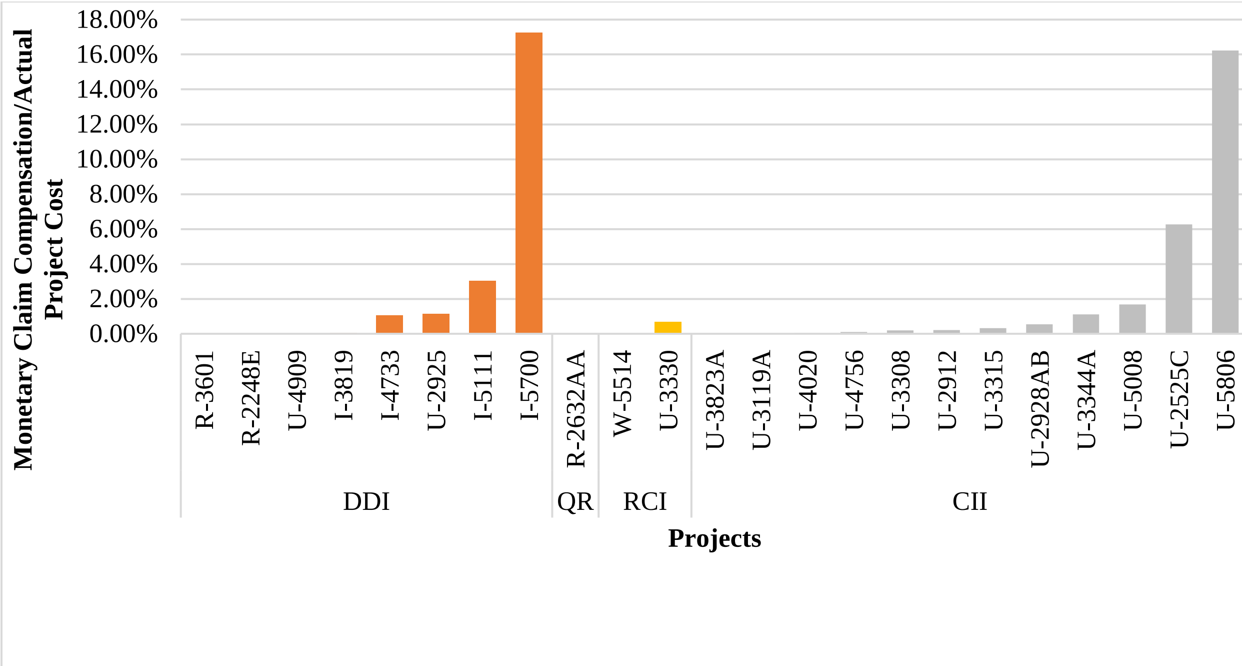
Figure 3.4 contains the same dataset as Figure 3.3 but focuses on the average number of claims per project design type. On average, RCI projects have the largest percentage of claims (3.64%) followed by DDIs (3.51%). The analysis results show that two DMUII projects have more claims filed than CII projects, inferring that DMUII projects are more prone to file a claim than CII projects.



QR: Quadrant roadway. **CII:** Conventional intersections and interchanges. **TI:** Turbine intersection.
CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **RCI**: Reduced conflict intersection.

Figure 0.4 Average Claims per Project

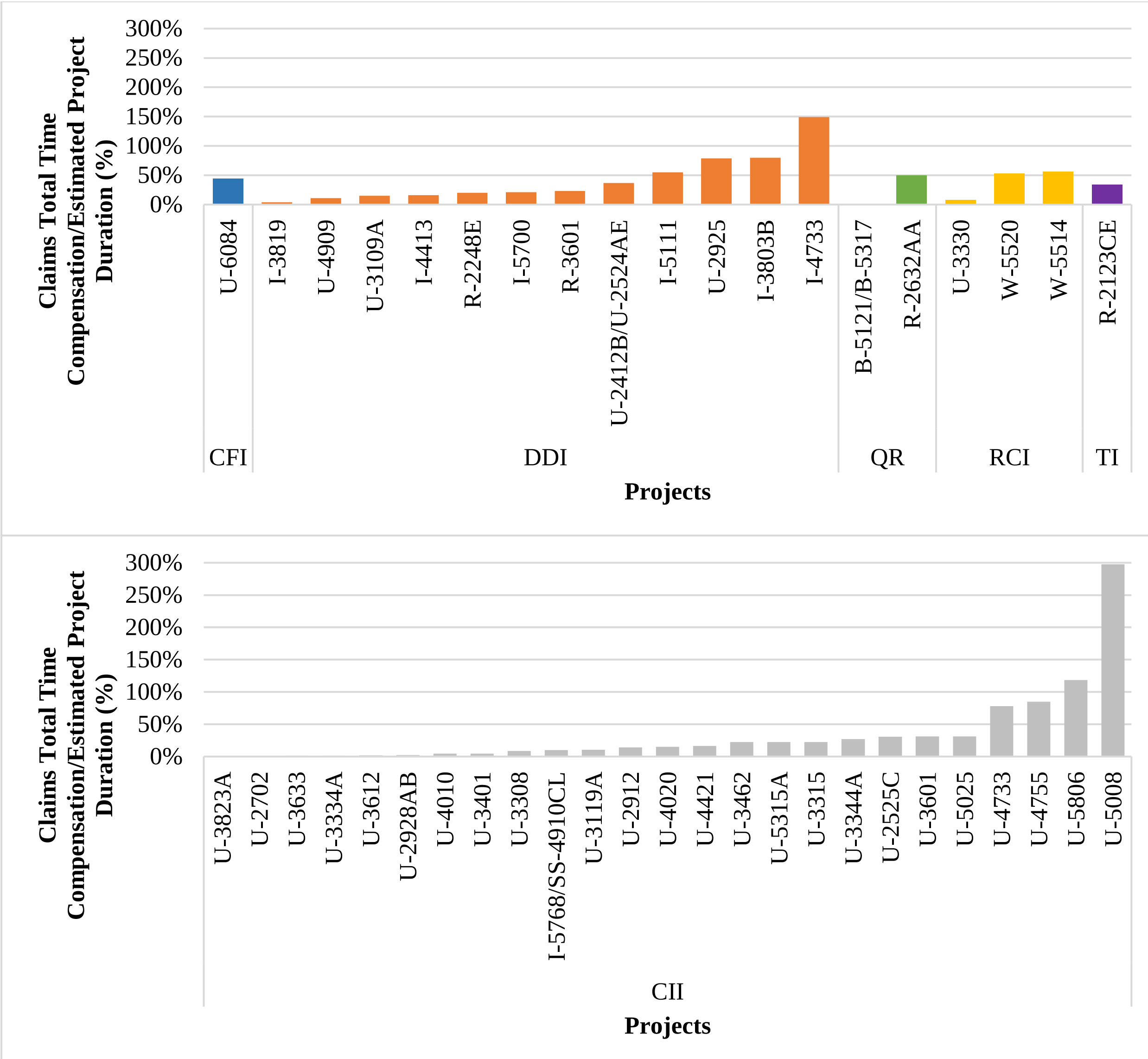
Because projects vary in size, the evaluation of the claims cost was normalized based on the total monetary compensation ($) that was granted based on the claims per contract bid cost. This evaluation allows the identification of the percentage at which a claim affects the overall project cost. Of the 45 projects that have claims, only 23 projects requested monetary compensation. Of these 23 projects, 11 are DMUIIs and 12 are CIIs. To do this analysis, the monetary compensation granted due to claims on a given project was divided by the actual project cost. This percentage allows us to normalize the data as a percentage of claims/project costs. To account for the impact of the design on a given project, the results were then multiple by the respective impact of the design (values presented in Table 3.4). Figure 3.5 presents a histogram of the results. Not all of the 23 projects are shown in the histogram because the cost difference for these projects is less than 1 percent. The designs that reflect the most changes are the CII and DDI projects.



DDI: Diverging diamond interchange. **QR**: Quadrant roadway. **RCI**: Reduced conflict intersection.
CII: Conventional intersections and interchanges.

Figure 0.5 Cost of Claims per Project

Figure 3.6 presents the results of the total time compensations (in days) granted for claims relative to the estimated project duration. Out of the 45 projects with claims, 44 requested time compensation, including 19 DMUIIs and 25 CII. The time compensations ranged from 0% to 297 percent. On average, the majority of claims exhibited a variation of approximately 28 percent. The design types with these adverse percentage differences are CIIs followed by DDI projects. RCIs and QRs also show some adverse changes in the schedule but they do not exceed 56 percent. Also, some CII projects are shown to exceed 100%, but they are considered to be outliers due to discrepancies in the accuracy of the dataset.



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

Figure 0.6 Claims per Project Schedule

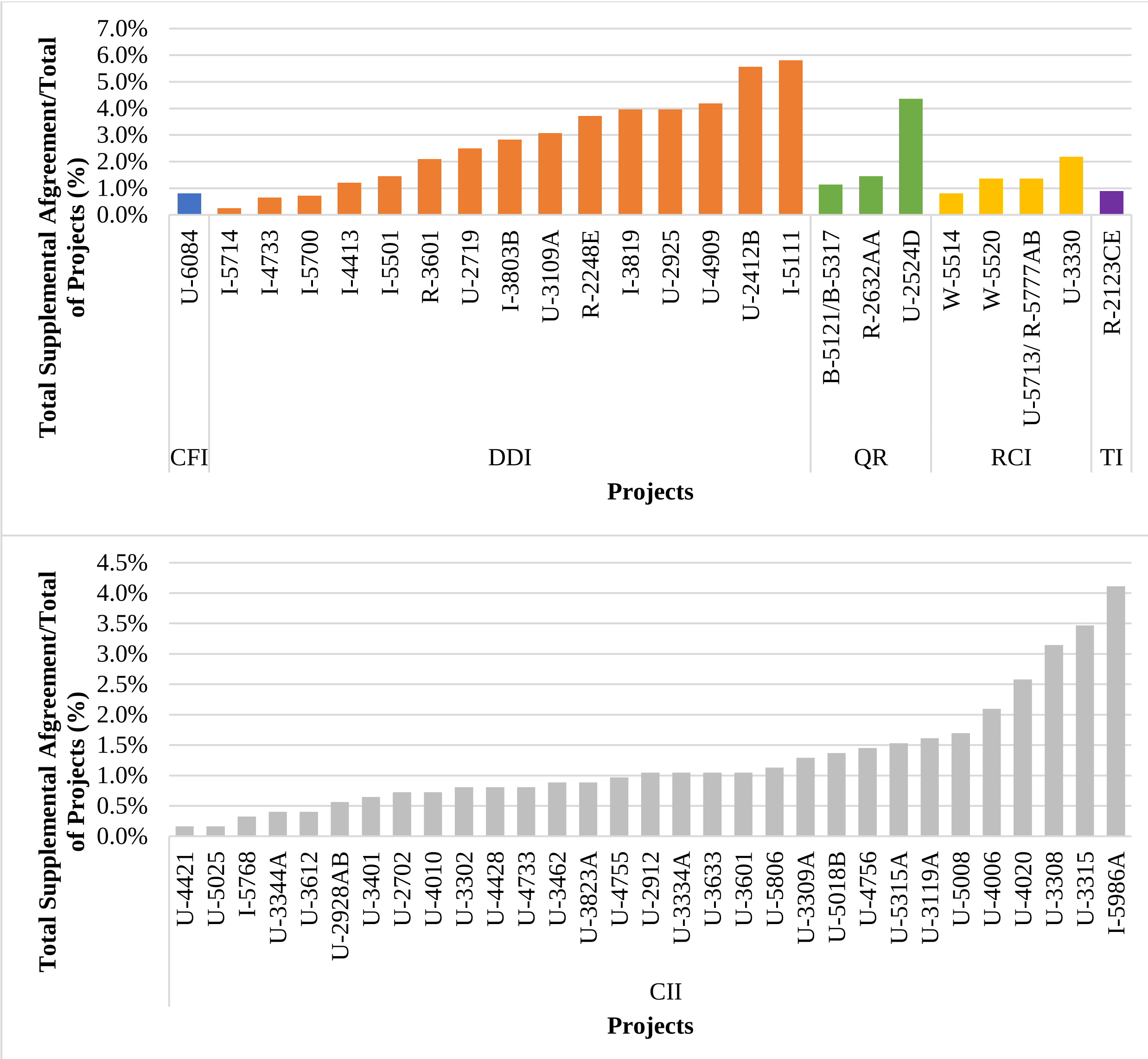
Based on the normalization efforts presented in Figures 3.5 and 3.6, Table 3.5 was developed to present a summary of the five most affected projects based on claims. The projects in bold with highlighted colors (CII U-5806 and CII U-5008) are those that appear among the top five projects requesting cost and schedule compensations. In terms of evaluating claims per project cost, DDI project I-5700 stands out with a staggering 17% increase in claims compared to the project cost. For claims per project schedule, CII U-5008 shows a 297% increase in claims that affected the project schedule.

Table 0.5 Most Affected Projects Based on Claims Data

Claims per Project Cost	Claims per Project Schedule
DDI I-5700 (17%)	**CII U-5008 (297%)**
CII U-5806 (16%)	DDI I-4733 (149%)
CII U-2525C (6%)	**CII U-5806 (118%)**
DDI I-5111 (3%)	CII U-4755 (85%)
CII U-5008 (2%)	CII U-4733 (78%)

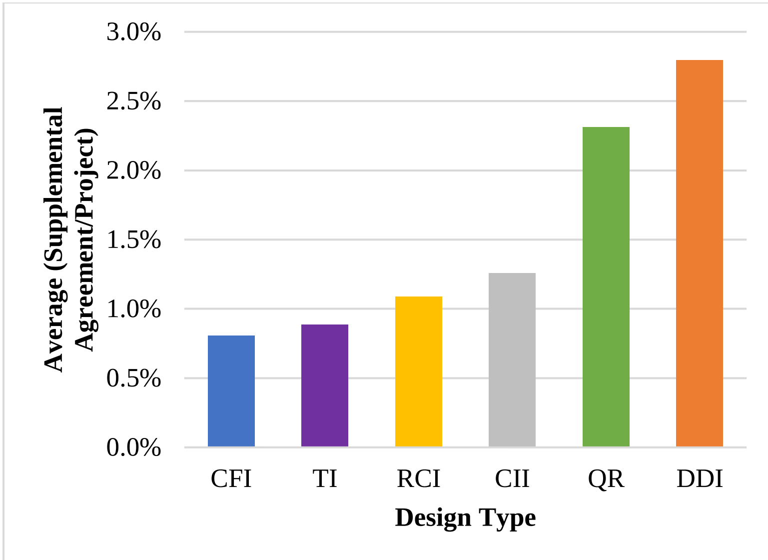
DDI: Diverging diamond interchange.
CII: Conventional intersections and interchanges.

Figure 3.7 presents the results of supplemental agreements per project. Similar to the analysis of the claims data, the total supplemental agreements per project were divided by the overall number of supplemental agreements. For example, CFI project U-6084 had a total of 10 supplemental agreements. Dividing this number by 1240 (the total number of supplemental agreements identified) yielded 0.8%, indicating that the CFI project contributed to < 1% of the total supplemental agreements that affected projects. The majority of projects have less than 1.5% supplemental agreements per project. Out of the 56 projects evaluated, three projects have more than 5% supplemental agreements and are considered the most problematic. Figure 3.8 utilized the same dataset as Figure 3.7, with a focus on the average supplemental agreement per project design type. On average, DDI projects have the largest number of supplemental agreements (2.8%), followed by QRs (2.3%) and CII (1.3%). These results suggest that these projects are more affected by inhibitors and that more supplemental agreements are needed for their successful execution.



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

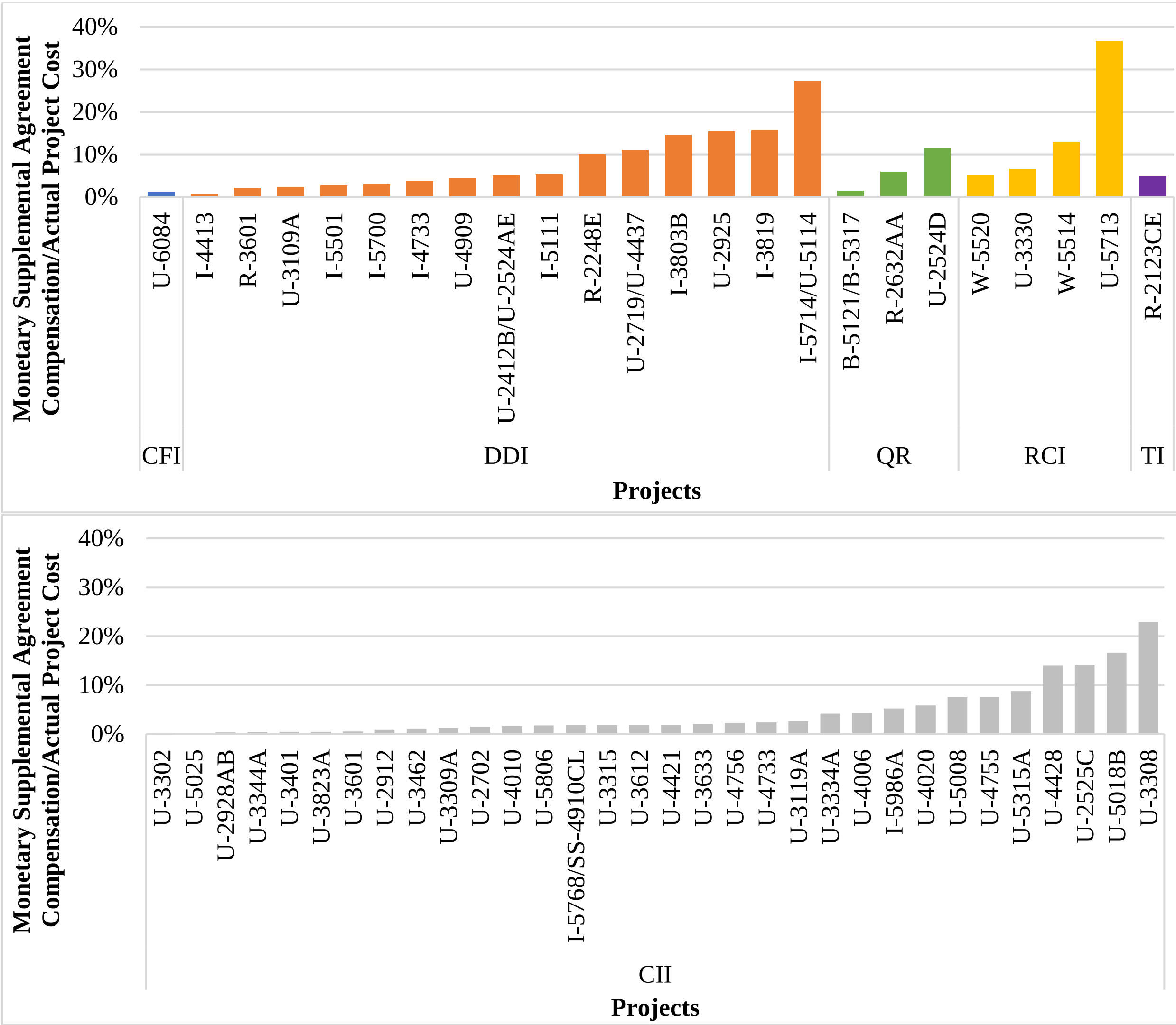
Figure 0.7 Supplemental Agreements per Project



CFI: Continuous flow intersection. **TI:** Turbine intersection. **RCI**: Reduced conflict intersection.
CII: Conventional intersections and interchanges. **QR**: Quadrant roadway. **DDI**: Diverging diamond interchange.

Figure 0.8 Average Supplemental Agreements per Project

Figure 3.9 presents histograms of the analysis results for the total monetary compensation ($) granted for supplemental agreements per contract bid cost. Of the 56 projects with supplemental agreements, monetary compensation was requested for only 55 projects. Of these 55 projects, 24 are DMUIIs and 32 are CIIs. Approximately half of the dataset exhibit differences of less than 5 percent. The designs with the largest changes are CII, DDI, RCI, and QR projects.



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

Figure 0.9 Cost of Supplemental Agreement per Project

Table 3.6 presents the five most affected projects based on supplemental agreements per project cost. The results indicate that CII U-3308 experienced a 23% increase in supplemental agreements compared to the project cost. The second most affected project is RCI U-project 5713 with an 18% cost increase due to supplemental agreements. Overall, it can be observed that 4 of the top five most affected projects have a CII design. Therefore, it can be concluded that CIIs are more prone to require filing for compensation on supplemental agreements.

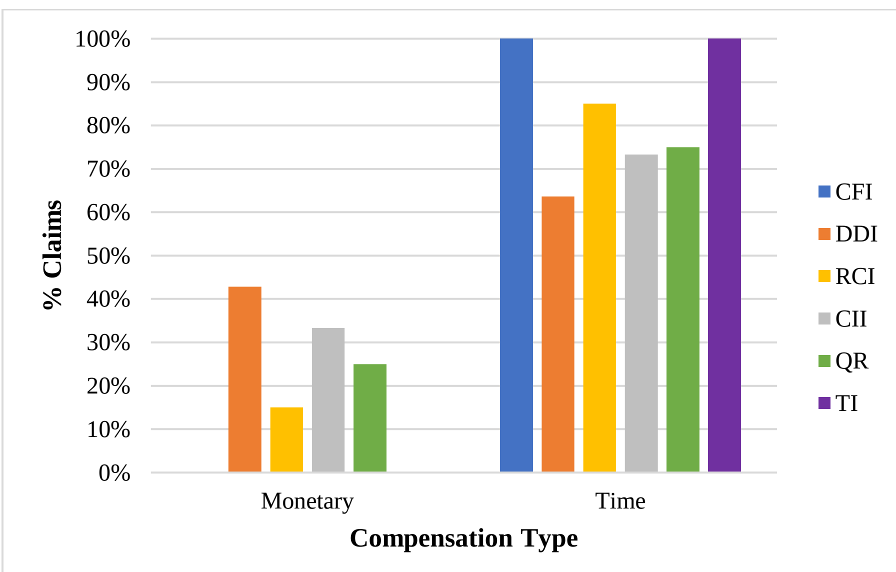
Table 0.6 Most Affected Projects Based on Supplemental Agreement Data

Supplemental Agreement per Project Cost
CII U-3308 (23%)
RCI U-5713 (18%)
CII U-5018B (17%)
CII U-2525C (14%)
CII U-4428 (14%)

CII: Conventional intersections and interchanges.
RCI: Reduced conflict intersection.

Compensation Granted

Claims compensations are granted in the form of monetary compensation or additional time compensation. Figure 3.10 illustrates the distribution of claims compensations by design type for the 45 projects being evaluated. The percentage of claims shown in Figure 3.10 is the result of the compensation type divided by the total of claims per design. For example, of the 12 DDI projects, 77 claims were identified. Of these, 33 (43%) were monetary compensations and 49 (64%) were time-related compensations. The design types that do not require monetary compensation are CFIs and TIs. The design types that correspond to the most requests for additional time are CFI, TI, and RCI. The largest amount of monetary compensation was requested for DDIs followed by CIIs.



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **RCI**: Reduced conflict intersection.
CII: Conventional intersections and interchanges. **QR**: Quadrant roadway. **TI:** Turbine intersection.

Figure 0.10 Percentage of Claims Compensations

Table 3.7 presents the total number of compensations granted per design type and quantifies the number of claims requested per project. As the data sample for DDI projects is the largest for all the project types, a direct comparison of project performance cannot be made. Therefore, to normalize the results, the amounts of the monetary and time compensations granted were divided by the total length of the project to best explain the extent to which claims affect project cost. The results indicate that CII designs lead to the most schedule variation (projects I-5768/SS-4910CL, presented in the last row on page 51, has 18.7% time total compensation granted) and that the DDI has the highest amount of monetary compensation granted (project I-5111 with 79% of monetary total compensation granted). The other designs, the CFI, QR, RCI, and TI, show only time compensation claims, and these are relatively low and moderate.

Table 0.7 Total Claims Compensation per Project

Projects	Time Compensation (Days)	Monetary Compensation Granted	Project Length (mile)	Time Compensation Granted/Project Length (Days/mile)	Monetary Compensation Granted/Project Length($/mile)	Time Total Compensations (%)	Monetary Total Compensations (%)
Continuous Flow Intersection (CFI)							
U-6084	260	$0.00	15.82	16.4	$0.00	1.216%	0.000%
Diverging Diamond Interchange (DDI)							
I-3803B	937	$0.00	5.15	182.0	$0.00	13.470%	0.000%
I-3819	63	$931,571.22	14.58	4.3	$63,879.17	0.320%	0.787%
I-4413	159	$0.00	25.60	6.2	$0.00	0.460%	0.000%
I-4733	819	$60,533.42	20.78	39.4	$2,913.17	2.916%	0.036%
I-5111	784	$36,100,000.00	5.63	139.4	$6,417,777.78	10.313%	79.077%
I-5700	321	$4,166,823.04	11.28	28.5	$369,458.31	2.106%	4.552%
R-2248E	331	$127,500.00	9.02	36.7	$14,135.87	2.715%	0.174%
R-3601	237	$8,685.66	15.51	15.3	$559.89	1.130%	0.007%
U-2412B/U-2524AE	487	$0.00	14.27	34.1	$0.00	2.526%	0.000%
U-2925	807	$8,149,754.09	44.79	18.0	$181,955.73	1.333%	2.242%
U-3109A	197	$0.00	10.99	17.9	$0.00	1.326%	0.000%
U-4909	142	$33,322.80	12.49	11.4	$2,667.75	0.841%	0.033%
Quadrant Roadway (QR)							
B-5121/B-5317	13	$0.00	17.07	0.8	$0.00	0.056%	0.000%
R-2632AA	367	$4,200.20	10.00	36.7	$420.02	2.716%	0.005%
Reduced Conflict Intersection (RCI)							
U-3330	77	$960,620.06	13.21	5.8	$72,722.50	0.431%	0.896%
W-5514	341	$4,239.00	3.38	100.8	$1,253.05	7.459%	0.015%
W-5520	370	$0.00	6.88	53.8	$0.00	3.979%	0.000%
Turbine Interchange (TI)							
R-2123CE	446	$0.00	7.64	58.4	$0.00	4.320%	0.000%
Conventional Intersections and Interchange (CII)							
I-5768/SS-4910CL	185	$0.00	0.73	252.9	$0.00	18.713%	0.000%

Table 3.7 Total Claims Compensation per Project (Continuation)

Projects	Time Compensation (Days)	Monetary Compensation Granted	Project Length (mile)	Time Compensation Granted/Project Length (Days/mile)	Monetary Compensation Granted/Project Length($/mile)	Time Total Compensations (%)	Monetary Total Compensations (%)
Conventional Intersections and Interchange (CII)							
U-2525C	171	$10,038,993.70	11.21	15.3	$895,852.57	1.129%	11.038%
U-2702	10	$0.00	20.22	0.5	$0.00	0.037%	0.000%
U-2912	143	$18,002.87	4.18	34.2	$4,306.84	2.531%	0.053%
U-2928AB	8	$14,680.95	5.38	1.5	$2,728.56	0.110%	0.034%
U-3119A	82	$1,514.08	8.93	9.2	$169.58	0.680%	0.002%
U-3308	108	$111,632.27	34.39	3.1	$3,245.92	0.232%	0.040%
U-3315	242	$101,868.92	29.72	8.1	$3,428.01	0.603%	0.042%
U-3334A	7	$45,201.60	5.72	1.2	$7,903.33	0.091%	0.097%
U-3344A	254	$0.00	8.25	30.8	$0.00	2.278%	0.000%
U-3401	22	$0.00	27.78	0.8	$0.00	0.059%	0.000%
U-3462	93	$0.00	8.98	10.4	$0.00	0.766%	0.000%
U-3601	128	$0.00	8.32	15.4	$0.00	1.139%	0.000%
U-3612	6	$0.00	8.68	0.7	$0.00	0.051%	0.000%
U-3633	14	$0.00	9.49	1.5	$0.00	0.109%	0.000%
U-3823A	1	$785.00	6.79	0.1	$115.68	0.011%	0.001%
U-4010	27	$0.00	24.13	1.1	$0.00	0.083%	0.000%
U-4020	143	$8,157.60	29.14	4.9	$279.91	0.363%	0.003%
U-4421	30	$0.00	5.39	5.6	$0.00	0.412%	0.000%
U-4733	345	$0.00	21.46	16.1	$0.00	1.190%	0.000%
U-4755	326	$0.00	10.81	30.2	$0.00	2.231%	0.000%
U-4756	0	$12,501.59	30.10	0.0	$415.33	0.000%	0.005%
U-5008	818	$300,000.00	39.11	20.9	$7,671.43	1.548%	0.095%
U-5025	148	$0.00	2.18	67.8	$0.00	5.016%	0.000%
U-5315A	200	$0.00	38.62	5.2	$0.00	0.383%	0.000%
U-5806	263	$2,000,000.00	32.26	8.2	$62,000.00	0.603%	0.764%
Total	**10932**	**$63,200,588.07**	**696.05**	**1351.5**	**$8,115,860.39**	**100%**	**100%**

Table 3.8 presents the total number of supplemental agreements compensations that were granted per project. Supplemental agreements involve only monetary compensation. To compare the performance of each project, the monetary compensation granted was divided by the length of the project. Subsequently, to compare the projects, the compensation cost per mile was divided by the total. The color-coded results are represented as follows: green means good, yellow means average, and red means problematic.

Table 0.8 Total Supplemental Agreement Compensation per Project

Projects	Monetary Compensation Granted	Project Length	Monetary Compensation Granted/Miles	Monetary Total Compensations (%)
Continuous Flow Intersection (CFI)				
U-6084	$92,159.40	15.82	$5,824.47	0.03%
Diverging Diamond Interchange (DDI)				
I-3803B	$21,988,084.48	5.15	$4,271,970.70	18.42%
I-3819	$16,440,755.27	14.58	$1,127,366.08	4.86%
I-4413	$103,325.01	25.60	$4,036.56	0.02%
I-4733	$218,116.04	20.78	$10,496.83	0.05%
I-5111	$15,951,856.22	5.63	$2,835,885.55	12.23%
I-5501	$242,376.34	36.59	$6,624.95	0.03%
I-5700	$739,846.05	11.28	$65,599.68	0.28%
I-5714	$4,336,447.50	4.30	$1,008,657.69	4.35%
R-2248E	$15,778,647.76	9.02	$1,749,371.82	7.54%
R-3601	$1,185,213.62	15.51	$76,400.69	0.33%
U-2412B	$2,168,267.61	14.27	$151,967.28	0.66%
U-2719	$19,146,879.98	4.77	$4,014,668.38	17.31%
U-2925	$13,718,434.64	44.79	$306,285.05	1.32%
U-3109A	$1,077,314.89	10.99	$98,007.30	0.42%
U-4909	$1,283,751.20	12.49	$102,774.16	0.44%
Quadrant Roadway (QR)				
B-5121/B-5317	$630,793.81	17.07	$36,946.49	0.16%
R-2632AA	$1,137,843.94	10.00	$113,784.39	0.49%
U-2524D	$7,876,583.91	28.83	$273,200.77	1.18%
Reduced Conflict Intersection (RCI)				
U-3330	$2,119,016.64	13.21	$160,417.41	0.69%
U-5713/ R-5777AB	$7,979,715.83	5.10	$1,565,251.95	6.75%
W-5514	$710,476.14	3.38	$210,016.75	0.91%
W-5520	$552,640.37	6.88	$80,327.90	0.35%
Turbine Interchange (TI)				
R-2123CE	$4,888,939.23	7.64	$640,006.59	2.76%

Table 3.8 Total Supplemental Agreement Compensation per Project (Continuation)

Projects	Monetary Compensation Granted	Project Mile	Monetary Compensation Granted/Miles	Cost per Mile /Total
Conventional Intersections and Interchange (CII)				
I-5768	$178,497.39	0.73	$244,005.93	1.05%
I-5986A	$5,437,969.69	4.97	$1,094,067.71	4.72%
U-2525C	$22,531,067.14	11.21	$2,010,611.33	8.67%
U-2702	$44,058.90	20.22	$2,178.47	0.01%
U-2912	$75,813.53	4.18	$18,136.93	0.08%
U-2928AB	$8,510.50	5.38	$1,581.74	0.01%
U-3119A	$144,912.34	8.93	$16,230.18	0.07%
U-3302	-$3,353.85	70.42	-$47.62	0.00%
U-3308	$13,132,181.03	34.39	$381,843.42	1.65%
U-3309A	$92,703.15	13.73	$6,749.95	0.03%
U-3315	$589,100.54	29.72	$19,823.92	0.09%
U-3334A	$639,829.38	5.72	$111,871.71	0.48%
U-3344A	$15,391.00	8.25	$1,865.39	0.01%
U-3401	$17,233.06	27.78	$620.39	0.00%
U-3462	$77,855.20	8.98	$8,670.24	0.04%
U-3601	$72,364.09	8.32	$8,699.20	0.04%
U-3612	$49,854.96	8.68	$5,743.29	0.02%
U-3633	$319,796.76	9.49	$33,701.66	0.15%
U-3823A	$30,515.71	6.79	$4,496.91	0.02%
U-4006	$389,808.38	26.39	$14,769.41	0.06%
U-4010	$54,695.41	24.13	$2,266.82	0.01%
U-4020	$1,133,708.57	29.14	$38,900.38	0.17%
U-4421	$27,689.00	5.39	$5,136.31	0.02%
U-4428	$798,910.56	10.85	$73,659.55	0.32%
U-4733	$90,286.80	21.46	$4,207.36	0.02%
U-4755	$260,687.34	10.81	$24,113.58	0.10%
U-4756	$256,961.22	30.10	$8,536.82	0.04%
U-5008	$1,342,603.52	39.11	$34,332.29	0.15%
U-5018B	$571,047.64	10.77	$53,006.66	0.23%
U-5025	$4,691.60	2.18	$2,148.75	0.01%
U-5315A	$1,447,073.08	38.62	$37,471.58	0.16%
U-5806	218671.84	32.26	$6,778.83	0.03%
Total	**$190,418,621.36**	**912.77**	**$23,192,068.53**	**100%**

Identification of Inhibitors

Figures 3.11 and 3.12 present schematic representations of the process for identifying inhibitors, which is similar to claims and supplemental agreement data. Note that a project can have multiple claims, and each claim might reflect multiple inhibitors. For example, a claim states:

Due to plan revisions causing additional earthwork, additional surveying, and delays from Hurricane Florence, it was agreed upon to provide 86 days to ICT 6 to facilitate negotiations of the release of claim dated 4-4-19.

This specific claim reflects two inhibitors, weather impact, and design errors. Of the 45 projects that involved claims, 183 claims were identified as Final. From these 183 claims, 219 inhibitors were identified.

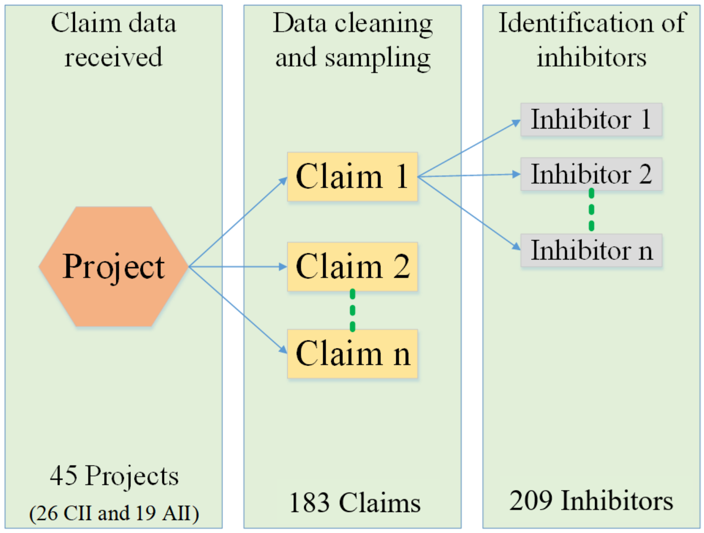


Figure 0.11 Process to Identify Inhibitors Involved in Claims

Figure 3.12 presents a schematic representation of the process to identify inhibitors in supplemental agreements. A project can have multiple supplemental agreements and each supplemental agreement can have multiple inhibitors. For example, a supplemental agreement is described as follows:

> *Due to the limited width of Right-of-way, personnel safety performing cross-sections, and the cost of performing photogrammetry, lump sum measurement of unclassified excavation will be used.*

This supplemental agreement is classified as having two inhibitors, contract changes and safety for workers. Of the 56 projects that involved a supplemental agreement, 1,240 were identified as Final. From these 1,580 inhibitors were identified.

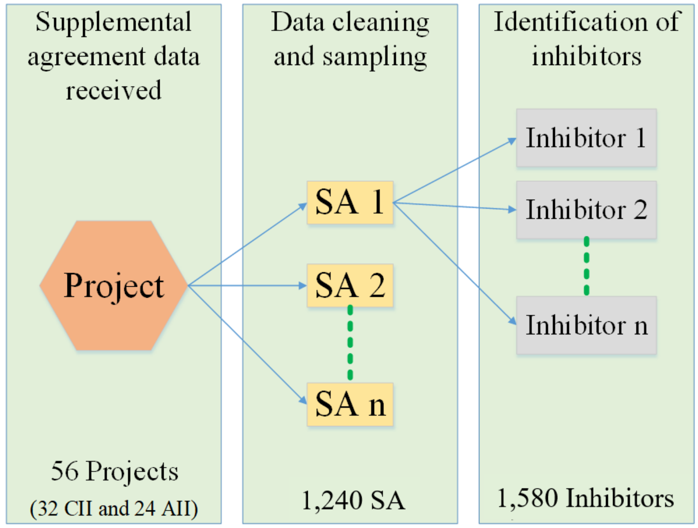


Figure 0.12 Process to Identify Inhibitors in Supplemental Agreement

Another area of interest is to identify the reasons for the claims submitted during these projects and which inhibitors caused them. Table 3.9 provides an overview of the total number of claims per design type; the inhibitors with the largest percentage per design are color-coded. Only percentages greater than 5% found to be affected by a particular design are color-coded. Red represents the most significant inhibitor found in a design that is greater than 25%, orange identifies the inhibitors ranging from 16% to 25%, and yellow identifies the inhibitors ranging from 5% to 15%. The findings indicate that the inhibitors that most frequently affected these projects during their construction are utility conflicts, contract changes, worker safety, weather impacts, and design errors.

Table 0.9 Total Inhibitors per Design Type for Claims Data

Inhibitors	Alternative Intersections and Interchanges					CII N=78
	CFI N=4	DDI N=93	QR N=5	RCI N=26	TI N=3	
Utilities	25%	13%	40%	31%	0%	41%
Contract changes	0%	14%	0%	19%	0%	15%
Safety of workers	0%	17%	0%	0%	0%	5%
Weather impact	50%	6%	0%	15%	0%	8%
Design errors	0%	2%	0%	23%	0%	6%
Inspection approval	25%	3%	0%	0%	0%	8%
Geotechnical issues	0%	6%	0%	0%	0%	3%
Construction sequencing	0%	6%	0%	0%	0%	1%
Water drainage during construction	0%	5%	0%	0%	0%	1%
Design changes	0%	2%	0%	0%	0%	4%
Permit acquisition	0%	2%	0%	0%	100%	0%
Signals and signage	0%	5%	0%	0%	0%	0%
Site access	0%	2%	0%	4%	0%	1%
Bridge construction	0%	3%	0%	0%	0%	0%
Contract errors	0%	2%	20%	0%	0%	0%
Environmental concerns	0%	1%	20%	4%	0%	0%
Design specifications	0%	0%	0%	0%	0%	3%
Material estimate change	0%	1%	0%	0%	0%	1%
Safety for drivers	0%	2%	0%	0%	0%	0%
Traffic control	0%	1%	20%	0%	0%	0%
Business Impact	0%	1%	0%	0%	0%	0%
Material delivery	0%	0%	0%	0%	0%	1%
Pavement Markings	0%	0%	0%	4%	0%	0%
Schedule change	0%	1%	0%	0%	0%	0%
Space constraints	0%	1%	0%	0%	0%	0%
Standards and specifications	0%	0%	0%	0%	0%	1%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.
N= Number of claims per project design type

Similarly, the inhibitors identified in supplemental agreements were classified by design type. Table 3.10 presents the results and the percentages shown in color indicate the inhibitors with the largest percentage per design. Note that only percentages greater than 5% found to be affected by a particular design are color-coded. Red signifies the largest inhibitor found in a design that is greater than 25%, orange identifies the inhibitors ranging from 10% to 20%, and yellow identifies the inhibitors ranging from 5% to 9%. The results indicate that the five most frequently occurring inhibitors that affect project performance based on supplemental agreement data are utilities, contract changes, material estimate change, signals and signage, and standards and specifications. Findings from Tables 3.9 and 3.10 indicate that inhibitors cannot be generalized for all DMUIIs, each design type needs to be evaluated to determine which are more predominant.

Table 0.10 Total Inhibitors per Design Type in Supplemental Agreement

Inhibitors	Alternative Intersections and Interchanges					CII N=742
	CFI N=11	DDI N=620	QR N=102	RCI N=91	TI N=14	
Utilities	9%	20%	16%	19%	14%	23%
Contract changes	9%	19%	19%	38%	0%	10%
Material estimate change	18%	9%	11%	2%	21%	15%
Signals and signage	64%	10%	6%	10%	29%	5%
Standards and specifications	0%	1%	2%	0%	0%	10%
Design changes	0%	6%	3%	5%	0%	5%
Geotechnical issues	0%	3%	2%	3%	7%	4%
Design specifications	0%	0%	5%	1%	0%	6%
Design errors	0%	3%	3%	3%	0%	4%
Traffic control	0%	4%	1%	7%	7%	1%
Bridge construction	0%	2%	4%	1%	0%	2%
Water drainage during construction	0%	3%	0%	0%	0%	2%
Right of way	0%	3%	2%	2%	0%	1%
Wall construction	0%	2%	6%	0%	0%	1%
Environmental concerns	0%	1%	3%	3%	0%	1%
Schedule changes	0%	1%	3%	0%	7%	1%
Site access	0%	2%	1%	0%	7%	0%
Water drainage	0%	0%	0%	0%	0%	2%
Multimodal transit accommodation	0%	1%	3%	2%	0%	0%
Safety for drivers	0%	1%	6%	0%	0%	1%
Pavement markings	0%	0%	0%	1%	0%	1%
Safety of workers	0%	2%	3%	1%	0%	1%
Space constraint	0%	1%	0%	0%	7%	0%
Construction sequencing	0%	1%	0%	0%	0%	0%
Equipment and labor estimate change	0%	0%	0%	0%	0%	1%
Additional cost	0%	0%	0%	0%	0%	1%
Contract errors	0%	0%	0%	0%	0%	0%
Cost estimate change	0%	0%	0%	0%	0%	0%
Safety for public	0%	0%	1%	0%	0%	0%
Work Zone Traffic Control	0%	0%	2%	0%	0%	0%
Business impact	0%	0%	0%	0%	0%	0%
Additional equipment	0%	0%	0%	0%	0%	0%
Delays in material delivery	0%	0%	0%	0%	0%	0%
Material safety	0%	0%	0%	0%	0%	0%
Permit acquisition	0%	0%	0%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges**N** = Number of supplemental agreements per project design type

Relevance of Inhibitors

Chi-square statistical analysis was conducted to test for any association between the inhibitors identified in the previous chapter using data sources such as interviews and surveys, claims, and supplemental agreements. Table 3.11 presents the results of the chi-square tests for independence and shows a statistically significant relationship (p-value = < 0.001). Thus, an association exists between the inhibitors identified from interviews and surveys, claims, and supplemental agreements. The Cramer's V value that suggests the relevance of the inhibitors listed in Table 3.11 is 0.322, which suggests that the magnitude of this relationship is moderate. The standardized residuals (ε_{ij}) that are greater than three are represented in bold numbers. For example, utilities (ε_{ij} = 3.06) are strongly linked to requests in supplemental agreements. In other words, this inhibitor is more likely to be present in supplemental agreements than other inhibitors.

As previously mentioned, inhibitors cannot be generalized for all DMUIIs. Therefore, identifying which inhibitors are the most relevant for each DMUII design type is of interest in this study. Claims and supplemental agreement data were used for statistical analysis. Table 3.12 presents the detailed results of the chi-square tests for independence of inhibitors per design type. The results show statistical significance (p-value < 0.05) among all the DMUII designs, which indicates an association between inhibitors. In other words, the results indicate that a statistical significance existed between inhibitors and was identified in claims, supplemental agreements, and interviews and surveys. Therefore, it is highly unlikely that results are random, they exhibit a meaningful connection. The Cramer's V values suggest that the magnitude of this relationship is high for the TI and CFI, moderate for the QR and RCI, and low for CII and DDI projects. Table 3.12 also presents the standardized residuals (ε_{ij}) for each inhibitor and highlights in bold the most influential ones. For example, CFI does not have an influential ε_{ij}, and signal and signage (ε_{ij} = 2.2) is strongly linked to requests in supplemental agreements for DDI projects.

Table 0.11 Chi-Square Test for Independence Results

Inhibitor	Interviews				Claims				Supplemental Agreement				O	Rank
	O	E	ε_{ij}	Rank	O	E	ε_{ij}	Rank	O	E	ε_{ij}	Rank	Mean	Total
Utilities	73	96.78	-3.35	1	23	21.53	0.36	1	160	137.69	3.06	2	85.3	1
Contract changes	0	72.59	-11.54	22	18	16.14	0.52	2	174	103.27	10.93	1	64.0	2
Signal and signage	4	35.91	-6.97	18	5	7.99	-1.14	8	86	51.10	7.41	3	31.7	3
Traffic control	51	32.51	4.23	3	2	7.23	-2.09	16	33	46.26	-2.95	6	28.7	4
Material estimate change	0	27.98	-6.87	22	1	6.22	-2.24	19	73	39.80	7.93	4	24.7	5
Right of way	50	26.84	5.80	4	0	5.97	-2.61	24	21	38.19	-4.19	9	23.7	6
Construction sequencing	53	25.33	7.13	2	6	5.63	0.16	6	8	36.04	-7.02	21	22.3	7
Safety for workers	35	24.95	2.61	8	16	5.55	4.74	3	15	35.50	-5.17	14	22.0	8
Space constraints	46	21.55	6.80	5	1	4.79	-1.84	19	10	30.66	-5.59	19	19.0	9
Safety for drivers	38	20.41	5.02	6	2	4.54	-1.27	16	14	29.04	-4.18	15	18.0	10
Geotechnical issues	17	18.90	-0.56	14	6	4.20	0.93	6	27	26.89	0.03	7	16.7	11
Environmental concerns	35	18.90	4.77	8	3	4.20	-0.62	12	12	26.89	-4.29	18	16.7	11
Design changes	0	17.77	-5.43	22	2	3.95	-1.04	16	45	25.28	5.86	5	15.7	12
Multimodal transit accommodation	32	17.39	4.51	10	0	3.87	-2.09	24	14	24.74	-3.22	15	15.3	13
Site access	25	16.63	2.64	12	3	3.70	-0.39	12	16	23.67	-2.35	13	14.7	14
Water drainage during construction	20	15.88	1.33	13	5	3.53	0.83	8	17	22.59	-1.75	12	14.0	15
Bridge construction	17	14.37	0.89	14	3	3.20	-0.12	12	18	20.44	-0.80	11	12.7	16
Public acceptance	37	13.99	7.90	7	0	3.11	-1.87	24	0	19.90	-6.64	33	12.3	17
Wall construction	16	13.61	0.83	16	0	3.03	-1.84	24	20	19.36	0.22	10	12.0	18
Design errors	0	12.85	-4.60	22	8	2.86	3.21	5	26	18.29	2.68	8	11.3	19
Business impact	28	11.72	6.09	11	1	2.61	-1.05	19	2	16.67	-5.34	25	10.3	20
Schedule change	0	5.29	-2.93	22	1	1.18	-0.17	19	13	7.53	2.95	17	4.7	21
Weather impact	0	4.54	-2.71	22	12	1.01	11.48	4	0	6.45	-3.75	33	4.0	22
Standards and specifications	0	3.78	-2.47	22	0	0.84	-0.96	24	10	5.38	2.94	19	3.3	23
High bids	9	3.40	3.86	17	0	0.76	-0.91	24	0	4.84	-3.25	33	3.0	24
Design specifications	0	3.02	-2.21	22	0	0.67	-0.86	24	8	4.30	2.63	21	2.7	25
Permit acquisition	0	2.27	-1.91	22	5	0.50	6.63	8	1	3.23	-1.83	28	2.0	26
Pavement markings	0	1.89	-1.75	22	1	0.42	0.94	19	4	2.69	1.18	23	1.7	27
Contract errors	0	1.51	-1.56	22	3	0.34	4.81	12	1	2.15	-1.16	28	1.3	28
Inspection approval	0	1.51	-1.56	22	4	0.34	6.61	11	0	2.15	-2.16	33	1.3	28

Table 3.11 Chi-Square Test for Independence Results (Continuation)

Inhibitor	Interviews				Claims				Supplemental Agreement				O	Rank
	O	E	ε_{ij}	Rank	O	E	ε_{ij}	Rank	O	E	ε_{ij}	Rank	Mean	Total
Equipment and labor estimate change	0	1.13	-1.35	22	0	0.25	-0.53	24	3	1.61	1.61	24	1.0	29
Safety for public	0	0.76	-1.10	22	0	0.17	-0.43	24	2	1.08	1.31	25	0.7	30
Work zone traffic control	0	0.76	-1.10	22	0	0.17	-0.43	24	2	1.08	1.31	25	0.7	30
Delays on material delivery	0	0.38	-0.78	22	0	0.08	-0.30	24	1	0.54	0.93	28	0.3	31
Material safety	0	0.38	-0.78	22	0	0.08	-0.30	24	1	0.54	0.93	28	0.3	31
Water drainage	0	0.38	-0.78	22	0	0.08	-0.30	24	1	0.54	0.93	28	0.3	31
Driver's expectation	1	0.38	1.28	19	0	0.08	-0.30	24	0	0.54	-1.08	33	0.3	31
Railroads	1	0.38	1.28	19	0	0.08	-0.30	24	0	0.54	-1.08	33	0.3	31
Schedule requirements	1	0.38	1.28	19	0	0.08	-0.30	24	0	0.54	-1.08	33	0.3	31
X^2 1012.89	**589**				**131**				**838**					

X^2	1012.89
df	76.00
p-value	<0.001
V	0.32

Table 0.12 Chi-Square Test Results per Alternative Intersections and Interchanges Design Type

Design	Inhibitor	Claims			Supplemental Agreement			O Mean	Rank Total	Chi-Square Results
		O	E	Ɛij	O	E	Ɛij			
CFI	Signals and signage	0	1.87	-2.2	7	5.13	2.2	3.5	1	
	Material estimate change	0	0.53	-0.9	2	1.47	0.9	1.0	2	X^2 12.44
	Utilities	1	0.53	0.8	1	1.47	-0.8	1.0	2	df 5
	Weather impact	2	0.53	2.5	0	1.47	-2.5	1.0	2	p-value 0.0291
	Contract changes	0	0.27	-0.6	1	0.73	0.6	0.5	3	V 0.83
	Inspection approval	1	0.27	1.7	0	0.73	-1.7	0.5	3	
	N	4				11				
DDI	Environmental concerns	12	0.41	2.7	124	2.59	-2.7	68.0	1	
	Site access	13	7.69	-3.1	119	48.31	**3.1**	66.0	2	
	Safety for public	5	0.96	1.1	60	6.04	-1.1	32.5	3	
	Pavement markings	0	2.20	-0.1	55	13.80	0.1	27.5	4	
	Equipment and labor estimate change	2	3.57	-1.5	37	22.43	1.5	19.5	5	
	Utilities	6	2.20	0.6	21	13.80	-0.6	13.5	6	
	Right of way	1	0.41	-0.7	25	2.59	0.7	13.0	7	
	Design errors	2	3.16	-0.1	20	19.84	0.1	11.0	8	
	Contract errors	16	1.10	-1.1	6	6.90	1.1	11.0	8	
	Geotechnical issues	5	0.14	-0.4	17	0.86	0.4	11.0	8	
	Wall construction	0	1.24	-1.2	17	7.76	1.2	8.5	9	
	Permit acquisition	3	18.67	-1.8	13	117.33	1.8	8.0	10	X^2 190.12
	Space constraint	2	0.55	0.7	14	3.45	-0.7	8.0	10	df 32
	Safety for drivers	6	8.93	-1.5	8	56.07	1.5	7.0	11	p-value <0.001
	Water drainage	0	0.41	**4.4**	14	2.59	-4.4	7.0	11	V 0.27
	Contract changes	1	0.41	1.0	9	2.59	-1.0	5.0	12	
	Inspection approval		1.92	-1.5	9	12.08	1.5	4.5	13	
	Weather impact	0	1.10	-0.1	9	6.90	0.1	4.5	13	
	Material delivery	1	3.02	1.2	8	18.98	-1.2	4.5	13	
	Material safety	1	1.10	**7.1**	7	6.90	-7.1	4.0	14	
	Design changes	0	0.41	2.7	8	2.59	-2.7	4.0	14	
	Schedule changes	2	1.24	-1.2	5	7.76	1.2	3.5	15	
	Construction sequencing	6	0.14	-0.4	0	0.86	0.4	3.0	16	
	Business Impact	1	1.37	-0.3	3	8.63	0.3	2.0	17	
	Multimodal transit accommodations	0	2.33	-1.7	3	14.67	1.7	1.5	18	

Table 3.12 Chi-Square Test Results per Alternative Intersections and Interchanges Design Type (Continuation)

Design	Inhibitor	Claims			Supplemental Agreement			O	Rank	Chi-Square
		O	E	Ɛij	O	E	Ɛij	Mean	Total	Results
DDI	Water drainage during construction	2	1.24	-0.2	1	7.76	0.2	1.5	18	
	Design specifications	3	0.14	-0.4	0	0.86	0.4	1.5	18	
	Material estimate change	1	18.40	-1.2	2	115.60	1.2	1.5	18	
	Traffic control	2	5.36	-1.6	1	33.64	1.6	1.5	18	
	Standards and specifications	0	3.02	**8.2**	2	18.98	-8.2	1.0	19	
	Signals and signage	0	1.92	**3.2**	1	12.08	-3.2	0.5	20	
	Safety of workers	0	0.27	-0.6	1	1.73	0.6	0.5	20	
	Bridge construction	0	3.98	2.2	1	25.02	-2.2	0.5	20	
	N	81				496				
QR	Contract changes	0	0.89	-1.1	4	18.11	1.1	1.1	1	
	Bridge construction	0	0.51	-0.8	19	10.49	0.8	0.8	2	
	Multimodal transit accommodations	1	0.28	-0.6	0	5.72	0.6	0.6	3	
	Contract errors	0	0.28	-0.6	3	5.72	0.6	0.6	3	
	Safety for public	0	0.28	-0.6	3	5.72	0.6	0.6	3	
	Wall construction	0	0.23	-0.5	5	4.77	0.5	0.5	4	
	Utilities	1	0.19	-0.5	3	3.81	0.5	0.5	5	
	Safety for drivers	0	0.14	-0.4	2	2.86	0.4	0.4	6	X^2 39.03
	Signals and signage	0	0.14	-0.4	11	2.86	0.4	0.4	6	df 21
	Design changes	0	0.14	-0.4	3	2.86	0.4	0.4	6	p-value 0.010
	Schedule changes	0	0.14	-0.4	2	2.86	0.4	0.4	6	V 0.36
	Traffic control	0	0.14	-0.4	6	2.86	0.4	0.4	6	
	Environmental concerns	0	0.09	-0.3	1	1.91	0.3	0.3	7	
	Design errors	0	0.09	-0.3	3	1.91	0.3	0.3	7	
	Right of way	0	0.09	-0.3	3	1.91	0.3	0.3	7	
	Site access	0	0.09	-0.3	6	1.91	0.3	0.3	7	
	Safety of workers	0	0.05	-0.2	1	0.95	0.2	0.2	8	
	Geotechnical issues	0	0.05	-0.2	2	0.95	0.2	0.2	8	
	Work Zone Traffic Control	1	0.84	1.4	1	17.16	-1.4	-1.4	9	
	Design specifications	2	0.19	2.0	16	3.81	-2.0	-2.0	10	
	Standards and specifications	0	0.09	**3.1**	6	1.91	-3.1	-3.1	11	
	Material estimate change	0	0.05	**4.5**	2	0.95	-4.5	-4.5	12	
	N	**5**				**102**				

Table 3.12 Chi-Square Test Results per Alternative Intersections and Interchanges Design Type (Continuation)

Design	Inhibitor	Claims			Supplemental Agreement			O	Rank	Chi-Square
		O	E	ε_{ij}	O	E	ε_{ij}	Mean	Total	Results
RCI	Utilities	5	5.28	1.5	35	19.72	-1.5	20.0	1	
	Safety for public	8	0.21	-0.5	17	0.79	0.5	12.5	2	
	Signals and signage	6	1.90	-1.6	3	7.10	1.6	4.5	3	
	Bridge construction	0	0.21	-0.5	9	0.79	0.5	4.5	3	
	Environmental concerns	0	0.21	1.9	6	0.79	-1.9	3.0	4	
	Design errors	0	1.90	3.5	5	7.10	-3.5	2.5	5	X^2 45.75
	Site access	4	0.21	1.9	0	0.79	-1.9	2.0	6	df 17
	Weather impact	0	0.85	**3.9**	3	3.15	-3.9	1.5	7	p-value <0.001
	Right of way	0	0.42	-0.7	3	1.58	0.7	1.5	7	V 0.39
	Geotechnical issues	0	0.63	-0.9	2	2.37	0.9	1.0	8	
	Multimodal transit accommodations		0.63	-0.9	2	2.37	0.9	1.0	8	
	Schedule changes	1	0.63	-0.9	1	2.37	0.9	1.0	8	
	Material estimate change	0	0.42	-0.7	2	1.58	0.7	1.0	8	
	Traffic control	0	1.27	-1.3	1	4.73	1.3	0.5	9	
	Design changes	1	1.06	-1.2	0	3.94	1.2	0.5	9	
	Pavement markings	0	0.42	1.0	1	1.58	-1.0	0.5	9	
	Contract changes	0	9.51	-2.1	1	35.49	2.1	0.5	9	
	Design specifications	1	0.21	-0.5	0	0.79	0.5	0.5	9	
	N	**26**			**91**					
TI	Environmental concerns	0	0.18	-0.48	4	0.82	0.48	2.0	1	
	Permit acquisition	0	0.53	**4.12**	3	2.47	-4.12	1.5	2	
	Utilities	3	0.35	-0.70	0	1.65	0.70	1.5	2	
	Traffic control	0	0.18	-0.48	2	0.82	0.48	1.0	3	X^2 17.00
	Signals and signage	0	0.71	-1.06	1	3.29	1.06	0.5	4	df 8
	Material estimate change	0	0.53	-0.88	1	2.47	0.88	0.5	4	p-value 0.0301
	Geotechnical issues	0	0.18	-0.48	1	0.82	0.48	0.5	4	V 1.00
	Site access	0	0.18	-0.48	1	0.82	0.48	0.5	4	
	Space constraint	0	0.18	-0.48	1	0.82	0.48	0.5	4	
	N	**3**				**10**				

Table 3.12 Chi-Square Test Results per Alternative Intersections and Interchanges Design Type (Continuation)

Design	Inhibitor	Claims			Supplemental Agreement			O	Rank	Chi-Square
		O	E	Ɛij	O	E	Ɛij	Mean	Total	Results
CII	Site access	32	0.39	1.04	167	3.61	-1.04	99.5	1	
	Environmental concerns	1	1.06	-1.09	115	9.94	1.09	58.0	2	
	Design specifications	12	4.64	-1.33	71	43.36	1.33	41.5	3	
	Equipment and labor estimate change	1	0.48	-0.73	73	4.52	0.73	37.0	4	
	Water drainage	2	1.74	-1.40	46	16.26	1.40	24.0	5	
	Geotechnical issues	3	3.09	-0.06	34	28.91	0.06	18.5	6	
	Weather impact	0	0.58	**7.51**	34	5.42	-7.51	17.0	7	
	Design errors	5	3.00	1.24	26	28.00	-1.24	15.5	8	
	Safety for public	2	1.45	-1.28	29	13.55	1.28	15.5	8	
	Cost estimate change	0	0.29	-0.57	18	2.71	0.57	9.0	9	
	Safety of workers	4	0.68	**4.27**	11	6.32	-4.27	7.5	10	
	Construction sequencing	1	0.19	1.93	14	1.81	-1.93	7.5	10	
	Contract changes	0	8.70	1.62	13	81.30	-1.62	6.5	11	X^2 181.57
	Right of way	0	0.87	-0.99	11	8.13	0.99	5.5	12	df 32
	Safety for drivers	0	0.39	-0.66	11	3.61	0.66	5.5	12	p-value <0.001
	Pavement markings	0	0.97	-1.04	10	9.03	1.04	5.0	13	V 0.22
	Additional cost	0	0.58	-0.80	9	5.42	0.80	4.5	14	
	Contract errors	0	0.29	-0.57	9	2.71	0.57	4.5	14	
	Water drainage during construction	0	1.55	-0.47	8	14.45	0.47	4.0	15	
	Wall construction	0	0.97	-1.04	8	9.03	1.04	4.0	15	
	Utilities	0	19.73	3.88	6	184.27	-3.88	3.0	16	
	Additional equipment	6	0.10	-0.33	0	0.90	0.33	3.0	16	
	Work Zone Traffic Control	6	0.10	-0.33	0	0.90	0.33	3.0	16	
	Bridge construction	0	1.45	-1.28	5	13.55	1.28	2.5	17	
	Inspection approval	1	0.58	**7.51**	3	5.42	-7.51	2.0	18	
	Design changes	0	3.87	-0.48	3	36.13	0.48	1.5	19	
	Signals and signage	0	3.29	-1.95	3	30.71	1.95	1.5	19	
	Standards and specifications	1	7.45	-2.61	1	69.55	2.61	1.0	20	
	Material estimate change	0	11.31	-3.47	1	105.69	**3.47**	0.5	21	
	Traffic control	0	1.06	-1.09	1	9.94	1.09	0.5	21	
	Schedule changes	0	0.87	-0.99	1	8.13	0.99	0.5	21	
	Multimodal transit accommodations	0	0.19	-0.46	1	1.81	0.46	0.5	21	
	Material delivery	1	0.10	**3.06**	0	0.90	-3.06	0.5	21	
	N	**78**				**742**				

Limitations

This study has the following limitations:

- The classification of inhibitors needs to be subcategorized. The current analysis does not break down the inhibitors into subsets to discern how an inhibitor affects a project. For example, a current claim may be classified as utilities-related, but this classification does not fully explain how utilities affected the project. The classification system needs to specify the proportion of the project that is being affected (e.g., construction activities, lane closure, the entire project, etc.), and how the inhibitor affected the project (e.g., suspension of work, additional work required, modifications to design, etc.).
- Claims and supplemental agreement data need to be evaluated based on site conditions, such as weather, accessibility of the construction site, and location (e.g., coastal, mountain, or piedmont regions in North Carolina). Some locations are more prone to be affected by site conditions than others.
- Also, a larger sample size for DMUII projects is needed. The sample size for this study is limited to a small number of NCDOT projects for some designs (e.g., only one CFI project). Including projects from other DOTs is recommended to address the small sample size issue.
- This study does not distinguish between inhibitors resulted from the type of DMUII vs inhibitors that are prone to be present based on the location of the project. To address for this concern, a record of the initial concerns linked to a project need to be disclosed (to the person evaluating claims and supplemental agreements) in order to quantify if the impact of the suspected inhibitors was minimum or to use this list of inhibitors to simply isolate them from the analysis and account for the ones that were not previously disclosed. In this study, no information about what the initial concerns pertain to each project were received, therefore, this analysis cannot be performed.

Conclusion

Transportation infrastructure is vital for national and regional economies. Therefore, completing projects within the budget and schedule is crucial when public funding is involved. Even though researchers have investigated transportation project performance, limited literature is available that focuses specifically on project design types. Accurately predicting a project's outcome is challenging, especially when little information is available about the construction and project performance of DMUII projects. This research is the first formal investigation into the identification of construction inhibitors that affect DMUII designs to evaluate and compare the overall project performance of DMUII designs versus CII designs using claims and supplemental agreement data.

Two strategies were evaluated to normalize data and estimate the magnitude of claims. The evaluation strategies focused on claim compensations and project schedule. The results indicate that CII is the design type with the number of claims filed. Based on this information, it can be concluded that CII are more prone to file claims than DMUII designs. The evaluation results for compensations indicate that projects with a CII designs yield the most schedule variation but that the highest monetary compensation was granted to a project with a DDI design. Inhibitors that affect DMUII and CII designs also were identified using claims data.

Similarly, supplemental agreement data were used to identify projects that are affected the most and to identify the inhibitors that affect these projects. Supplemental agreements were normalized in terms of compensation. The results indicated that CII is the design that yields the most cost variations which indicate that CIIs are more prone to file a supplemental agreement. This finding further proves that, despite the lack of unfamiliarity surrounding DMUII projects, their construction performance is not exacerbated compared to projects with CII designs.

Chi-square tests for independence were performed to validate the findings, and the results indicate that the most common inhibitors for DMUII projects are utility conflicts, construction sequencing, signal and signage, traffic control, and material estimate changes. This initial list of inhibitors is a good indication of what is affecting DMUIIs. However, finding in this research also determines that inhibitors cannot be generalized for all DMUIIs, each design type needs to be evaluated to determine which are more predominant. Therefore, this study also identifies and categorized the most relevant inhibitors based on the design type. A checklist to help project managers, designers, contractors, and others determine whether a given project is more or less constructable was developed and is attached in appendix C. This checklist provides the inhibitors per design type and a list of generic inhibitors that can be utilized to determine the most important factors that should be considered to gauging constructability of any highway project.

The level of effort for this analysis took approximately 212 hours. This estimated level of effort does not account for the data collection effort. The time is considering 30 hours of research to investigate effective methods to analyze claims and supplemental agreements. The data cleaning process for claims took approximately 4 hours and 8 hours for supplemental agreements. The process to categorize each claim took 45 hours and 65 hours for supplemental agreements. Lastly, the analysis portion of this study took around 30 hours for claims and 30 hours for supplemental agreements. This effort can be replicated as more data becomes available for other DMUII designs.

ASSESSING THE PERFORMANCE OF ALTERNATIVE INTERSECTIONS AND INTERCHANGES VERSUS CONVENTIONAL DESIGNS USING COST AND SCHEDULE DATA

A challenge associated with diverse, modern, and unconventional intersections and interchanges (DMUII) designs lies in the construction industry's negative perception of them, which is based on the belief that DMUIIs incur additional construction time and cost compared to projects with conventional intersection and interchange (CII) designs. To evaluate the legitimacy of this perception, a comprehensive analysis of project performance was conducted that considers cost and schedule data from DMUII and CII projects constructed in North Carolina. By effectively identifying differences in project performance between DMUIIs and CIIs, the construction industry's current perception of DMUIIs can be assessed properly and transportation agencies may be able to consider DMUII projects as possible sustainable solutions to several transportation problems.

Data Sample

Project cost and schedule data for a total of 57 projects were obtained from the Highway Construction and Materials System (HiCAMS), which is managed by the North Carolina Department of Transportation (NCDOT). These 57 projects are the same dataset utilized for the claims and supplemental agreement data introduced in the previous chapter and the selection of this sample size was described in "data sample" sub-section. The analysis in this chapter focuses on analyzing the changes in cost and schedule of projects. The purpose of this study is to analyze changes in cost and schedule to determine what design type was more affected and quantify that impact. Figure 4.1 presents the project characteristics, cost data, and schedule data for the 57 NCDOT projects.

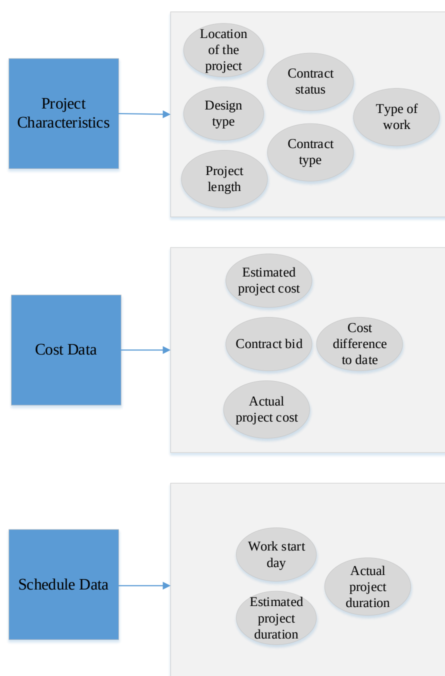


Figure 0.1 Project Information Obtained from NCDOT for 57 Construction Projects

Methodology

Figure 4.2 presents the methodology that was used to evaluate project performance in terms of cost and schedule variations using data obtained from the NCDOT. The figure presents the type of data utilized, the analytical method, and the results obtained from this study. Frequency analysis results are reported as histograms and percentage tables and include cost differences to date (overrun/underrun values) as well as contract bid data, estimated project cost, and actual project cost. Descriptive frequency analysis was also performed to evaluate project performance in terms of schedule variations. This analysis used estimated and actual project duration data and helped to identify the most problematic projects and to determine differences in project performance between DMUIIs and CIIs.

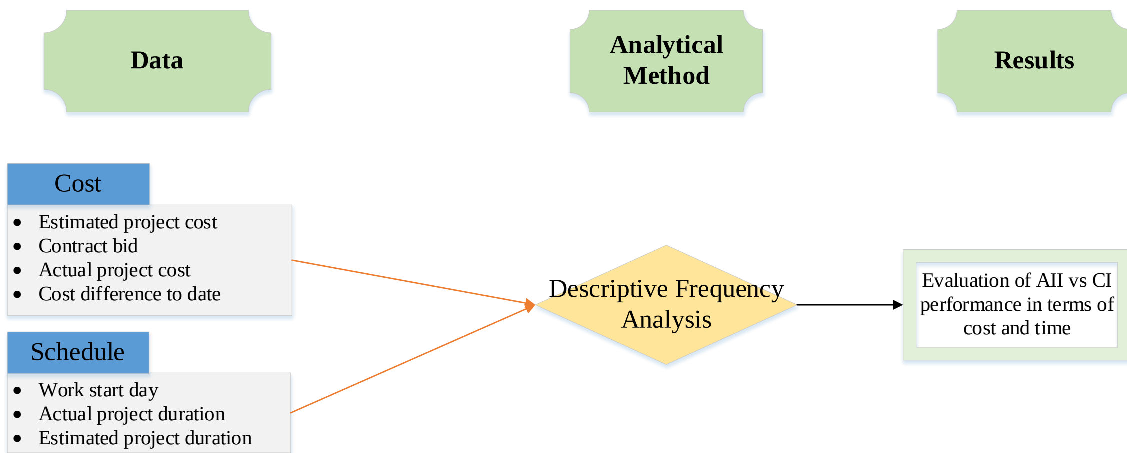
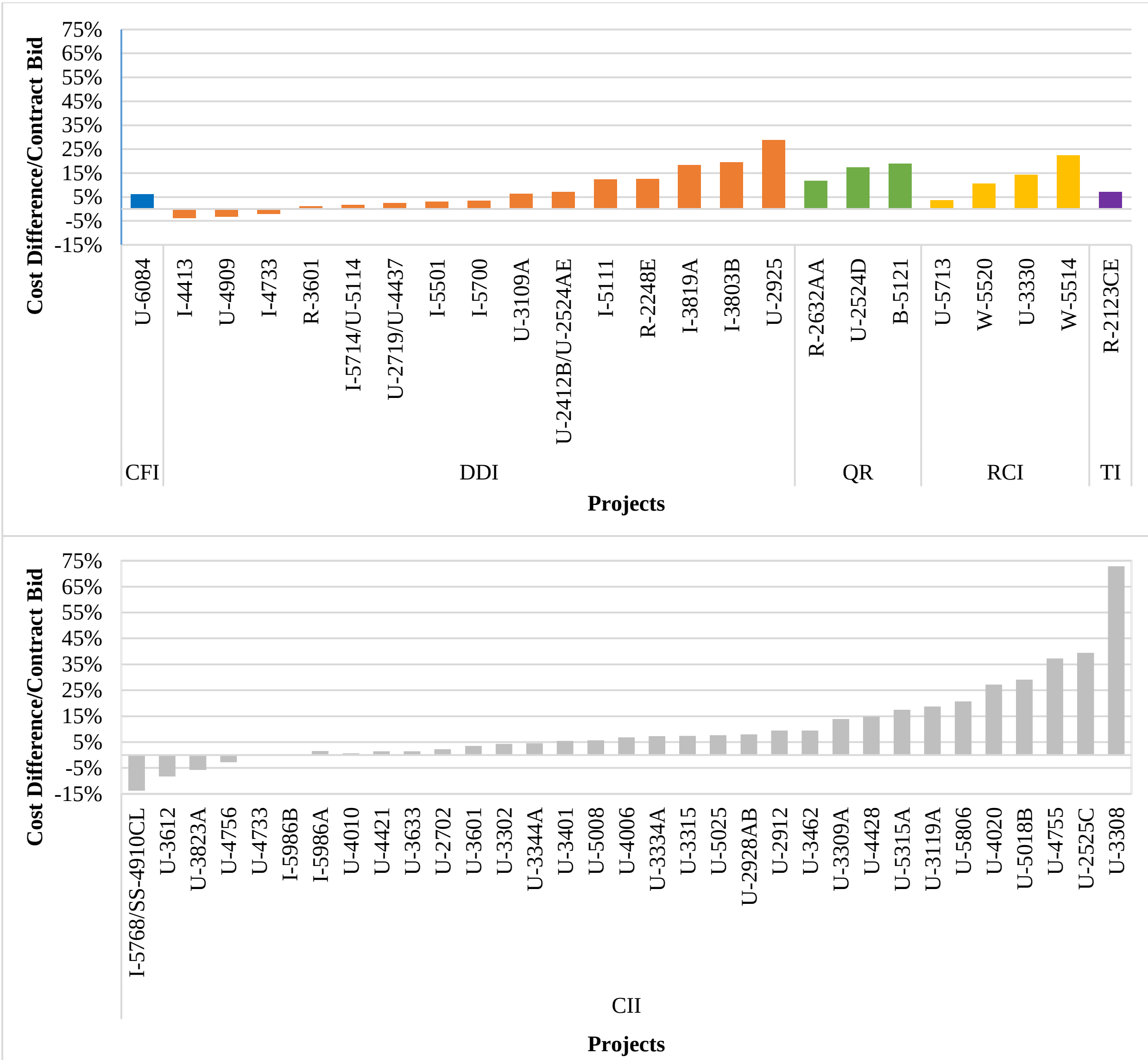


Figure 0.2 Methodology to Determine Differences between Alternative vs Conventional Intersections and Interchanges

Analysis

Cost (Total Difference)

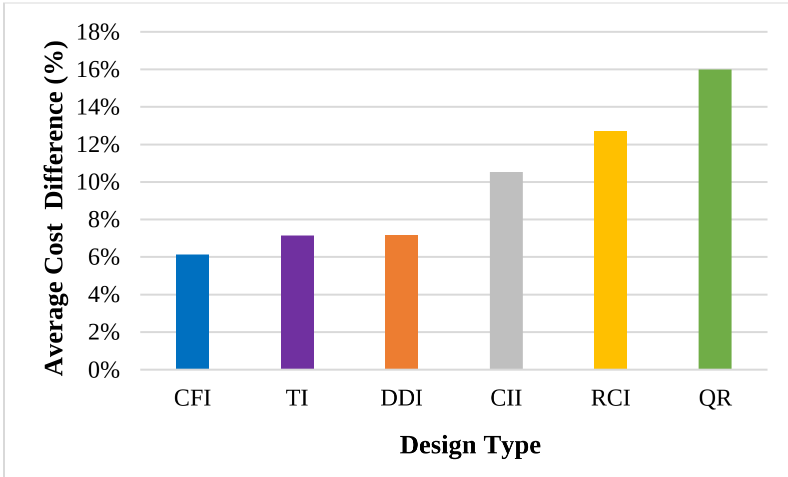
Figure 4.3 presents the results for the cost differences, which were determined by dividing the cost difference (the difference between the estimated project cost and the actual cost required to perform the work) by the contract bid (the value of the winning bid awarded by the NCDOT). The results are presented as percentages to allow project performance to be identified easily. For example, continuous flow intersection (CFI) project U-6084 had a contract bid cost of $7,183,515 and a cost difference of $439,570, which yielded a 6% total cost difference. The majority of the projects showed a < 15% cost difference. The projects with the most variation and over 15% cost difference are CII designs. The diverging diamond interchange (DDI) is the design with the second highest cost difference (29%), but the percentage of difference is not as great as that of the CII projects (73%).



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

Figure 0.3 Cost Difference per Project

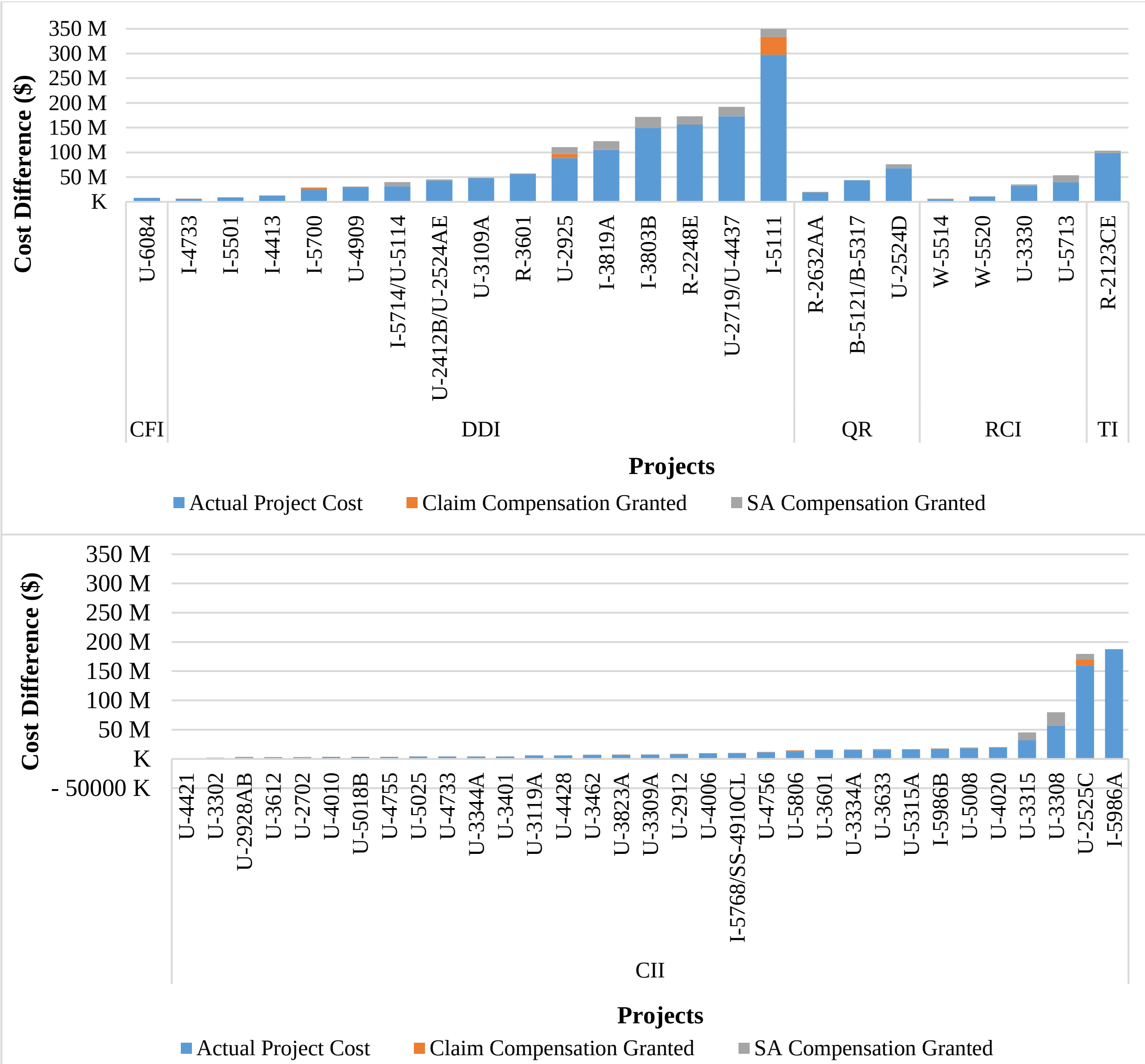
Figure 4.4 presents the averaged results for the cost difference per contract bid for each design type. As shown, QR is the design type with the largest percentage of the cost difference between the initially contracted cost and the final cost. The second largest cost difference is shown for reduced conflict intersection (RCI) projects, followed by CIIs. Even though this results are indicative of the performance, using averages is not always ideal. It is important to remember that for this analysis, sample sizes vary per design type. For the cost and schedule analysis, the sample sizes were 1 CFI, 15 DDI, 3 QR, 4 RCI, 1 TI, and 32 CIIs.



CFI: Continuous flow intersection. **CII:** Conventional intersections and interchanges.
DDI: Diverging diamond interchange. **QR**: Quadrant roadway. **RCI**: Reduced conflict intersection.
TI: Turbine intersection.

Figure 0.4 Cost Difference per Design Type

Figure 4.5 explains the extent to which the cost difference resulted from claims and supplemental agreements. As shown, most claims and supplemental agreements have an impact on the overall cost of the projects. The projects that were affected the most by cost differences are DDI project I-5111 and CII U-2525C. Another important finding is that supplemental agreements impacted the cost more than claims, as evidenced by the DDI I-3819A and CII U-3308 projects where supplemental agreements account for about a quarter of the overall cost.

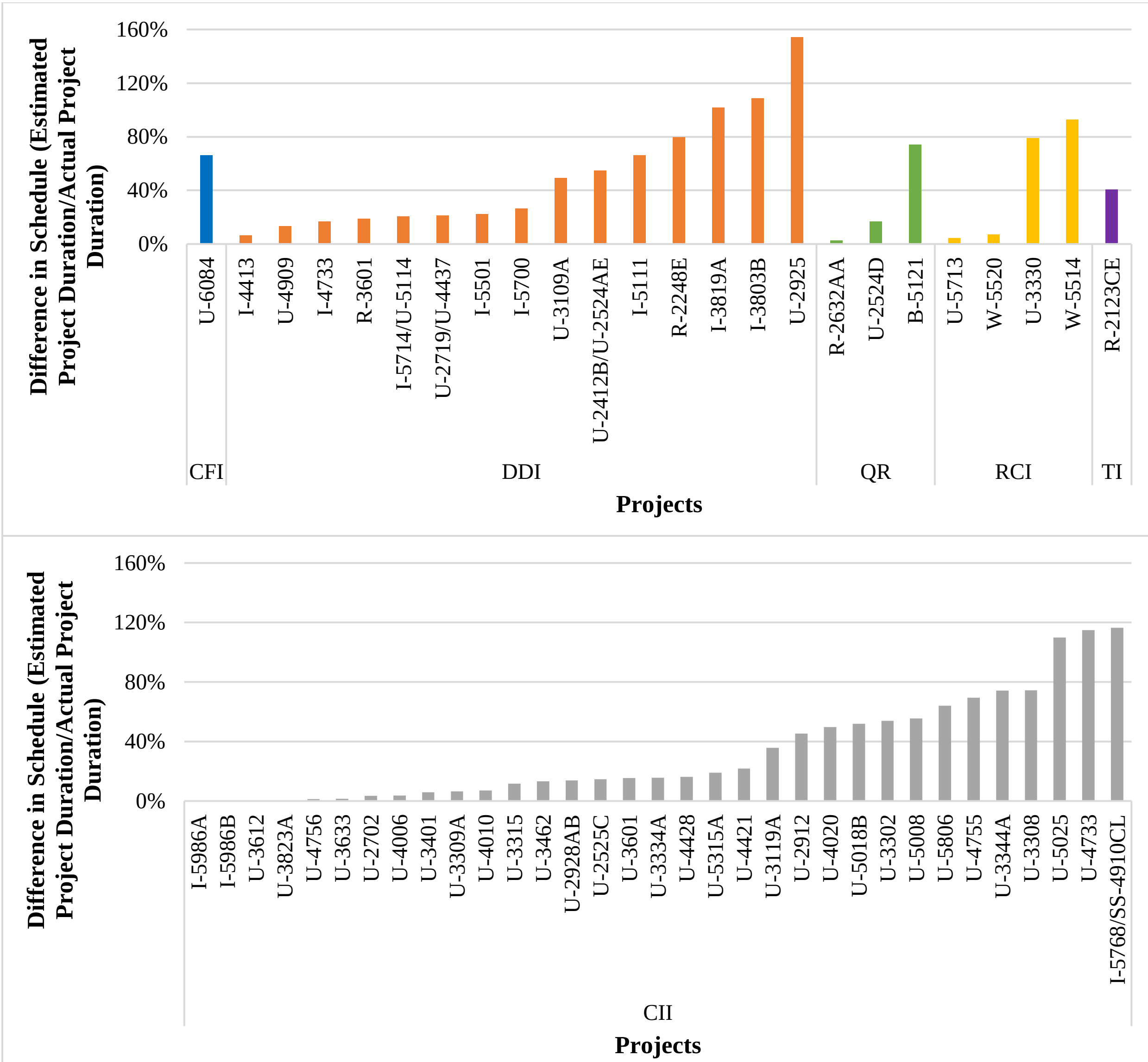


CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

Figure 0.5 Percentage of Difference in Cost in Terms of Claims and Supplemental Agreement

Schedule Variation (Total Difference)

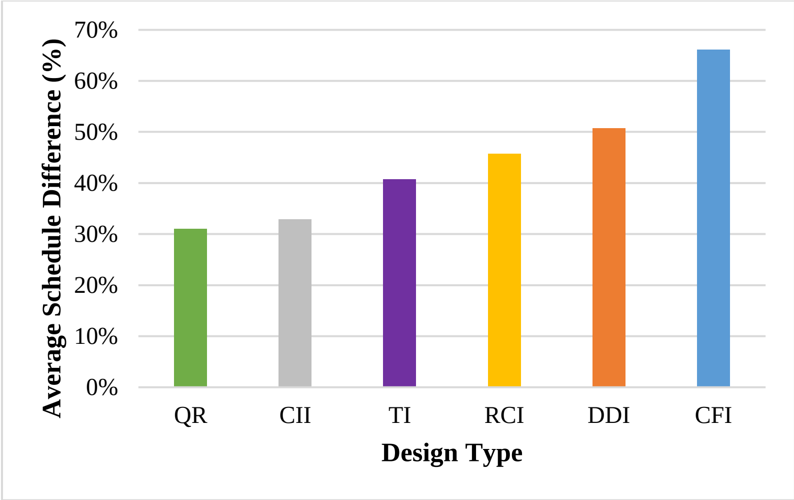
The 57 projects were evaluated in terms of their schedule variations. Figure 4.6 presents the results for schedule variations between the estimated project duration, which is the expected number of days needed to complete the project, and the actual project duration, which is the actual time for the project to be completed. The results were evaluated in terms of percentage to facilitate identification of the performance of the projects. All the projects were affected significantly by changes to their schedule. On average, all the designs exhibited schedule variations of over 30 percent. Although significant variations are evident in the figure, the DDI (U-2925) design reflects the greatest schedule variations. Other designs that reflect change percentages that exceed 90% include CII and RCIs.



CFI: Continuous flow intersection. **DDI**: Diverging diamond interchange. **QR**: Quadrant roadway.
RCI: Reduced conflict intersection. **TI:** Turbine intersection. **CII:** Conventional intersections and interchanges.

Figure 0.6 Project Schedule Variations

Figure 4.7 presents the averaged results for the schedule difference per design type. As shown, QR is the design type with the lowest schedule difference of 31%. The designs with the largest schedule difference were CFIs, DDIs, and RCIs. Even though this results are indicative of the performance, it is important to notice that using average is not always ideal since sample size per design type is not the same. For example, in the case of CFI and TI, sample size includes only one project.



CFI: Continuous flow intersection. **CII:** Conventional intersections and interchanges.
DDI: Diverging diamond interchange. **QR**: Quadrant roadway. **RCI**: Reduced conflict intersection.
TI: Turbine intersection.

Figure 0.7 Schedule Difference per Design Type

Project Performance

Table 4.1 lists the top five projects affected by cost and schedule variations. In terms of project costs, four of the top five projects have CII designs, which means that CII are more prone to be affected by cost variation. In terms of schedule variations, the project most impacted is a project with DDI design. However, by evaluating the top five projects with largest schedule variation, projects with DDIs and CII seem to be the most affected. This indicates that overall, CIIs and DDIs experience the largest cost and schedule variations in comparison to other design types.

Table 0.1 Top Five Projects with Most Variations in Cost and Schedule

Project Cost	Project Schedule
CII U-3308 (73%)	DDI I-4733 (154%)
CII U-2525C (39%)	CII I-5768/SS-4910CL (116%)
CII U-4755 (37%)	CII U-4733 (115%)
CII U-5018B (29%)	CII U-5025 (110%)
DDI U-2925 (29%)	DDI I-5714/U-5114 (109%)

CII: Conventional intersections and interchanges. **DDI**: Diverging diamond interchange.

Limitations

This study had potential limitations that offer opportunities for future work. The variations in cost and schedule data can be applied for further in-depth analysis to account for the year when the projects were constructed in order to determine whether projects with above average cost and schedule change variation were experienced among the first such designs to be completed. That is, unfamiliarity with the design type could be a cause of these differences (accounting for inflation, of course). Also, a larger sample size for DMUII projects is recommended. The sample size for this study was limited to a small number of projects for some designs, which limits the generalizability of the conclusions and results.

Conclusion

This study compared the cost and schedule performance of DMUII and CII designs in several NCDOT projects. Analysis of the variation in the cost and schedule data indicates that CII and DDI projects show the greatest variance in cost and schedule differences. The level of effort for this analysis took approximately 40 hours to perform the categorization and analyze results. The cost and schedule data indicated a plausible methodology of how cost and schedule data can be collected and analyzed. To obtain stronger results, a national (multistate) analysis is needed. To do so, a multistate database with projects constructed over many years will be needed to perform similar analysis. By doing so, findings can be utilized by transportation agencies to better understand project performance and the design types that can be constructed to promote efficient resource allocation.

CASE STUDY: EVALUATION OF ROADWAY CONGESTION AND DETOURS DUE TO WORK ZONE TRAFFIC CONTROL MEASURES

Departments of Transportation exhaustively work on minimizing disruptions due to construction activities. In the case of North Carolina Department of Transportation (NCDOT), a systematic approach to analyze and implement detour routes is used. When faced with road closures, construction projects, accidents, or other events that necessitate work zone traffic control (WZTC) measures, NCDOT carefully evaluates potential routes based on factors like traffic flow, safety, and road capacity to select the most suitable detour route. However, detours are not always ideal to manage construction work zone activities that take place in transportation networks since they often contribute to disruptions to normal traffic flow. Understanding the impacts of WZTC measures by utilizing other approaches such as the evaluation of travel time, roadway congestion, and road user costs (RUCs) is essential for effective traffic management and planning. This research performs a comprehensive case study of two NCDOT projects that were undertaken to evaluate the effects of WZTC measures on roadway congestion. The performance of a diverse, modern, and unconventional intersections and interchanges (DMUII) and a conventional intersection and interchange (CII) constructed in North Carolina was evaluated and the impacts of different WZTC measures on travel time, roadway congestion, and RUC were systematically analyzed.

The primary objective of this case study is to assess the effectiveness of various measures employed for WZTC and their influence on key performance indicators. First, travel time was analyzed to determine the additional time and distance vehicles must travel due to WZTC measures. Roadway congestion analysis also was conducted using the travel time index (TTI) (that is based on free flow), which provides a valuable metric for assessing congestion levels and delays experienced by road users within work zones and detour routes. Moreover, an RUC model is introduced to estimate the economic impact and user costs associated with WZTC activities. This model quantifies the monetary consequences and potential productivity loss that result from disruptions caused by WZTC. An evaluation of WZTC measures can provide valuable insights and recommendations to determine whether a DMUII or CII design is more conducive to effective WZTC. In conjunction with this evaluation, actionable recommendations were developed to reduce work zone delays and minimize RUCs.

Methodology

Traffic control measures for a DMUII diverging diamond interchange (DDI) project and a CII project in North Carolina were evaluated in this study in terms of travel time, roadway capacity analysis, and RUC.

Travel Time

In this study, ‘travel time’ refers to the time required for a vehicle to travel from point A to point B. Travel time is an important consideration in determining how much further vehicles must travel due to WZTC measures compared to ordinary traffic conditions. Equation 1 is used to calculate travel time.

$$Travel\ Time = \frac{Distance(miles)}{AverageSpeed\ (mph)} \quad (1)$$

Roadway Congestion Operations

Iteris ClearGuide software (Iteris 2023) was employed in this study to analyze roadway congestion. ClearGuide is comprehensive and advanced software that was developed to assist traffic engineers and planners in analyzing and optimizing signal operations and improving overall traffic flow. This software integrates various modules and functionalities to assist in the management and control of traffic signal systems and offers such features as traffic signal timing optimization, adaptive signal control, and real-time traffic data analysis. ClearGuide allows users to conduct comprehensive traffic signal timing studies, evaluate different scenarios, and optimize signal plans based on specific objectives, such as reducing delays, improving intersection capacity, or prioritizing certain movements (Iteris 2021). The software also provides real-time monitoring and reporting capabilities, allowing users to analyze and visualize key performance metrics and make informed decisions for traffic signal management.

One particular feature of ClearGuide is that it allows the user to create routes and access historical data from 2015 up to real-time data. For this study, ClearGuide was used to recreate the routes and detours used in the DDI and CII projects. Historical data were retrieved for each project and the monthly performance reports of the routes and detours were generated. ClearGuide's performance report feature lets users select up to three performance measures across selected routes and filter the report to a particular time of day (e.g., PM peak) and days of the week (Iteris 2021). The performance measure selected for this case study is the TTI. The granularity of the analysis was monthly and the TTI was applied for the entire day, with no filters for AM or PM peak times.

The TTI is a metric that is used to measure congestion levels and delays experienced by road users compared to free-flow conditions. Iteris (2021) defines the TTI as the ratio of the average travel time to the free-flow travel time. In other words, the TTI provides a numerical value that indicates the relative increase in travel time compared to an ideal, uncongested scenario where traffic flows smoothly at free-flow speeds. The TTI value of 1 indicates no congestion or delay (i.e., the travel time is the same as for free-flow conditions) and values greater than 1 indicate higher levels of congestion and longer travel times. For example, if the TTI value for a specific road segment is 1.2, the actual travel time on that segment is 20% longer than the expected travel time under free-flow conditions. The TTI is a valuable tool for this study as it allows congestion levels to be evaluated, traffic performance to be monitored, and the impact of WZTC measures to be assessed.

Road User Cost (RUC) Model

Determining the value of travel time in terms of RUC is important in transportation scenarios because it allows the WZTC impacts to be quantified. Currently, several different approaches are taken by DOTs to estimate RUCs (Winston and Langer 2006; Florida DOT 1997; Choi 2020). In this study, the RUC associated with lane and road closures was evaluated in terms of travel delay costs and vehicle operating costs, which are the only parameters considered by the Federal Highway Administration (FHWA) (FHWA 2011; FHWA 2022). By effectively calculating the RUC, the impact of WZTC on the DDI and CII can be determined. The following set of attributes is needed for this analysis:

- Average annual daily traffic (AADT)
- Location (e.g., Wake County, NC)
- Project year (e.g., 2020)
- Speed limit (e.g., posted, work zone, and detour speed limits)
- Length of the work zone, detour(s), etc.
- Vehicle value of time ($/hour)
- Vehicle operating costs ($/mile)

These attributes were collected from project designs, and NCDOT records. The vehicle operating cost was obtained from outside sources such as the American Association of State Highway and Transportation Officials (AASHTO), the American Automobile Association (AAA), the American Transportation Research Institute who publish these values on a yearly basis.

The RUC analysis performed in this chapter involves various assumptions and uncertainties that can influence the accuracy and reliability of the results. Firstly, one of the main challenges lies in estimating the future travel demand accurately. Predicting traffic volumes, mode choices, and travel patterns is inherently complex and subject to uncertainties due to factors like changing demographics, economic conditions, and technological advancements. To address this uncertainty, local values such as AADT for the intersection evaluated, vehicle cost and values of time from the location of the project were utilized to reduce uncertainties that may lead to deviations from actual outcomes.

Secondly, the analysis relies on certain assumptions regarding travel behavior and preferences. Assumptions about travel time values can significantly affect the overall road user cost estimates. Small variations in these assumptions can lead to substantial differences in the outcomes, making it essential to carefully consider and validate these assumptions based on real-world data. Due to the sensitivity of the analysis, the use of real travel time records, produced from reputable sources (e.g. NCDOT and FHWA) were utilized.

Travel Delay Cost

Expenses associated with 'lost opportunity' due to road users spending additional time on the road are referred to as the travel delay cost (Shrestha et al. 2021), as expressed in Equation 2.

$$Travel\ Delay\ Cost = Delay\ time\ (hrs) * Hourly\ Dollar\ Value\ of\ Delay \quad (2)$$

The travel delay cost varies depending on the type of vehicle (car or truck) and the type of trip. The delay experienced by each vehicle is influenced by factors such as whether the vehicle took a detour, different speed limits, and the length of the work zone. Equations 3, 4, and 5 are used to compute the value of time (VOT) for different scenarios, and Equations 6 and 7 are used to compute delays per vehicle.

VOT for Vehicle and Trucks

The VOT for cars and trucks is calculated on an hourly basis and these where determined based on average wage estimated by NCDOT. For this analysis, the VOT for cars was $12.75 and $50 for trucks.

Delay Time Due to Detour

Equation 3 was used to calculate the delay time for vehicles that make a detour. The calculation involves the difference between the time required to travel along the detour route at the detour speed limit and the time required to travel along the original route at the posted speed limit.

$$Delay\ Time\ (Due\ to\ \ Detour) = \left(\frac{Detour\ Length}{Detour\ Speed\ Limit}\right) - \left(\frac{Normal\ Route\ Length}{Posted\ Speed\ Limit}\right) \quad (3)$$

Delay Time by Avoiding Detour

Equation 4 was used to calculate the delay time for vehicles that avoid a detour by determining the difference between the time it takes to travel at the speed limit within the work zone and the time required to travel at the posted speed limit. This calculation helps quantify the extent of the delay experienced by vehicles that pass through the work zone without deviating from their original route.

$$Delay\ Time\ (Not\ Taking\ Detour) = \left(\frac{Work\ Zone\ Effective\ Length}{Work\ Zone\ Speed\ Limit}\right) - \left(\frac{Work\ Zone\ Effective\ Length}{Posted\ Speed\ Limit}\right) \quad (4)$$

Vehicle Operating Cost

Vehicle operating costs are the additional costs associated with vehicles that must travel longer distances due to WZTC measures and can be calculated using Equation 5 (Shrestha et al. 2021).

$$Vehicle\ Operating\ Cost\ (VOC) = \ Unit\ Cost\ per\ Mile * Miles\ Travelled\ per\ Vehicle * Number\ of\ Vehicles \quad (5)$$

The unit cost per mile can be calculated for various vehicle types and roadway characteristics. For this research, to calculate the unit cost per mile, the sum of the calculated VOC for cars and trucks was utilized. The calculation of the anticipated VOC involves considering the original distance and the original cost per mile. Subsequently, the updated expected vehicle operating cost should be calculated based on the actual distances traveled and the unit costs per mile. This calculation should be performed for two scenarios: a) when the vehicle does not take a detour, and b) when the vehicle takes a detour.

In the case where a vehicle does not take a detour, the distance covered per vehicle remains the same for both the actual condition (work zone) and the base condition (no-work zone). However, the unit cost per mile may vary depending on the operating speed, which is determined by the specific data source used. As a result, even if the total distance remains unchanged, the unit cost per mile can vary, potentially leading to an increased or decreased vehicle operating cost.

When a vehicle takes a detour, the new distance will correspond to the distance of the detour, and the unit cost per mile will be determined by the speed at which the detour is taken. Generally, detours tend to be longer than the original route. Therefore, opting for a detour would typically result in an overall increase in the total vehicle operating cost.

Analysis

The case study involves a comparison assessment of WZTC strategies for a DDI project in Wake County, NC that was under construction at the time of this writing with expected completion in 2024 and a CII project in Cabarrus County, NC that had been constructed in 2018. Both projects were evaluated based on travel time, roadway congestion operations, and road user cost impact. Analysis and comparison of the assessment results provide a better understanding of the performance of DMUII projects compared to CII projects.

I-5700 Project

Construction for the NCDOT DDI project I-5700 began on February 3, 2020, and is expected to be completed by February 11, 2024. Figure 5.1 shows the location of this project at the intersection of I-40 and Airport Boulevard. This project was a design bid build (DBB) project with a DDI design and it is currently under construction. The scope of this project requires grading, drainage, paving, signals, and structures work on 0.798 miles. The contract bid of the project was $34,895,403, where 84% of the total cost was designated for roadway construction, 13% for structure, and 3% for culvert items. At the moment the actual project cost is $36,084,881 ($1.1 million over budget), recall that the project is still under construction and its final cost is subject to change.

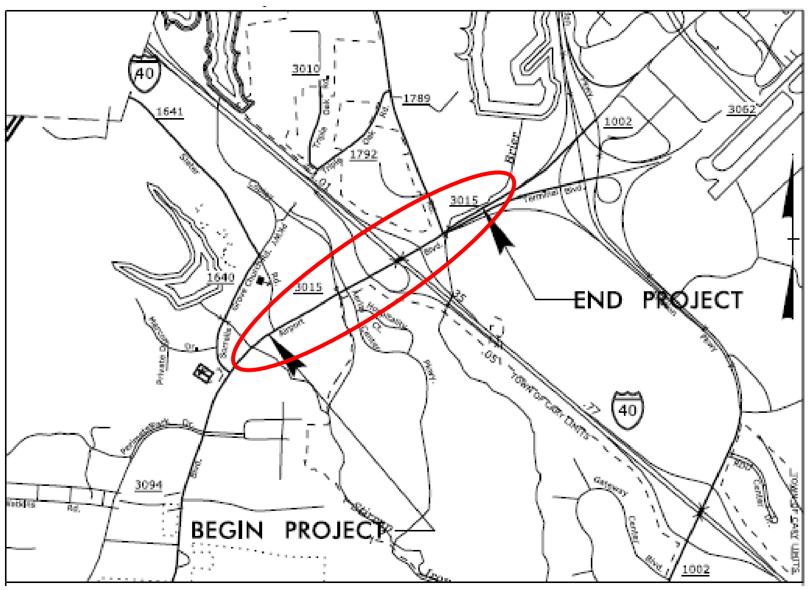


Figure 0.1 NCDOT I-5700 Location Site (I-40 and Airport Boulevard)

Figure 5.2 shows that the I-5700 site is being constructed above I-40 and requires the construction of two bridges and involves 12 traffic movements.

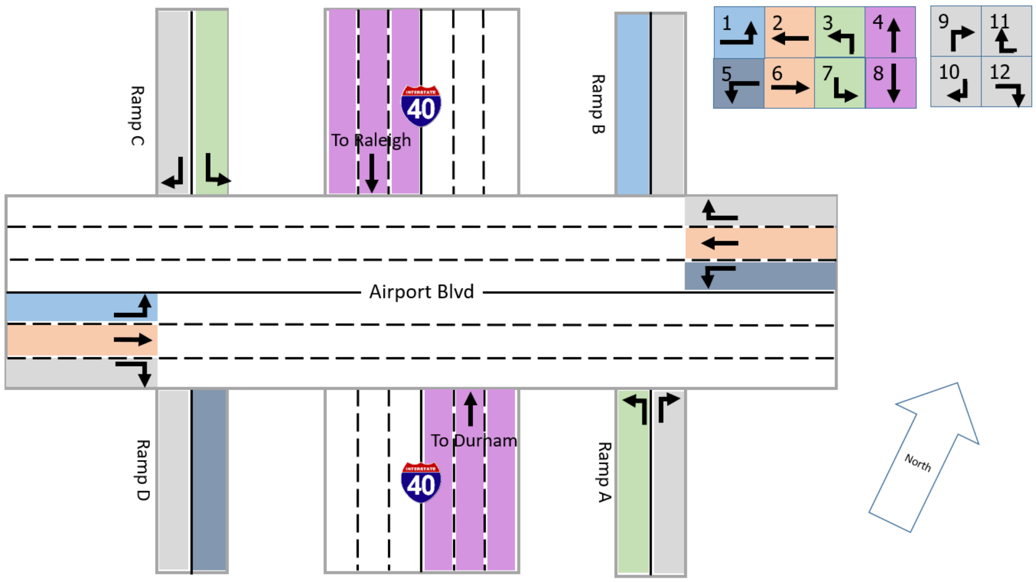


Figure 0.2 Traffic Movement in I-5700 Project

The I-5700 project requires five construction phases to construct the two bridges and modify traffic patterns to achieve the final DDI geometric configuration. Although the project has five phases, the project design manages to avoid lane reductions or other commonly used WZTC methods to separate construction activities from traffic. Only two phases require the closure of ramps and these WZTC specifications are the ones utilized for this study.

Figure 5.3 presents the first closure of Ramps B and C where traffic was shifted to the Phase II pattern on the night of September 6, 2022. The construction area is represented by a red rectangle. The installation of temporary markings, activation of temporary signals, and installation of detour signs were completed earlier on the same day. The new pattern closed the I-40 westbound on-ramp and the I-40 eastbound off-ramp for 105 days (until December 20, 2022).

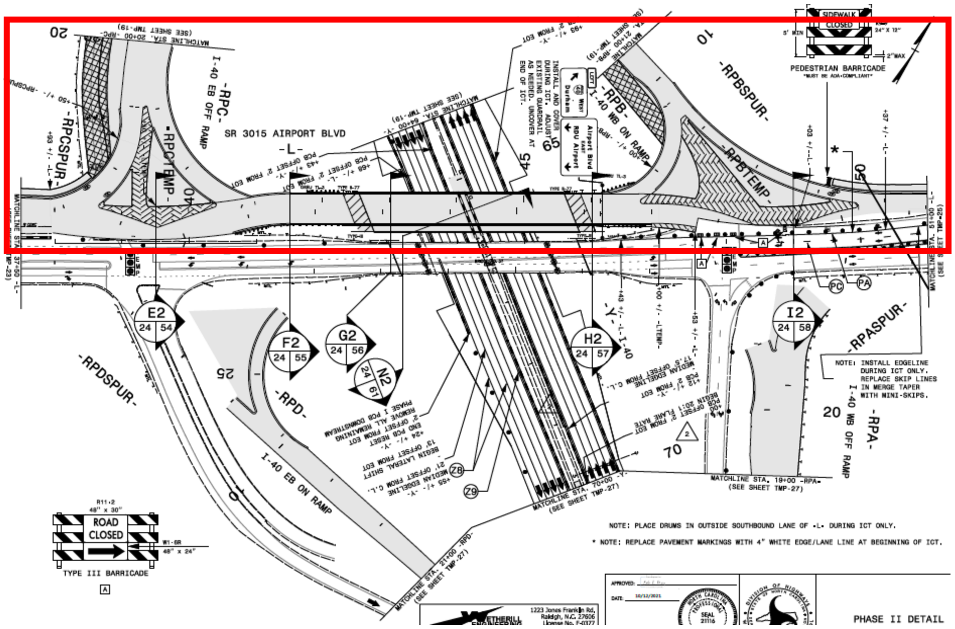


Figure 0.3 Phase II Closure of Ramps B and C in I-5700 Project

Figure 5.4 shows the two detour routes that were used to accommodate the closure of Ramps B and C. Detour 1 (D1) is shown in blue and accommodates eastbound traffic from I-40 to Airport Boulevard. Detour 2 splits into two patterns, D2A and D2B, shown in yellow. D2A accommodates traffic originating from Raleigh-Durham International Airport (RDU) that is destined for westbound I-40, and D2B accommodates northbound Airport Boulevard traffic, also destined for westbound I-40.

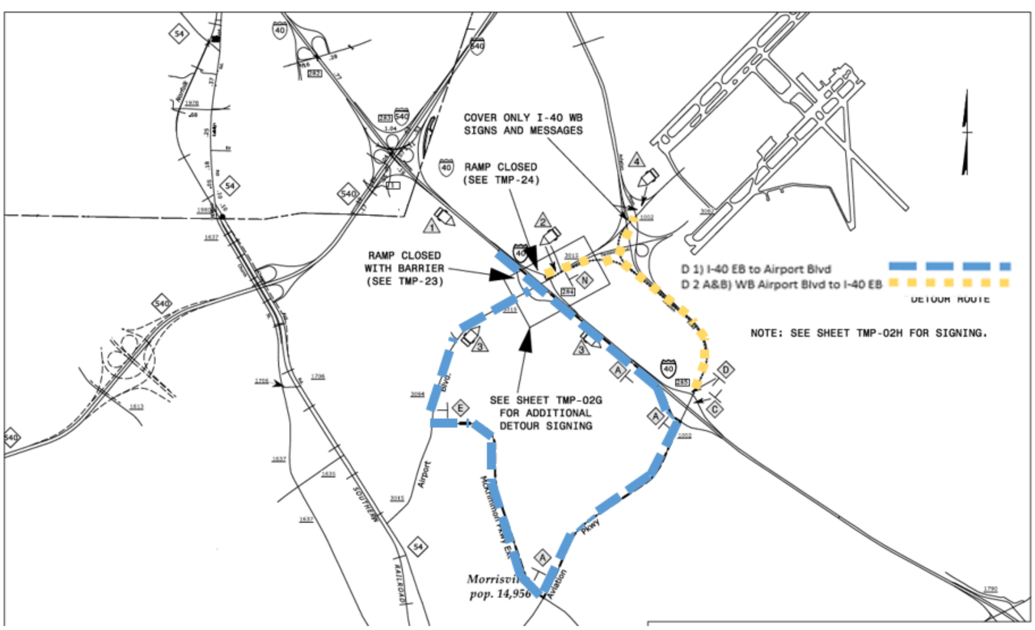


Figure 0.4 Detour Routes to Accommodate Ramp Closures in I-5700 Project

Figure 5.5 shows the construction areas (red circles) for the closure of Ramps A and D which are expected to be completed in 2023. Traffic will be shifted to the Phase III pattern for 120 days.

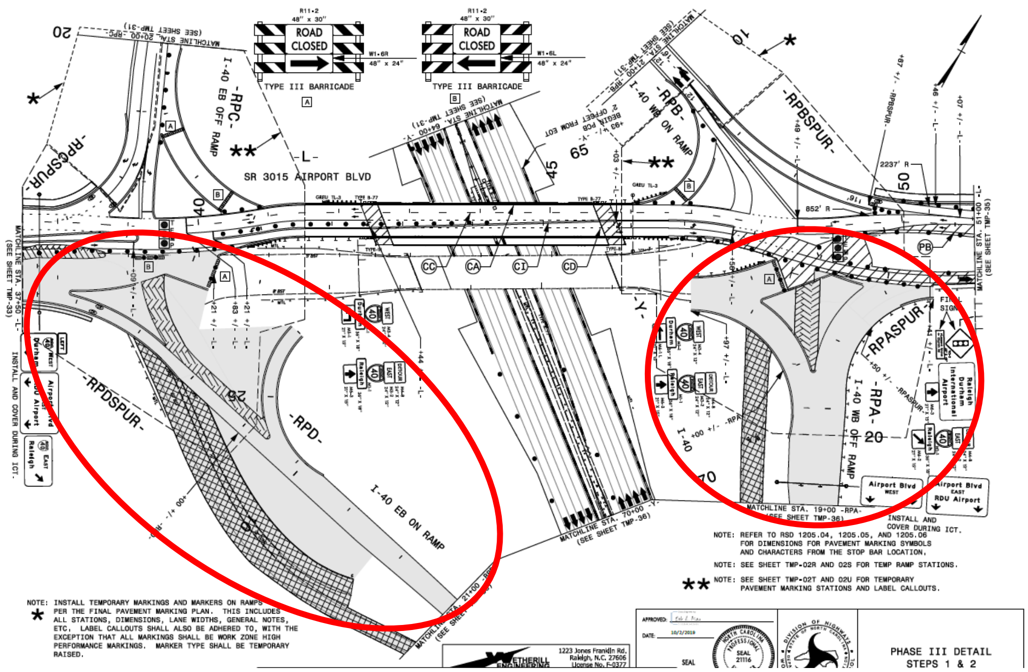


Figure 0.5 Phase III Closure of Ramps A and D in I-5700 Project

Figure 5.6 shows the three detour routes (D3, D4, and D5) that were used to accommodate the closure of Ramps A and D. Detour 3 is split into two patterns, D3A, and D3B, and is shown in purple. D3A accommodates westbound traffic from I-40 to southbound Airport Blvd. D3B accommodates westbound traffic from I-40 to NB Airport Blvd. D4 is shown in green and accommodates eastbound traffic from Airport Boulevard to I-40 eastbound. D5 is shown in orange and accommodates southbound traffic from Airport Boulevard to I-40.

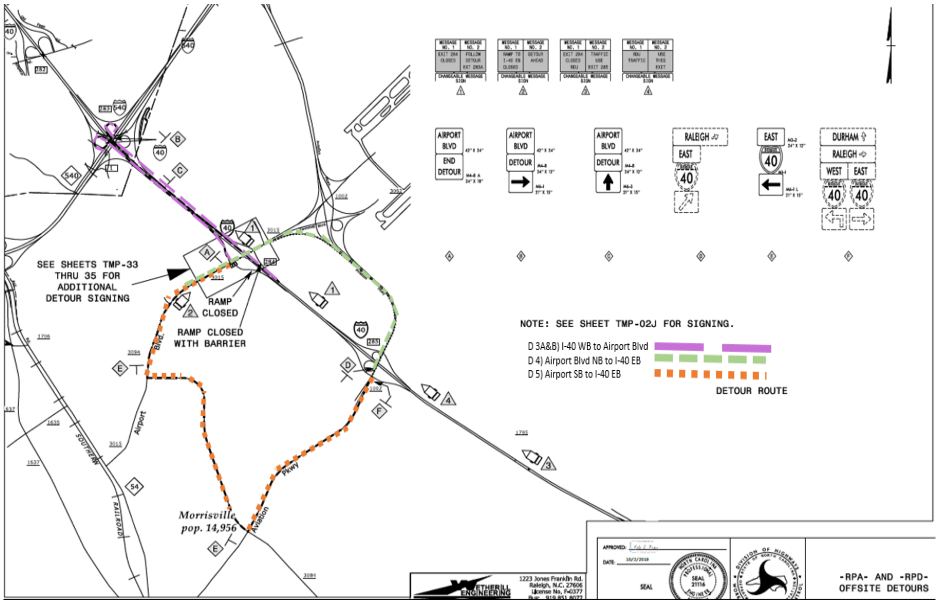


Figure 0.6 Detour Routes for D3A, D3B, D4, and D5 in I-5700 Project

Travel Time Due to Work Zone Activities

Table 5.1 presents the analysis results for travel time that is due to WZTC activities. For this evaluation, the routes were linked to their respective detour route(s). The routes were created in Iteris ClearGuide to determine the origin to destination (route length) of all 12 respective movements and detours. The average speed limit was also retrieved from ClearGuide. The additional distance traveled due to detours was calculated by subtracting the detour length from the route length. Not all routes were affected by WZTC; therefore, these routes do not have added travel time. To calculate the travel time due to WZTC, the travel time needed to navigate the detours was subtracted from the travel time needed to navigate the normal route. As shown, Routes 5 and 7 were the routes most affected by WZTC because the added travel time is ≥ 5 minutes.

Evaluation of Roadway Congestion Operations

Roadway congestion operations were evaluated using the TTI. The scenarios evaluated required historical records for the time prior to construction, during construction, and post construction. For the DDI 1-5700 project, the roadway congestion operations were evaluated for April and October because seasonal traffic volumes are stable in these months and better represent traffic normal conditions in a given year. The TTI values for project I-5700 were calculated based on the times of the closure of Ramps B and C, as no other closures had yet taken place at the time of this study. The WZTC measures required for the construction of Ramps B and C included rerouting Routes 1, 7, 10, and 11 from September to December 2022. The pre-construction data included 2015, 2016, and 2019 and the construction data included 2020, 2021, and 2022 (the project began in February 2020). The post construction data included February and April 2023 when the road closures ended for Ramps B and C.

Table 0.1 Evaluation of Travel Time Due to Work Zone Traffic Control Measures in I-5700 Project

Route and Movement	Traffic Movement		Detour	Original Route Length (mile)	Detour Length (mile)	Additional Distance Travel due to Detour (mile)	Speed Limit (mile/hr.)		Travel Time (min/veh.)		Added Travel Time due to WZTC (min/veh.)
	Origen	Destination					Route	Detour	Route	Detour	
1	Airport Boulevard NB	I-40 WB	D2A	1.03	3.67	2.64	45	55	1.4	4.0	2.6
2	Airport Boulevard SB	Airport Boulevard SB	No Detour	0.38	No Detour	0	45	55	0.5	No Detour	No Detour
3	I-40 WB	Airport Boulevard SB	D3A	0.54	4.6	4.06	45	55	0.7	5.0	4.3
4	I-40 WB	I-40 WB	No Detour	1.24	No Detour	0	65	55	1.1	No Detour	No Detour
5	Airport Boulevard SB	I-40 EB	D5	1.92	4.65	2.73	45	55	2.6	5.1	2.5
6	Airport Boulevard NB	Airport Boulevard NB	No Detour	0.36	No Detour	0	45	55	0.5	No Detour	No Detour
7	I-40 EB	Airport Boulevard NB	D1	0.87	6.08	5.21	45	55	1.2	6.6	5.5
8	I-40 EB	I-40 EB	No Detour	0.95	No Detour	0	65	55	0.9	No Detour	No Detour
9	I-40 WB	Airport Boulevard NB	D3B	0.4	5.24	4.84	45	55	0.5	5.7	5.2
10	I-40 EB	Airport Boulevard SB	D1	0.59	5.75	5.16	45	55	0.8	6.3	5.5
11	Airport Boulevard SB	I-40 WB	D2B	1.54	3.4	1.86	45	55	2.1	3.7	1.7
12	Airport Boulevard NB	I-40 EB	D4	1.68	4.71	3.03	45	55	2.2	5.1	2.9

Table 5.2 presents the monthly TTI values for the 12 routes in the DDI project. The table indicates that before construction began, the 12 routes experienced some level of congestion. The most congested routes prior to construction are Routes 2, 3, 6, 8, 10, and 12, shown in orange and yellow. Congestion levels during construction from 2020 to 2021 decreased for most of the routes. A likely reason for this reduction is COVID-19 restrictions that led to less travel and reduced traffic counts. Therefore, the TTI results may not be indicative of impacts due to WZTC measures. Although WZTC at Routes 2 and 6 (at Airport Boulevard) did not require speed limits or lane reductions, these routes remained congested during the construction period.

Table 0.2 Monthly Travel Time Index Values for Routes in I-5700 Project

	Months \ Routes	1	2	3	4	5	6	7	8	9	10	11	12
Before Construction	Apr 2015	1.12	1.17	1.1	1.04	1.11	1.25	1.16	1.16	1.04	1.08	1.17	1.11
	Oct 2015	1.14	1.19	1.14	1.09	1.13	1.27	1.17	1.15	1.09	1.08	1.21	1.11
	Apr 2016	1.04	1.04	1.04	1.03	1.07	1.05	1.06	1.15	1.02	1.08	1.01	1.08
	Oct 2016	1.04	1.03	1.05	1.06	1.08	1.03	1.06	1.18	1.04	1.1	1.01	1.1
	Apr 2019	1.06	1.15	1.12	1.03	1.13	1.16	1.12	1.22	1.06	1.14	1.01	1.13
	Oct 2019	1.11	1.26	1.22	1.05	1.2	1.23	1.18	1.3	1.12	1.18	1.04	1.19
During Construction	Apr 2020	1.03	1.1	1.06	1.03	1.03	1.09	1.04	1.03	1.02	1.01	1.01	1.03
	Oct 2020	1.05	1.2	1.09	1.01	1.05	1.15	1.07	1.05	1.01	1.03	1.01	1.01
	Apr 2021	1.03	1.2	1.16	1.04	1.06	1.1	1.04	1.04	1.02	1.01	1.02	1.03
	Oct 2021	1.04	1.36	1.25	1.02	1.1	1.14	1.09	1.05	1.08	1.07	1.08	1.04
	Apr 2022	1.08	1.31	1.32	1.07	1.12	1.25	1.19	1.17	1.11	1.2	1.05	1.1
	Oct 2022	1	1.08	1.09	1.05	1.08	1.08	1	1.13	1.09	1	1	1.1
After Construction	Feb 2023	1.05	1.29	1.18	1.04	1.13	1.42	1.34	1.11	1.13	1.3	1.01	1.1
	April 2023	1.1	1.43	1.26	1.03	1.17	1.45	1.33	1.17	1.14	1.26	1.04	1.12

Next, the TTI was used to evaluate the routes affected by the closure of Ramps B and C. Figure 5.7 presents the results obtained for Routes 1, 7, 10, and 11. As mentioned, because construction started around the time that COVID-19 restrictions were put in place, the TTI values decrease at the beginning of the construction period but are shown to increase beginning in 2022 when the COVID-19 restrictions ended. The figure shows that traffic from I-40 to Airport Boulevard (Routes 7 and 10) on Ramp C correlates with low to moderate TTI values during construction, but once Ramp C was opened (February 2023), congestion for those routes increased. Routes 1 and 11 accommodate traffic from Airport Boulevard to I-40 on Ramp B, and the TTI values are shown to increase during construction to post construction, but congestion is considered to be relatively light.

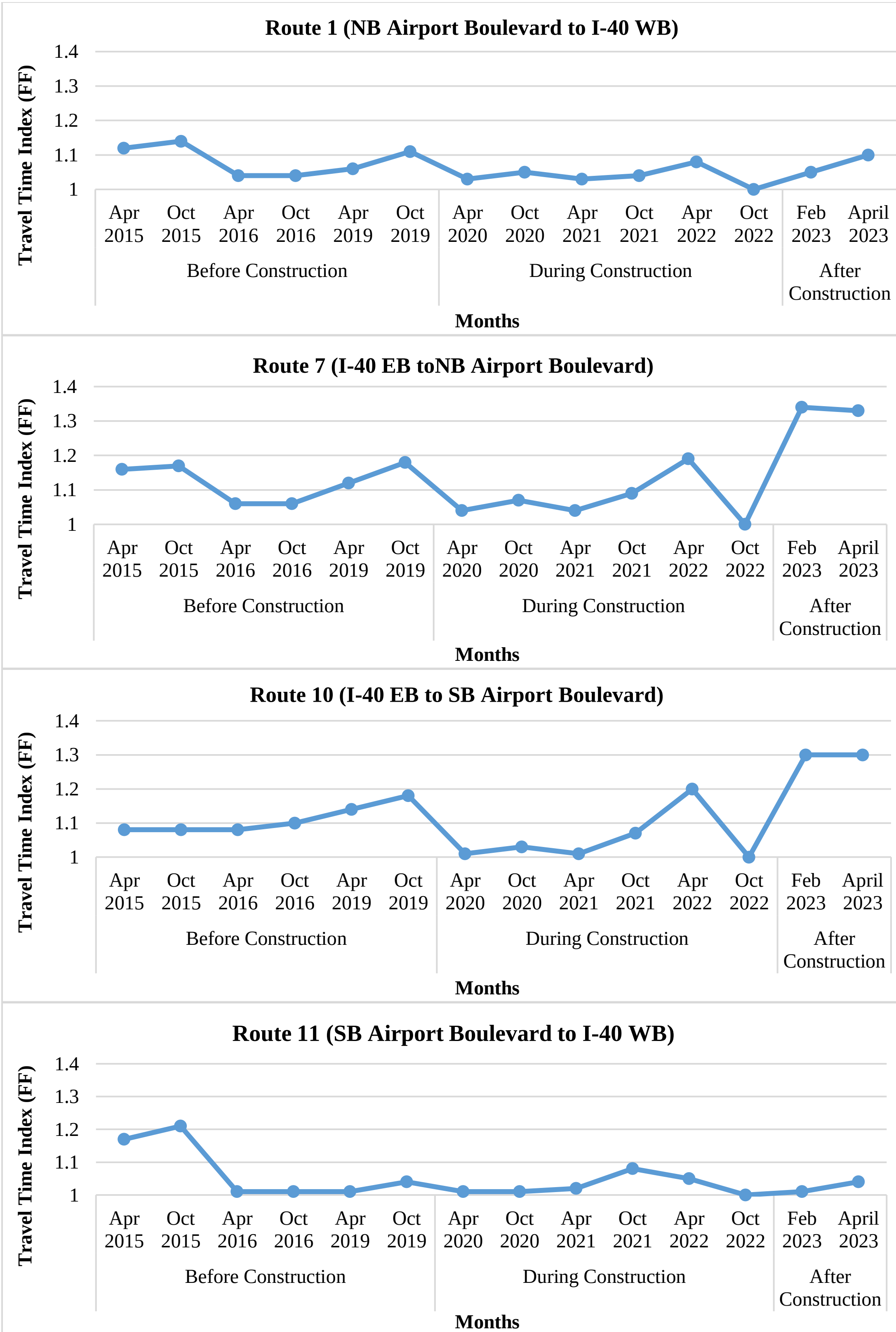


Figure 5.7 Travel Time Index Values for Routes Affected by Closure of Ramps B and C in I-5700 Project

Table 5.3 presents the TTI values in April 2015 and October 2015 for each detour route. Since the I-5700 project started construction activities until February 2020, the TTI values for April 2015 and October 2015 were used for the 'before construction' evaluation. The TTI values for April 2021, October 2021, and April 2022 were used for the 'during construction' evaluation. Even though there was no lane or roadway closure during this period (April 2021-April 2022), it is assumed that some of the traffic originally traveling through I-40 and Airport Boulevard will seek alternative routes to avoid the construction area. Because the ramps were closed for only 105 days, the 'ramps B&C closed' cover only September 2022 to December 2022. The 'post-construction' covers February 2023 and April 2023.

Table 0.3 Monthly Travel Time Index Values for Detours in I-5700 Project

	Detours / Months	D1	D2A	D2B	D3	D4	D5
Before Construction	Apr 2015	1.16	1.13	1.14	1.04	1.11	1.18
	Oct 2015	1.16	1.17	1.19	1.06	1.14	1.19
During Construction	Apr 2021	1.05	1.03	1.03	1.02	1.04	1.05
	Oct 2021	1.06	1.02	1.01	1.01	1.03	1.07
	Apr 2022	1.1	1.05	1.04	1.12	1.05	1.08
Ramps B&C Closed	Sep 2022	1.04	1.05	1.06	1.05	1.09	1.02
	Oct 2022	1.04	1.05	1.06	1.12	1.08	1.02
	Nov 2022	1.04	1.04	1.05	1	1.09	1.03
	Dec 2022	1.03	1.04	1.04	1.06	1.08	1.02
Post Construction	Feb 2023	1.04	1.16	1.04	1.07	1.06	1.08
	April 2023	1.18	1.1	1.05	1.25	1.17	1.05

Figure 5.8 presents the TTI results for detour routes 1A, 2A, and 2B that were in place due to the closure of Ramps B and C. The TTI values suggest that the detour routes maintained constant TTI values until the ramp closures ended, but these values are not indicative of any impact due to WZTC measures.

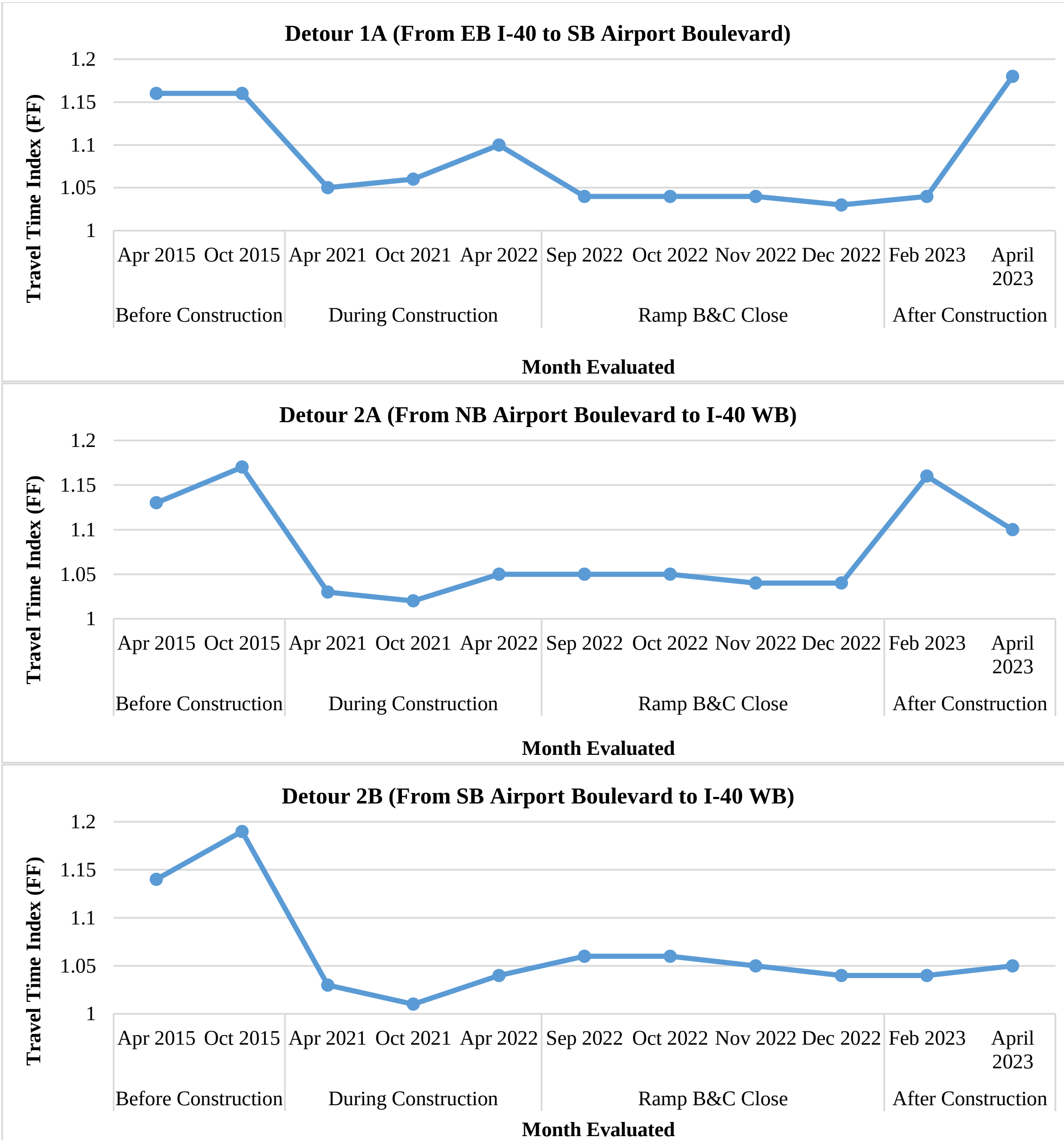


Figure 0.8 Travel Time Index of Detour Routes Due to Closure of Ramps B and C in Project I-5700

Road User Cost in I-5700 Project

The RUCs for the DDI project were calculated for the two road closures that were implemented by the design plans described introduced in figure 5.1. The WZTC for project I-5700 included two road closures. The first closure was to allow the construction of the new alignment on Ramps B and C and lasted 120 days, and the second closure was for the construction of Ramps A and D and lasted 105 days. Note that work zone measures that require lane closures were not utilized for the WZTC measures performed in the DDI project. This was possible due to construction of a new bridge (away from traffic) than upon being built, traffic was shifted from the old bridge to the new bridge, allowing construction activities to be separated from traffic.

Detour Travel Delay Cost

To determine RUC, the first step was to determine the travel delay cost, considering only the cost due to detours in this case. To do these calculations, the data presented in Table 5.4 were determined. To calculate the percentage of AADT for cars and trucks, historical records of NC projects in urban (local) routes were used.

Table 0.4 RUC Data Input for Diverging Diamond Interchange Project

Variable	Value	
Project Information		
County	Wake	
Project Year	2020	
Route Type	Local	
Data Input		
AADT:	**Car**	**Truck**
	95.5% AADT	4.5 % AADT
Posted speed limit (mile/hr.):	Varies per route	
Work zone speed limit (mile/hr.):	Varies per route	
Detour speed limit (mile/hr.):	Varies per route	
Additional distance travel due to detour (mile)	Varies per route	
Length of normal route (miles):	Varies per route	
Length of work zone route (miles):	Varies per route	
Length of detour route (miles):	Varies per route	
Work Zone Configurations		
Closure ramps A&D	105 days	
Closure ramp B&C	120 days	
Likelihood of taking a detour	100%	

First, the travel delay cost based on the location and the route type was calculated. To do so, The VOC for cards and trucks introduced in the methodology was utilized. Once the VOT was calculated, the travel time for normal conditions (posted speed) and for the detour route was calculated using Equation 1 where the speed limit was utilized for the speed and the length of the route to determine the total distance traveled. Subsequently, Equation 2 was utilized to calculate travel delay costs for cars and trucks. The sum of the cars and truck values resulting from the 12 routes was $67,971.90. Details of the parameters utilized for travel delay cost can be found in Appendix D Tables D.1 and D.2.

Vehicle Operating Cost

The VOC was calculated by utilizing Equation 5 introduced in the methodology. The VOC first utilizes the vehicle (e.g. car and truck) unit cost per mile and multiplies this value by the additional miles from the detour. The additional miles from the detour are calculated by multiplying the miles traveled per vehicle times the number of vehicles taking that route. Once the additional miles from the detour are known, the value is multiplied by the unit cost per mile. Details of the parameters utilized for travel delay cost can be found in Appendix D Table D.3.

RUC Total

Table 5.5 presents the RUCs for the DDI project that were calculated per day and based on delays caused by detour routes and additional operating costs. Of the 12 routes, only Routes 3, 5, 9, and 12 were affected by the closure of Ramps A and D, and only Routes 1, 7, 10, and 11 were affected by the closure of Ramps B and C. The overall resultant RUC is $5.6 million, which was calculated by adding the daily RUCs on those routes and multiplying the sum by the total of days of closure. Appendix D provides summary tables of the RUC with full calculations and parameters.

Table 0.5 Road User Cost in I-5700 Project

WZTC Ramp Closures	Detour Travel Delay Cost	Additional Vehicle Operating Costs	Total RUC
Ramps A&D (105 days)	$1,306,963	$1,160,425	$2,467,388
Ramps B&C (120 days)	$1,700,122	$1,498,797	$3,198,918
Total			**$5,666,306.43**

Even though these results are high, if the project had opted for a conventional widening of the existing diamond interchange instead of the conversion to a DDI, the outcome and performance of the detour would have likely been different. With a conventional widening approach, the primary focus would have been on expanding the existing interchange to accommodate increased traffic demands. This will involve permanent lane reductions to allow for construction activities to happen and the ramp will also need to be closed in order to account for new geometric alignments due to widening. Therefore, opting for a CII at this location would have incurred greater travel time, larger congestion, and larger RUC impact.

While such a design might have alleviated congestion to some extent, it may not have addressed certain traffic congestion and safety concerns as effectively as DDI. The DDI, on the other hand, is not just better for construction activities but also offers unique features that enhance traffic efficiency and safety for construction and also for after construction operations.

U-5806 Project

The second project in the case study is NCDOT project U-5806 in Cabarrus County, NC which is a CII design. This project was a DBB project that requires grading, drainage, paving, signals, and structures work for a 0.434 miles project. The contract bid was $10,216,655, where 53% of the total cost was designated to roadway construction, 34% to structure, and 13% to wall items, and the actual project cost resulted in $12,328,466 ($2.1 million over budget). Figure 5.9 shows the location of the U-5806 project. Construction began on August 13, 2018, and ended on August 18, 2022, lasting 1,571 working days. This project required improvements along the intersection of SR-2894 (Concord Mills Boulevard) and entrance #1 at Kings Grant Pavilion (See Figure 5.9 for the location of the project).

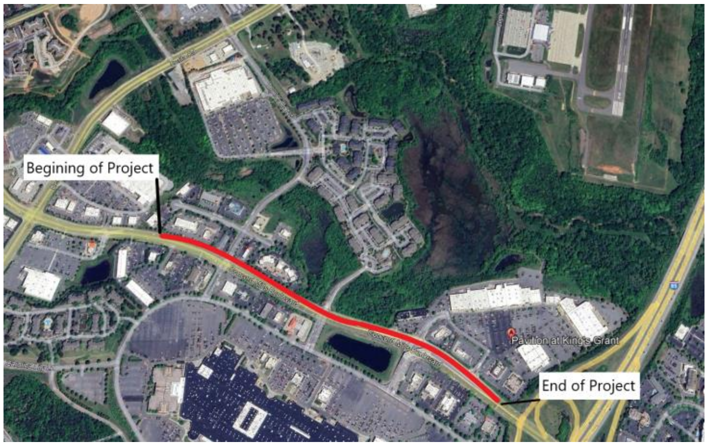


Figure 0.9 NCDOT U-5806 Location Site (Concord Mills Boulevard and Entrance #1 at Kings Grant Pavilion)

Figure 5.10 shows that the U-5806 CII project involved only two traffic movements because the construction activity took place on a corridor, thus requiring traffic flow to be maintained and the use of temporary traffic patterns during the daytime. Since the minor streets intersecting along the corridor do not have AADT available and since these minor streets do not have traffic lights, their volume is considered to be neglected for this calculation. The project required temporary lane closures, traffic stops, and temporary road closures with off-site detours for specific construction items. The closures due to construction activities were performed at night because the only times allowed for closure were 7 PM to 6 AM during weekdays and 10 PM to 10 AM on weekends. As night-time traffic levels are relatively low, no significant impact was expected from construction activities. Therefore, for calculation purposes, the evaluation was focused only on lane closure activities due to WZTC.

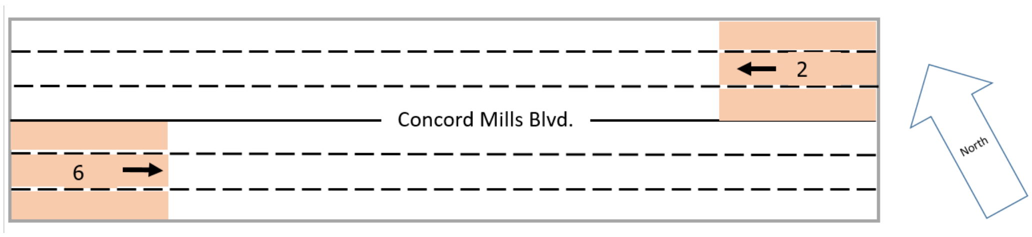


Figure 0.10 Traffic Movements in U-5806 Project

Travel Time Due to Work Zone Traffic Control

Table 5.6 presents travel time data that relates to WZTC measures for CII project U-5806. These calculations follow the same methodology used for DMUII project I-5700. The only difference is that the construction site for U-5806 is a corridor and does not intersect with another road where minor streets intersect but no traffic lights are required. Therefore, U-5806 only accounts for traffic in two movements, and no detour routes are considered. Iteris ClearGuide was used to determine the origin to destination (route) length, retrieve the average speed limit, and calculate the additional distance traveled due to speed limit reduction. To calculate the travel time due to WZTC measures, the travel time required to navigate the route during normal conditions was subtracted by the travel time required to navigate the route during WZTC activities. The added travel time due to WZTC is relatively insignificant for the CII project.

Table 0.6 Travel Time Due to Work Zone Traffic Control in U-5806 Project

Movement	Traffic Movement		Original Route Length (mile)	Work Zone Length (mile)	Speed Limit (mile/hr.)		Average Travel Time (min/veh.)		Added Travel Time due to WZTC (min/ veh.)
	Origen	Destination			Original Route	During WZTC	Original Route	During WZTC	
2 ←	WB Concord Mills Blvd (From I-85)	WB Concord Mills Blvd (To Bexley Way)	0.55	0.55	45	35	0.7	0.9	0.2
6 →	EB Concord Mills Blvd (From Bexley Way)	EB Concord Mills Blvd (To 1-85)	0.55	0.55	45	35	0.7	0.9	0.2

Evaluation of Roadway Congestion Operations

TTI values were used to evaluate roadway congestion operations for project U-5806. The scenarios evaluated include historical records for the time before construction, during construction, and post construction. Data for April and October were evaluated because these months best reflect seasonal traffic volumes and normal traffic conditions in a given year. Because project U-5806 is a completed project, the TTI values could be calculated for the entire construction period. Pre-construction TTI values covered April 2017, October 2017, and April 2018, during construction, TTI values covered 2018 to 2022 (based on start and end dates of 8/13/2018 to 8/18/2022), and post-construction TTI values covered October 2022 and April 2023. ClearGuide allows the TTI values to be evaluated for specific periods, and therefore, all three sets of TTI calculations (pre-construction, construction, and post-construction) are based on 7 PM to 6 AM for weekdays and 10 PM to 10 AM for weekdays.

Table 5.7 presents the TTI values for the two routes (2 and 6) for the applicable months and indicates that, prior to construction, the routes experienced some level of congestion. During construction from 2020 to 2021, congestion levels decreased. The likely reason for this decrease is that COVID-19 restrictions reduced the traffic flow. Therefore, the TTI results are not indicative of any impact due to WZTC measures during this period. The post-construction results suggest that traffic congestion returned to 2018 conditions.

Table 0.7 Monthly Travel Time Index Values in U-5806 Project

	Months \ Route	2	6
Before Construction	Apr 2017	1.13	1.17
	Oct 2017	1.1	1.14
	Apr 2018	1.08	1.15
During Construction	Oct 2018	1.04	1.12
	Apr 2019	1.09	1.14
	Oct 2019	1.16	1.32
	Apr 2020	1.05	1.06
	Oct 2020	1.03	1.05
	Apr 2021	1.01	1.05
	Oct 2021	1.03	1.04
	Apr 2022	1.06	1.05
After Construction	Oct 2022	1.03	1.04
	Apr 2023	1.05	1.12

Figure 5.11 presents TTI data for Routes 2 and 5 and shows the impact of the WZTC measures on traffic over time. Traffic volumes in the area were influenced by night-time construction activities. An increase in congestion is indicated by the TTI values for both routes from October 2018 to October 2019. Due to COVID-19 restrictions, a decrease in congestion is reflected in the TTI values during the second year of construction.

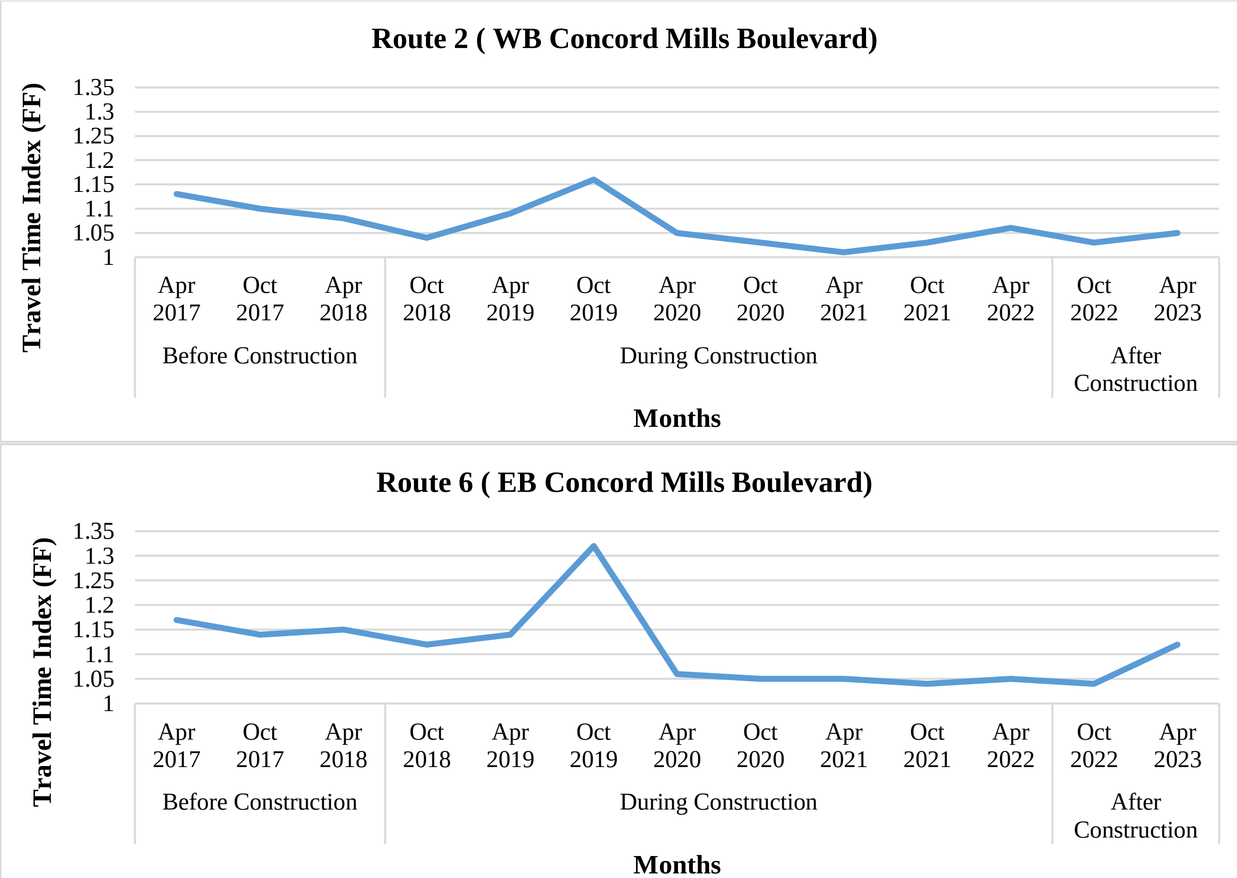


Figure 0.11 Travel Time Index Values for Routes 2 and 6 in U-5806 Project (From EB Concord Mills Boulevard)

Road User Cost in U-5806 Project

The RUC for the CII project U-5806 was calculated for lane closures performed according to the design plans that indicated WZTC measures during daily activities, and lane reductions in night construction work.

Work Zone Travel Delay Cost

To determine RUC for the CII project, the first step was to determine the travel delay cost, which in this case only includes the cost due to detours. To do these calculations, the data input presented in Table 5.8 was determined as the percentage of AADT for cars and trucks and their historical records of NC projects in urban (local) routes. Notice that project U-5806 does not require any detour routes, therefore the input for this project is $0.

Table 0.8 RUC Data Input for U-5806 Project

Variable	Value	
Project Information		
County	Cabarrus	
Project Year	2018	
Route Type	Local	
Data Input		
AADT:	**Car**	**Truck**
	95.5% AADT	4.5 % AADT
Posted speed limit (mile/hr.):	Varies per route	
Work zone speed limit (mile/hr.):	Varies per route	
Detour speed limit (mile/hr.):	Varies per route	
Additional distance travel due to detour (mile)	Varies per route	
Length of normal route (miles):	Varies per route	
Length of work zone route (miles):	Varies per route	
Length of detour route (miles):	Varies per route	

The work zone travel delay cost for the CII project utilizes VOC cost for cars and trucks introduced in the methodology. Subsequently, the travel time along the route (normal conditions at posted speed) and the travel time at the work zone route were calculated using Equation 1 where the speed limit was utilized for the speed and the length of the route to determine the total distance traveled. Subsequently, Equation 2 was utilized to calculate travel delay costs for cars and trucks. The sum of the cars and truck values resulting from routes 2 and 6 was $684.22 per day. Details of the parameters utilized for travel delay cost can be found in Appendix E Tables E.1 and E.3.

Vehicle Operating Cost

The VOC for the CII project resulted in $0 since the WZTC measures on this project do not require a detour route.

RUC Total

The RUCs were calculated in terms of daily work zone delay costs and additional operating costs. The project lasted for 1,571 days. The night-time closures were from 7 PM to 6 AM. To adjust the calculations, the AADT was calculated (see results in Appendix E Table E.2). Findings of the incurred RUC for this project are displayed in Table 5.9. It can be observed that the RUC resulting from the CII project was $491,850.

Table 0.9 Road User Cost in U-5806 Project

WZTC Time	Work Zone Travel Delay Cost ($/day)	Additional Vehicle Operating Costs ($/day)	Total RUC
1,571 Days	$313.08	$0	**$491,850**

Conclusions

Work zone activities in transportation networks often lead to disruptions in normal traffic flow, making it crucial to understand the impacts of WZTC measures. This study evaluates three approaches to determine the impact of WZTC and these are travelling time, roadway congestion operations, and RUC. The analysis of travel time, roadway congestion operations, and RUC in this case study has led to valuable insights into differences in performance between DMUII and CII projects in North Carolina.

The travel time evaluation revealed that the I-5700 project with a DDI design required permanent ramp closures. I-5700 had a greater impact on travel time due to the required detour routes that added additional time to the ordinary route. On the other hand, the U-5806 project with a CII design did not require roadway closures. U-5806 experienced reduced speed limits due to WZTC measures, which resulted in a less significant impact on travel time compared to the DDI project. Consequently, in terms of travel time, the CII project had fewer impacts. The analysis of roadway congestion operations using the TTI indicated significant differences in congestion levels caused by WZTC measures. The CII project exhibited worse performance during construction, as evidenced by the higher TTI values.

On the evaluation of road user cost, both projects were evaluated based on their impact on a daily basis. Since the DDI and CII project have different impacts on users (e.g., one includes major detours and the other just lane closure and a reduction in speed limit), a per user rating was carried out in which both the hours and duration of each control measure were considered. The RUC obtained indicated a greater RUC impact on the DDI project. Based on these findings, it can be concluded that the evaluation of roadway congestion operations in WZTC generates different impacts based on the control measures applied. For example, the U-5806 project just reduced the speed limit and performed lane closures at nighttime. This allowed the CII project to have a lower impact on travel time and RUC but faced challenges related to roadway congestion operations. On the other hand, DDI projects require the reconstruction of ramps and more complex construction activities that require a total closure and mandatory detour of the traffic.

In the case study presented in this chapter, an analysis was performed on a DDI and CII project and the results obtained provide a reasonable strategy to assess roadway congestion operations due to WZTC. The level of effort for this analysis took around 108-126 work hours. Since the researchers did not need any training to determine travel delay cost, the time spent in this calculations were 3-4 hours. For the vehicle operating cost, the Iteris ClearGuide (database already available to NCDOT employees) was used, for this analysis, the learning time of the database and its capabilities took approximately 40 hours and the analysis was performed in 10-17 hours. Lastly, the RUC calculations too the longest time of all. The research (training) component took approximately 6 hours, the analysis around 40-50 hours, and data collection (e.g., fuel cost) took around 9 hours.

It is also important to acknowledge that study is limited to present the results of a sample size of two projects (DDI and CII). A larger sample size and other DMUII designs need to be considered in further research. In addition, the evaluation of future projects presumably would not be affected by unique conditions, such as those that resulted from the COVID-19 restrictions in this case study. Despite the case study’s limitations, the findings shed light on the complexities of WZTC measures for both CII and DDI projects and their implications for travel time, roadway congestion operations, and RUC. Overall findings from this chapter are promising since they show how DOTs can potentially analyze and compare detours.

ENHANCERS FOR ALTERNATIVE INTERSECTION AND INTERCHANGE PROJECTS: EVALUATING TECHNIQUES AND PROVIDING IMPLEMENTATION STRATEGIES TO PROMOTE PROJECT EFFICIENCY

When attempting to achieve a sustainable transportation system, multiple aspects such as design, construction process, delivery methods, and design practices need to be considered (Shin et al. 2008). Construction concepts such as sustainable practices and emerging technologies that have the potential to promote the sustainable construction of projects are referred to in this research as construction enhancers. Although limited research is available that addresses construction enhancement techniques associated with diverse, modern, and unconventional intersections and interchanges (DMUII) designs, an overview of related studies of the utilization of enhancement techniques that aid in the improvement of construction was undertaken. To validate the literature findings, interview, and survey participants (introduced in Chapter 2) were asked about the effectiveness of each technique. Based on the results, a process is being developed to tailor already existing North Carolina Department of Transportation (NCDOT) programs (e.g., the Constructability Review program) to DMUII projects in order to enhance the construction.

Methodology

Figure 6.1 presents a schematic illustration of the methodology that was used to identify and implement construction enhancers. The first step involves a literature review to identify construction enhancers and evaluate their effectiveness in current case studies and evaluate current enhancing techniques used by other DOTs. After identifying the construction enhancers, surveys and interviews were conducted to gather knowledge from stakeholders (consultants, designers, and contractors) who have experience in building project with DMUII designs, to validate the usefulness of these techniques for implementation into project with DMUII designs . These surveys and interviews focused on the enhancing techniques that participants consider effective in projects with DMUII designs . Participants also identified disadvantages associated with the enhancers and provided recommendations for ways DOTs can improve construction for projects with DMUII designs . After validating the enhancers, a plan was developed to implement them into NCDOT business processes. The NCDOT already has implemented several programs to improve project efficiency, some of which have incorporated certain enhancing techniques. The implementation effort aims to identify existing NCDOT programs and provide strategies for the further integration of enhancers to improve construction practices on NCDOT projects that had DMUII designs.

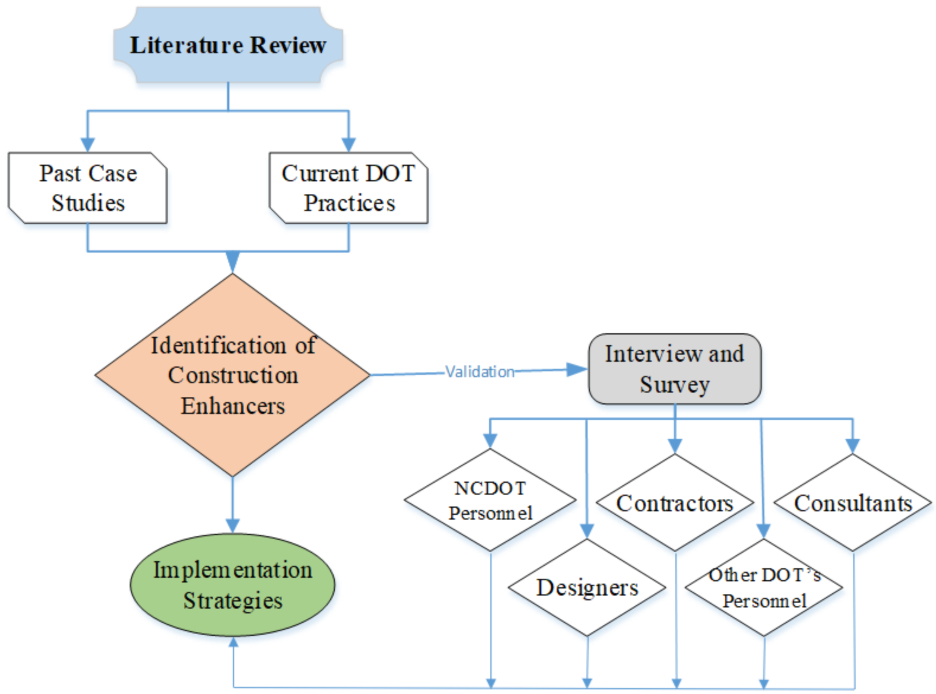


Figure 0.1 Methodology for Identification and Implementation of Construction Enhancers for NCDOT Alternative Intersection and Interchange Projects

Construction Enhancement Techniques

Numerous studies have identified enhancement techniques that can significantly improve overall project performance. This section identifies the already existing and proven enhancement techniques that can be utilized to improve transportation infrastructure projects.

<u>Constructability Reviews</u>

Abudayyeh et al. (2004) identified that the majority of constructability-related publications in ASCE journals are from the United States, and they were mainly published from 1991-2002. Since then, constructability studies have eased. This might be because construction is one of the largest industries, one of the oldest, and one of the least researched in the United States (Abudayyeh et al. 2004). This section identified major studies performed by the Construction Industry Institute, American Association of State Highway and Transportation Officials (AASHTO), and National Cooperative Highway Research Program (NCHRP) that focused on promoting the buildability, biddability, and most importantly, constructability of a project without affecting schedule or cost.

Constructability was first introduced to construction in the 1970s (Construction Industry Institute Australia 1996) and is a measure of how constructible a project is. It aims to address how projects meet standards that are well-known to the construction community (AASHTO 2000) and how projects meet generally accepted cost and schedule expectations. Without the focus on constructability, a project typically experiences an increased number of change orders, violations of construction schedules, and safety concerns (Ansyorie 2019).

The Construction Industry Institute started to perform studies on constructability concepts in the 1980s and their first set of constructability publications was related to best practices. These publications include reports on the conceptual planning phase (Construction Industry Institute 1986), design and procurement phase (Construction Industry Institute 1986; O'Connor et al. 1986), constructability program implementation (Tatum et al. 1987), constructability improvement in project planning, contractual approach (Tatum et al. 1986), constructability inhibitors (Construction Industry Institute 1987; Construction Industry Institute 1987b), and implementation tools (Tatum et al. 1987; Construction Industry Institute1987; Construction Industry Institute1987b; O'Connor and Miller 1994).

In addition to those, the Construction Industry Institute published nine additional reports on constructability implementations. These publications include practical guidance and practices on constructability implementation (Construction Industry Institute 1993), inhibitors in constructability (O'Connor and Norwich 1993; O'Connor 2006), construction cost influences (Russell et al. 1992; Russell et al. 1992b), lessons learned, constructability program maturity, and implementation tool#1 (O'Connor 2006), along with other journal publications from these studies (Radtke and Russell 1993; Russell et al. 1994).

All of these extensive Construction Industry Institute studies concluded that the successful implementation of constructability requires a complete understanding of construction procedures. Most of the time, organizations feel they are implementing constructability, but in reality, their efforts are implemented late in the process and fail to achieve significant benefits (Russell et al. 1992c). In addition, Construction Industry Institute studies indicate that the only way to ensure the success of a constructability program is by performing measurements of the process and tailoring the program to specific project types.

Following the Construction Industry Institute studies, in 1997 the NCHRP published a report on constructability processes for projects related to transportation facilities (Anderson and Fisher 1997). The NCHRP study attempts to quantify the benefits associated with the constructability review process for transportation projects. This report is tailored to the constructability review practices at DOTs and how to implement constructability review programs. This study first provides an overview of constructability review (CR) programs, and implementation guidelines, and describes in detail each constructability function and its steps, actions, and tools. In addition, it identifies inhibitors affecting CR programs, presents the outcomes, and suggests future tools to measure constructability.

In 2000, the AASHTO published a constructability review of best practices guide (Madson et al. 2022). The work presented in this guide emphasized the importance of implementing a CR program due to its numerous benefits. Some of the benefits identified included: the enhancement of early planning, minimization of scope changes, reduction of design-related change orders, improvement of contractor productivity, development of construction friendly specifications, enhancement of quality, reduction of delays, meeting of schedules, improvement in the public image of the industry, promotion of public/WZTC safety, reduction of conflicts, disputes, and claims, and a decrease in construction and maintenance costs.

This report does not provide any information on how DOTs can measure cost-benefits or the time when CRs should be implemented. Despite the efforts to address CR practices at DOTs, this AASHTO report does not present information related to the constructability practices for a DMUII project. The relevant information from this report includes the identification of best practices and the identification of benefits.

To ensure that a project is constructible, or simply to enhance constructability, a CR is often performed. The primary goal of a CR is to assemble industry experts from multiple disciplines (construction, structures, geo-technology, utilities, etc.), to identify potential design and construction inhibitors that would negatively impact project cost, duration, and safety (Construction Industry Institute 1986) and to suggest corrections early in the design process that would enhance the attainment of more sustainable construction. However, to enhance the benefits and the impact of a CR, it is necessary to know when to implement it. Othman (2021) emphasized that CRs enhance transportation projects if implemented across all phases of a project (conceptual planning, design and procurement, and field operations). The actual impact is observed only when a CR is performed at the appropriate time in the project's life cycle. DOTs have recognized the importance of CRs and have developed checklists and other tools to determine the appropriate time to perform them (Smadi and Tran 2020).

Modularization and Prefabrication

In construction, modularization and prefabrication (M&P) refers to the methods used to build, construct, and assemble some parts of the process off-site and under controlled conditions (RealProjectives 2019). M&P has been used in multiple building components for decades (some examples include modular bridges, houses, offices, etc.). However, in transportation projects, M&P has seen limited use because most transportation infrastructure is horizontal construction and M&P units cannot be fully implemented in this form of construction. M&P has only been implemented, thus far, for construction components such as prefabricated walls, precast concrete systems, and bridge modules (El-Abidi and Ghazali 2015).

M&P has been used in multiple industries for decades. As highlighted by El-Abidi and Ghazali (2015), in transportation projects, M&P is utilized for activities such as prefabricated walls, precast concrete systems, and accelerated bridge construction models. In the context of the utilization of M&P for projects with DMUII design, Martinez et al. (2015) and RealProjectives (2019) found that M&P has the potential to improve the construction process by decreasing construction time and generating cost savings. Also, M&P can reduce uncertainties that arise due to weather delays, enhance construction by improving site planning and minimizing material storage on-site, reduce labor costs, improve safety, and minimize errors (Martinez et al. 2015; RealProjectives 2019). Additionally, the use of M&P techniques can help minimize waste production in projects with DMUII designs (Martinez et al. 2015; RealProjectives 2019).

M&P techniques also have certain inhibitors that need to be considered. These include negative perceptions associated with past practices, shortage of skilled labor, and the need for making more complex decisions and a front-loaded design (El-Abidi and Ghazali 2015; RealProjectives 2019). In this study, it was also found that M&P the approval process for M&P can also be complicated, and transportation costs and risks can pose additional challenges. Additionally, M&P techniques may require higher capital costs (El-Abidi and Ghazali 2015; RealProjectives 2019). An effective way to diminish the impact of some of these inhibitors is by adopting Building Information Modeling (BIM) practices. BIM has the potential to reduce coordination errors, monitor procurement and completion times, and monitor design constraints for fabricators (Mostafa et al. 2020).

Automation

Labor shortage ultimately impacts the overall performance of a project. From early 2020 to the present, the construction industry has suffered from a shortage of skilled labor which has resulted in low productivity (Castro-Lacouture et al. 2007). Therefore, it is important to consider using automation in projects with DMUII designs. Automation for transportation infrastructure consists of performing a task that can rely on automating processes utilizing tools such as BIM, or geographic information systems (GIS) for linear construction work activities such as road construction, paving, drilling, trench excavation, and pipe laying (Karimi and Iordanova 2021; Haas et al. 1995).

The capabilities of construction automation tools (e.g., robots) are improving considerably and at an accelerated pace (Castro-Lacouture et al. 2007). However, despite their benefits, it is important to acknowledge that this constructability enhancer needs further development. Some activities such as excavating operations and trenching require precise control and current automation technologies may not be up to the required accuracy levels under the often difficult conditions of the construction environment (Haas et al. 1995). However, due to the rapid evolution of technology, automation has the potential to be more precise and to be a strong enhancer of transportation projects. Once automation technologies achieve maturity, they have the potential to improve productivity over traditional operations (Shah et al. 2009). Therefore, construction automation is a promising catalyst for addressing challenges related to the construction of projects with DMUII designs.

3D/4D Modeling

The utilization of 3D modeling in transportation infrastructure projects is less common compared to its use in building construction. However, incorporating 3D modeling can greatly contribute to identifying areas that require constructability assessment, which is crucial for complex and diverse infrastructure projects. By integrating 3D modeling into the design process, spatially constrained sites can be effectively managed, traffic flow can be assessed, worker and public safety can be ensured, and schedule and cost can be closely monitored.

One effective approach to introducing visualization into construction is through the implementation of BIM. BIM is a process that emphasizes the development, use, and transfer of data to enhance the design, construction, and operation of a project. By incorporating 3D images into the design process, BIM improves synchronization, parameterization, and project integration across various units, including construction, bridges, and utilities. This integration significantly reduces problems during construction.

In transportation projects, BIM can be utilized for the 3D design of structures, roadways, railways, tunnels, site profiles, and engineering, traffic, and utilities. This enables the production of more accurate and consistent designs. Ahuja et al. (2017) have identified 15 BIM capabilities that contribute to project development and construction, including design coordination, visualization, M&P, construction sequencing and scheduling, energy, and environmental analysis, integrated site planning, change management, structural analysis, MEP system modeling, quantity take-off, facility management, constructability analysis, collaboration and coordination, BIM for as-built, and BIM for the supply chain management. However, the effectiveness of BIM's capabilities depends on the extent to which organizations develop and implement it. To fully leverage the benefits of BIM, organizations like NCDOT should incorporate its use across all disciplines and throughout all stages of a project.

There are several benefits associated with the use of BIM. These benefits can be classified into four areas: technical design, visualization and communication, construction planning, and work area management. Overall, these benefits improve project performance and enhance cost, schedule, and quality. They also improve communication, the construction process, and coordination among project stakeholders (Shah et al. 2009; Herritt 2012).

BIM offers various capabilities, one of which is the utilization of 3D modeling for constructability reviews. By integrating design and construction processes, BIM enhances design constructability and identifies clashes and design errors, thereby improving quality. This, in turn, leads to cost and time savings in the overall project (Sacks et al. 2018; Fadoul et al. 2021).

Moreover, BIM enables the modeling of construction activities and schedules, facilitating the exploration of different designs and execution plans that enhance the design. It also allows for quantifying constructability by observing the effects of design decisions (Zhang et al. 2016; Hijazi et al. 2009). BIM's contribution to constructability and the corresponding constructability inhibitors are as follows:

1. Technical Design: BIM aids in detecting design conflicts and addressing pavement and earthwork issues (O'Brien 2012).
2. Visualization and Communication: BIM assists in conceptualizing the 3D geometric design, communicating design ideas, and obtaining approvals or acceptance from organizations (O'Brien 2012; Parve 2015).
3. Construction Planning: BIM facilitates the review of construction schedules and sequencing, utility relocation, right-of-way acquisition processes, as well as traffic phasing and detour scheduling (O'Brien 2012; American Institute of Steel Construction 2019).
4. Work Area Management: BIM supports planning equipment location and construction methods, managing materials, organizing the site, and ensuring proper access (O'Brien 2012; Parve, 2015).

In terms of construction planning, O'Brien (2012) highlights the significant role of BIM in enhancing construction planning, sequencing, and utility relocation. This is particularly crucial for tasks such as reviewing traffic phasing and scheduling detours, which are inherently challenging. However, to accomplish this effectively, it is essential to accurately determine the locations of existing utilities and have a clear understanding of the proposed relocation period.

However, the implementation of BIM comes with multiple limitations. Some of these limitations include a lack of education and training, software limitations, and resistance to change (Herritt 2012). Transportation agencies and some design and construction firms have been hesitant to incorporate BIM due to the challenges of learning a new technology while also serving clients and maintaining profitability (Eastman et al. 2011). Furthermore, the process of adopting, implementing, and learning about data tracking and sharing is time-consuming (Vaughan et al. 2013), which may be particularly challenging for older employees in transportation agencies.

Software limitations pose another significant limitation, particularly when it comes to change tracking in complex BIM models. As the complexity of a BIM model increases, it becomes more difficult to keep track of multiple versions, leading to interoperability issues in some cases. Interoperability refers to the ability of software platforms to link or share information (American Institute of Steel Construction 2019). Lack of interoperability decreases project efficiency by limiting the ability to share data.

Another reason for the slow adoption of BIM and 3D modeling by transportation agencies is the relationship with industry. When a transportation agency adopts this technology, it also requires all external design and construction firms to adopt it for the life cycle benefits to be realized. However, implementing 3D modeling is challenging for small firms due to various factors such as cost, learning curve, required computing expertise, hardware, and training.

This makes it more suitable for larger firms with greater financial and personnel resources, as they are typically involved in complex and expensive projects that justify the investment. Transportation agencies have a responsibility to delay the widespread implementation of such technologies until a reasonable segment of the industry can participate or until a unique project type (such as DMUIIs) emerges that justifies the adoption.

To overcome these limitations, it is important to promote early collaboration between stakeholders, including architects, contractors, and other design disciplines, throughout the project's lifetime. Additionally, using a neutral file format can help avoid interoperability issues (American Institute of Steel Construction 2019). By following these practices, the use of BIM technology can be enhanced.

Departments of Transportations Practices

Studies conducted by Herritt (2012) and Jeffers (2019) examined the use of advanced modeling techniques in transportation infrastructure projects. Herritt's national survey, with an 18/50 response rate, revealed that approximately 13 Department of Transportation (DOT) have been employing 3D modeling since the early 2000s. However, the adoption of BIM or 3D modeling remains uncommon among DOTs due to various ongoing challenges. These challenges include limited software knowledge, software limitations, and resistance to change. Among the 13 DOTs utilizing 3D modeling, its implementation has been limited to specific areas such as reconstruction, grading projects, intersection improvements, storm sewer/drainage improvements, and bridge replacements.

In Jeffers'(2019) more recent survey, with a 32/50 response rate, it was discovered that only 19 DOTs currently use 3D modeling, while 9 DOTs are considering partial implementation. However, even among these 19 DOTs, the use of 3D modeling is not fully integrated. The survey indicated that 3D modeling is primarily employed for visualization (16 DOTs), design (10 DOTs), detailing (10 DOTs), analysis (9 DOTs), plan production (4 DOTs), staking layout (2 DOTs), quality take-off (5 DOTs), conflict resolution (8 DOTs), constructability reviews (6 DOTs), and providing information to contractors (4 DOTs). These findings are consistent with Herritt's study.

Both surveys demonstrate that the adoption of 3D and 4D modeling practices in DOTs is an ongoing process, with reluctance to fully embrace these techniques. However, the North Carolina Department of Transportation (NCDOT) plans to incorporate Bentley's software for all projects by 2025 and aims to implement 3D modeling by 2024. This initiative intends to maximize the utilization of 3D models and improve project delivery in terms of economics, efficiency, and design quality.

Although 3D modeling has been utilized in DOT projects for many years, its usage has primarily been limited to facility visualization, and the full potential of BIM applications has not been fully realized (Chong et al. 2016).

Staging and Sequencing

Even though performing construction staging is standard practice for every construction project, it is important to emphasize how significant the staging and sequencing of activities are for the success of a project. Analyzing the scheduling and sequencing of a construction project can eliminate potential conflicts that would result in schedule disruption (Excelize 2021). Prior research (Excelize 2021; Tynan 1999; Hancher et al. 2003; Wong et al. 2006; United States Army Corps of Engineers 2013) has emphasized the importance of planning staged projects. For example, Reeder and Nelson (2015) found that focusing on solving staging and constructability concerns before construction helps to reduce risks that result in cost and schedule overruns. Similarly, Zhan and El Diraby (2006) suggested that paying significant attention to staging and sequencing for the installation of accelerated bridge construction can aid in mitigating construction risks during design. Special attention needs to be given to staging considerations for projects that involve innovative practices. These would especially include DMUIIs. The findings indicated that properly staged and sequenced projects are enhanced and the overall benefits result in a more buildable, cost-effective, and maintainable project.

Business Process Improvements

The idea of finding different methods and procedures that can enhance the construction of DMUIIs is important. One of the areas includes the evaluation of the contract type that a project with DMUII designs should encompass. In a study performed by Smadi and Tran (2019) and Smadi et al. (2020), the differences between contract types utilized by the Departments of Transportation Agencies were investigated. The types of contracts evaluated were design bid build (DBB), design build (DB), and construction manager/general contractor (CM/GC).

Smadi et al. (2020) found that traditional DBB creates shortages in construction knowledge among the stakeholders. This is because on a DBB project, the owners procure separate professionals for both design and construction, and the contractors' input is usually involved in the project after the design is completed (Smadi and Tran 2019). To address the deficiency of contractors' input on DBB, Antoine and Molenaar (2016) found that some DOTs incorporate contractors in the design and construction by allowing contractors to solicit Alternative Technical Concepts (ATC). The ATC method allows contractors the opportunity to propose alternative approaches that are as good as or even better than the requirements in the final request for proposal. By incorporating ATC into DBB projects, projects have the potential to improve constructability, enhance innovation, shorten schedules, reduce risks, and ultimately save costs (Antoine and Molenaar 2016).

On the other hand, DB and CM/GC projects ensure that construction knowledge is incorporated early in the design phase, which helps to reduce design deficiencies. For these types of contracts (DB and CM/GC) the contractors' perspectives are incorporated into the design phase early in the process and ultimately, constructability can be enhanced.

Analysis

Interviews and Surveys

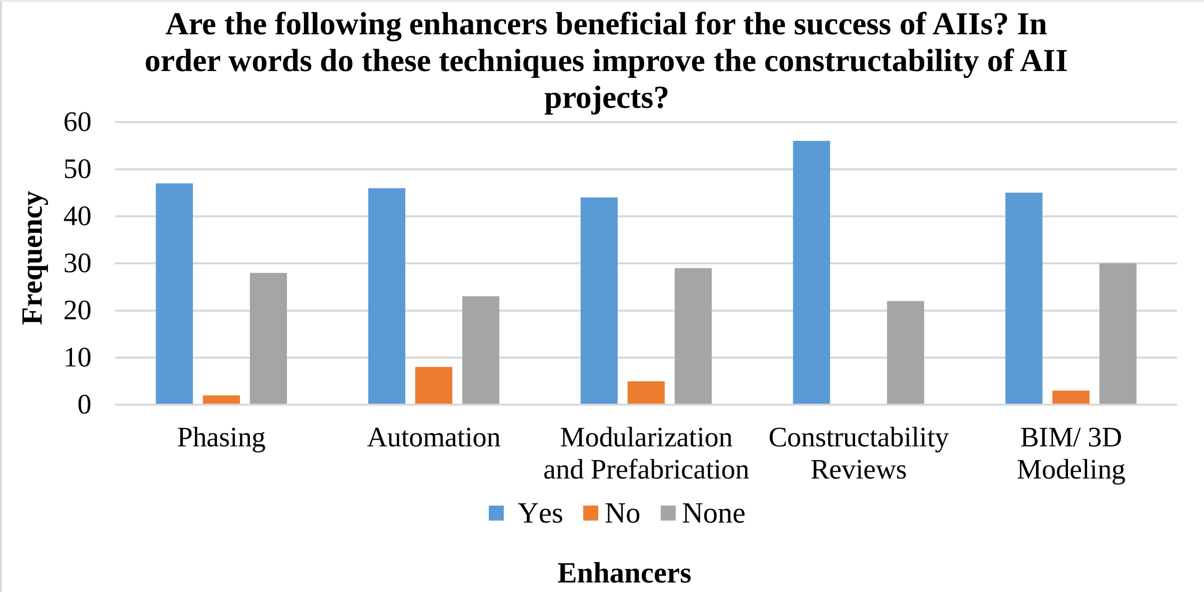
Benefits of Construction Enhancers

To supplement the effectiveness of the construction enhancers previously found in the literature, the survey and interview participants introduced in Chapter 2 answered specific questions that identified the benefits and disadvantages of techniques proven to be effective to enhance construction. Participants agreed that the five enhancers provide benefits. The benefits identified by participants are displayed in Figure 6.2.

According to participants, the most beneficial enhancer is CR, as it allows them to improve project efficiency through interaction and feedback from multiple experts. Additionally, the presence of CRs enables designers to address any issues or concerns during the design stage, leading to a reduction in project delays and cost savings. The participants (n = 47) also highlighted the importance of phasing. They emphasized that proper planning and organization of phasing plans for DMUIIs are essential for maximizing project performance, particularly in space-constrained locations. Therefore, more emphasis should be placed on this aspect.

Automation (n = 46) is the third most common enhancer identified by participants. This enhancer allows practitioners to reduce human errors and enhance safety. Most importantly, due to the shortage of skilled labor, the use of automation is a clear advantage. Similarly, BIM/3D modeling was considered to be beneficial (n = 45) because it allows consultants and designers to better visualize conflicts and helps to identify potential inhibitors during construction, planning, and staging.

Lastly, with a total of 44 responses, M&P is also considered to be an enhancer for projects with DMUII designs. Participants indicated that M&P shorten on-site construction time and improve safety conditions in the construction process.



*__None__ = participants who responded "I don't know" or decided to not answer the question.

Figure 0.2 Assessment of the Benefits of Construction Enhancers

Disadvantages of Enhancer Techniques

To further investigate the extent to which enhancers are beneficial, the survey asked participants to identify disadvantages that could overshadow the benefit of the enhancers. Table 6.1 displays the results of the disadvantages of construction enhancements previously identified by participants. It can be observed that NCDOT participants consider the cost as the main disadvantage (n = 9) for BIM/3D modeling, followed by the learning curve of the technology (n = 8). However, the results from all other stakeholders (consultants, contractors, and other DOTs) indicate that the learning curve of the technology is the most predominant disadvantage. Similarly, consultants perceive automation to be a costly technology. On the contrary, NCDOT personnel, contractors, and other DOTs acknowledge that automation requires a learning curve.

The remaining enhancers (CR, M&P, and sequencing) have more consistent results. The participants consider CRs and sequencing to be of value, but time-consuming. For M&P, participants also consider them to be costly. In general, enhancers are well-perceived by participants since the majority of participants recognized few to no significant disadvantages associated with the respective enhancers.

Table 0.1 Disadvantages of Construction Enhancement Tools and Techniques

Inhibitors	NCDOT					Consultants				
	Sequencing	Automation	Modularization and Prefabrication	Constructability Reviews	BIM/ 3D Modeling	Sequencing	Automation	Modularization and Prefabrication	Constructability Reviews	BIM/ 3D Modeling
Requires a learning Curve	0	11	6	3	8	0	1	1	1	2
Time Consuming	5	2	1	6	5	0	0	0	2	1
Costly	5	7	9	1	9	0	2	1	0	1
Lack of Accuracy	0	7	6	0	1	0	0	2	0	0
None	22	5	10	22	9	4	1	0	1	0
Total	**32**	**32**	**32**	**32**	**32**	**4**	**4**	**4**	**4**	**4**

Inhibitors	Contractors					Other DOTs				
	Sequencing	Automation	Modularization and Prefabrication	Constructability Reviews	BIM/ 3D Modeling	Sequencing	Automation	Modularization and Prefabrication	Constructability Reviews	BIM/ 3D Modeling
Requires a Learning Curve	0	10	3	0	13	1	9	3	1	11
Time Consuming	5	2	2	7	3	5	1	0	6	5
Costly	4	6	11	2	4	2	7	8	1	2
Lack of Accuracy	1	3	1	1	1	1	1	1	2	0
None	11	0	4	11	0	11	2	8	10	2
Total	**21**	**21**	**21**	**21**	**21**	**20**	**20**	**20**	**20**	**20**

Recommendations to Enhance Construction of DMUII Projects

During the interviews, participants were asked to provide feedback or suggestions regarding necessary business or construction process changes to enhance the design and construction of DMUIIs. Surprisingly, the majority of participants (n = 14) chose not to respond to this particular question. Out of the respondents, four participants expressed the belief that no changes are required to improve the construction and design of DMUIIs. However, a few specific areas were mentioned by participants who did provide feedback.

Three participants highlighted the importance of utility relocation, while three others emphasized the significance of public perception. Additionally, two participants emphasized the need to focus on traffic control. These individuals feel that greater attention should be given to identifying and relocating utilities prior to starting construction. Furthermore, participants stressed the importance of prioritizing traffic control, as DMUIIs are a relatively new concept, and users may not be familiar with them. Consequently, efforts in managing traffic control are considered crucial.

One participant directly mentioned that construction inhibitors are more likely to emerge for projects with DMUII designs during construction due to a lack of knowledge of best construction practices for them. Therefore, educating contractors and consultants about how to efficiently construct projects that have a DMUII design and how to identify inhibitors is a critical next step in promoting their adoption.

Implementation Strategies

After identifying and ranking the enhancement techniques based on their effectiveness, the next step is to determine ways to incorporate these techniques into NCDOT projects that have a DMUII design.

NCDOT Constructability Review Program

DOT resources are limited and depend primarily on public funding. Thus, determining ways to execute a project effectively without incurring cost or schedule overrun is important and can be accomplished by integrating programs that aid the early detection of problems in the project development process. Many DOTs address these concerns by implementing Constructability Review (CR) programs that aim to enhance project performance by introducing construction knowledge from experts into the design process.

The NCDOT's CR program is managed by the Value Management Office (VMO) (Value Management Office 2021). The VMO gathers a diverse representation of project stakeholders, including experienced engineers, contractors, architects, construction managers, and material suppliers, to identify, examine, and resolve potential challenges for a project prior to construction (NCDOT 2021). The NCDOT has used CRs for over a decade to enhance project design documents by incorporating construction knowledge into the design process. However, initially, the NCDOT did not have guidance as to when a CR meeting should take place or the parameters that would dictate the need for a CR. In 2019, research to assess the effectiveness of the NCDOT's current CR program and identify strategies to enhance its success was performed (Akhnoukh et al. 2023). Input from various parties, including experienced construction managers, contractors, design engineers, and construction inspectors, was sought to improve the CR process. Their expertise helped identify critical factors that affect construction projects and dictate the need for a CR (Bonilla et al. 2022; Akhnoukh et al. 2021). The research group then developed guidelines to aid the NCDOT in determining the optimal time to hold CR meetings, offered recommendations for follow-up meetings, and provided tools to measure the effectiveness of the CR meetings (Akhnoukh et al. 2023b). This research outcome provided the NCDOT with a formal process for conducting successful CRs, ultimately improving construction efficiency and enabling stakeholders to complete their activities within the planned schedule and budget.

Currently, based on the recommendations from survey respondents, CRs are a fundamental part of ensuring the success of a project. Recently, the NCDOT's CR program underwent improvements that included the development of a checklist to aid stakeholders in determining which projects need a CR. The current NCDOT checklist includes eight main categories:

1. **General:** to assess general project constraints and special considerations.
2. **Traffic management:** to evaluate different aspects within the construction project that may impact the continuity of traffic during the construction phase, entrance and exit from the construction site, and accommodation of residents, commuters, and businesses in the construction site vicinity.
3. **Project complexity:** to address any unusual aspects during the project construction phase.
4. **Structural issues:** to accommodate any special provisions related to the design and construction of structures, which includes the strength of construction materials, the availability of nontraditional construction sections, and the need for temporary structures to serve traffic and pedestrians.
5. **Right-of-way:** to evaluate the existing design provisions and measures taken to avoid problems in entering or exiting the construction site, and to ensure seamless traffic flow during the construction phase.
6. **Unfamiliar construction practices:** to evaluate and assess items not included in the other categories and that may evolve due to the special nature of the project.
7. **Cost:** to evaluate projects with a budget that exceeds $10 million. NCDOT projects over $10 million should be subjected to special CR scrutiny.
8. **Utility issues:** to evaluate items relevant to existing or future utilities.

Recall that inhibitors that affect projects that have a DMUII design have been previously identified (findings from Chapters 2 and 3). The current categories in the checklist apply to any type of project, including DMUIIs, as they address the major inhibitors associated with projects that have a DMUII design. However, a new category called Alternative Intersections and Interchanges is recommended to help practitioners detect challenges not addressed in the current checklist. Table 6.2 shows the recommended items to be incorporated into this new category, which was developed based on inhibitors that are exclusively affecting projects with DMUII designs and are not featured in the current CR checklist.

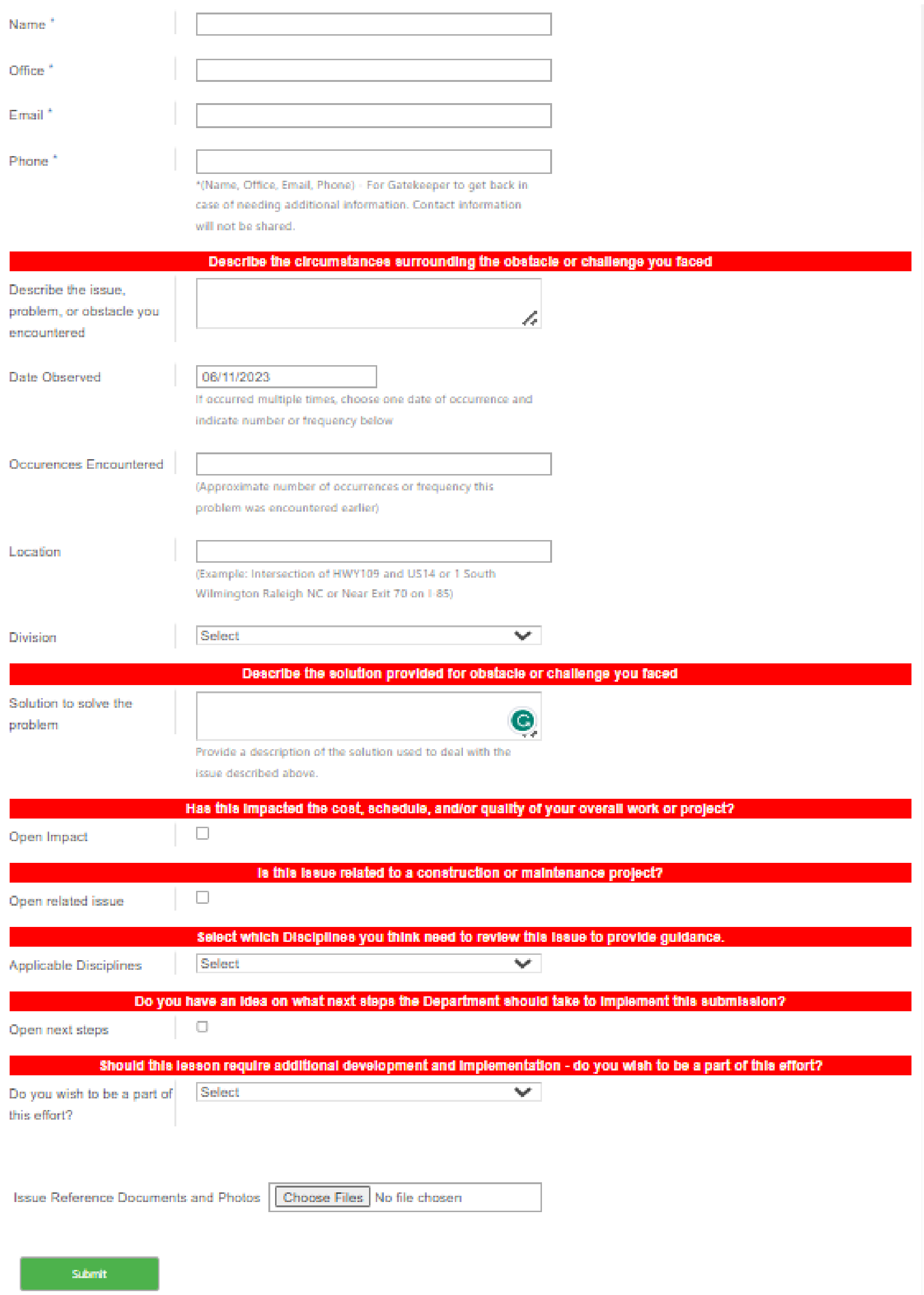
Table 0.2 DMUII Category Recommended for Constructability Review Checklist

#	Alternative Intersections and Interchanges
1	Is the traffic control plan clear, complete, approved, and in compliance with NCDOT standards?
2	Are there any concerns about the requirements and provisions for temporary safety devices such as guard rails, attenuators, and earth mounds?
3	Have the traffic control signs, warning devices, and barricades been placed in the correct locations without encroaching on lanes?
4	Is there a detour facility in place (if necessary), and is the maintenance of traffic adequately addressed, including side streets?
5	Have the traffic operation requirements been properly addressed, including signing, pavement markings, and signals?
6	Does the earthwork design account for temporary borrow, additional excess material, detour material, embankment, etc.?
7a	Have signals and signage been placed in appropriate locations?
b	Is there any concern about the visibility of signals and signs?
8	Is there sufficient clearance within the work zone for operations (e.g. crane operation, material storage, etc.)?
9	Are the exits and entrances to the work zone adequate and safe?
10a	Are there any concerns about how the transition from one phase to the next is handled?
b	Are there any concerns related to safety between the phasing?
11a	Are there any concerns about safety related to clearance for driveways and entrances to businesses?
b	Are the tie-ins reasonable, or are they too steep?
c	Will water accumulate in tie-ins?
12a	Are there any drainage problems between phases?
b	Can water reach inlets or drainage structures during phase transitions and throughout each phase?
13	Have the geometrics and roadway alignment been properly considered, including curve data, sight distance, vertical datum, centerline, etc.?

NCDOT Communicate Lessons, Exchange Advice, Record (CLEAR) Program

The CLEAR (Communicate Lessons, Exchange Advice, Record) database is a system developed to facilitate NCDOT the sharing of lessons learned and best practices and to collate and share data during a project's lifecycle about activities that may be useful for future NCDOT projects. Its overall purpose is to enhance project control, consider innovative ideas, and add value to the state of North Carolina. The CLEAR database allows end-users (NCDOT personnel) to contribute their insights, experiences, and recommendations related to specific topics or projects (Jaselskis et al. 2020). The tools and features integrated into the CLEAR database aim to foster knowledge sharing and enable continuous improvement by capturing and disseminating valuable insights from various sources.

Figure 6.3 shows a screenshot of the online form utilized by end-users to document information for the CLEAR database. The database enables users to search for existing records or contribute new information. In addition to adding information to the database, end-users can use it as a search tool to sort information by keywords, division, region, county, cost and schedule impacts, project type, and project phase, thereby catering to the various groups within the NCDOT. To ensure that information is stored correctly, training materials and standard operating procedures are available to guide stakeholders, including end-users and the gatekeeper (the person who is responsible for reviewing and approving valid lessons to be included in the lessons learned/best practices database), in entering information, searching for lessons learned/best practices, and reviewing submitted information. The CLEAR database has become a valuable resource for users seeking guidance and lessons learned in a particular field or project domain.



Name *

Office *

Email *

Phone *

*(Name, Office, Email, Phone) - For Gatekeeper to get back in case of needing additional information. Contact information will not be shared.

Describe the circumstances surrounding the obstacle or challenge you faced

Describe the issue, problem, or obstacle you encountered

Date Observed: 06/11/2023

If occurred multiple times, choose one date of occurrence and indicate number or frequency below

Occurences Encountered

(Approximate number of occurrences or frequency this problem was encountered earlier)

Location

(Example: Intersection of HWY109 and US14 or 1 South Wilmington Raleigh NC or Near Exit 70 on I-85)

Division: Select

Describe the solution provided for obstacle or challenge you faced

Solution to solve the problem

Provide a description of the solution used to deal with the issue described above.

Has this impacted the cost, schedule, and/or quality of your overall work or project?

Open Impact

Is this issue related to a construction or maintenance project?

Open related issue

Select which Disciplines you think need to review this issue to provide guidance.

Applicable Disciplines: Select

Do you have an idea on what next steps the Department should take to implement this submission?

Open next steps

Should this lesson require additional development and implementation - do you wish to be a part of this effort?

Do you wish to be a part of this effort? Select

Issue Reference Documents and Photos: Choose Files No file chosen

Submit

Figure 0.3 NCDOT CLEAR Program: Lessons Learned Form

The NCDOT plans to further enhance the CLEAR program by developing a data dashboard for visualizing uploaded content as well as implementing an artificial intelligence model to automatically disseminate relevant information to end-users (Jaselskis et al. 2020). The CLEAR program is expected to bring great benefits to the NCDOT, leading to improved project management and operational performance. Further, the CLEAR program is of vital importance to ensure the success of projects with DMUII designs. The construction process of projects that have a DMUII design is not familiar to everyone and, therefore, the documentation of lessons learned and best practices is vital. However, as promising as the CLEAR program may be, the form shown in Figure 6.3 that currently captures lessons learned does not allow for the identification of project type. Therefore, a section should be added that asks end-users if the project includes a DMUII and, if so, to specify the type of work required in the project. By adding this question, the information collected in the database should soon allow users to retrieve findings from past DMUII projects.

NCDOT OpenRoads Designer Program

Currently, the NCDOT develops project plans and specifications using 2D modeling software. 2D modeling consists of creating 2D drafting plans or drawings. 3D modeling adds the third dimension and thus provides 3D visualization of a 2D drawing. 3D modeling enables users to view, rotate, and move through the model to see the project from different points, angles, and perspectives. It also enables users to determine interference, sometimes referred to as clashes (conflict points). Other models, referred to as building information models (BIMs), allow designers to reduce coordination errors, monitor procurement and completion times, and monitor design constraints. One characteristic of 4D BIMs is the addition of time to the 3D spatial model, which enables users to visualize the sequence of project activities and the coming together of all the materials and equipment to form (in the case of this study) a new intersection. In short, it aids designers in gaining a visual understanding of the project.

The NCDOT is undergoing a statewide, technology-focused, OpenRoads Designer (ORD) implementation initiative that is aimed to move the NCDOT's computer-aided design and drafting (CADD) operations from Bentley MicroStation to Bentley Connect ORD. ORD is a next-generation civil design technology platform that allows for a more comprehensive, multi-disciplinary, 3D modeling application that will advance the delivery of the NCDOT's transportation projects from the conceptual design stage through construction. The ORD initiative involves a major transition that requires training and testing for several hundred NCDOT engineers and for the private engineering firm consultants who work with the NCDOT. The current efforts of the ORD initiative team are focused solely on the implementation of 3D modeling in general. The team's goal is to provide guidelines and a set of informational materials to aid NCDOT personnel to transition from designing in 2D to 3D, detect potential design workflow changes necessary for ORD and 3D modeling, and assess the impact of converting projects from 2D to 3D. Figure 6.4 presents the timeline for the current ORD implementation plan.

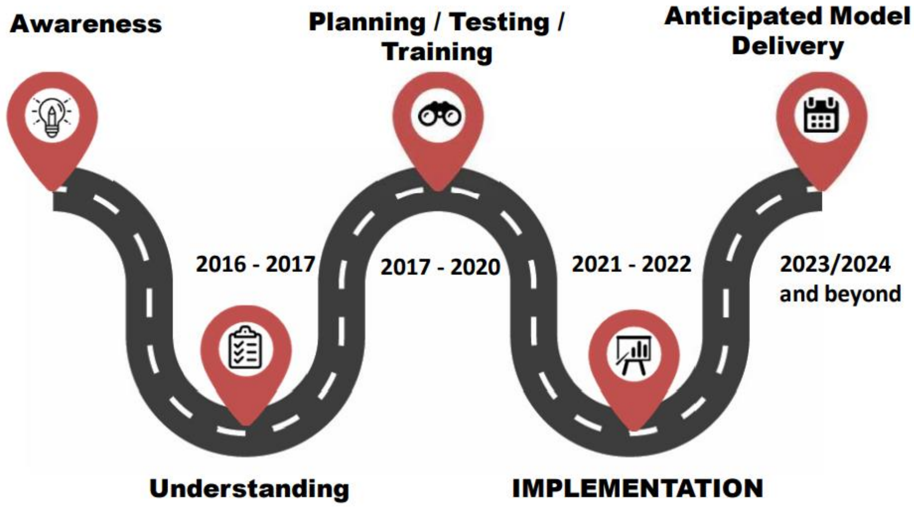


Figure 0.4 NCDOT Open Road Implementation Plan (Garland et al. 2021)

The NCDOT is currently in the planning/testing/training phase of the ORD initiative which has been delayed due to the pandemic. The projects used in this phase include projects already let or built and are referred to as ‘test projects. These projects were selected to test the capabilities of ORD and identify any software issues. Other projects used in this phase are ongoing projects with completed designs and already let and are referred to as ‘pilot projects.’ The test and pilot projects require simple alignment designs, railroads, and hydro work. Because NCDOT 3D modeling software is at the testing stage, a constructability 3D modeling evaluation for a DMUII project is not currently possible. However, once the ORD initiative is fully implemented, it can be used for any type of project, including DMUIIs. The implementation plan does not include the use of BIM capabilities or cost or schedule data in the models but is focused solely on the creation of 3D models so that the NCDOT can transition to 3D modeling. These models are only for design specification and visualization purposes, so the concept of constructability and its future incorporation into ORD remains to be clarified. Thus, research is needed to identify ways that ORD can help with constructability. As ORD becomes available for projects that have a DMUII design, ORD models can be utilized to evaluate the constructability of projects with a DMUII design based on design omissions, ambiguity, coordination, unforeseen conditions (e.g., weather), resource constraints, and construction performance (Virtual Building Studio 2019). The following features are needed for this purpose:

- Visualization or space review (3D)
- Clash detection (3D)
- Design coordination (3D)
- Alternative models (3D)
- Sequencing of works (4D)
- Logistical planning (4D)
- Measurement check

Conclusion

Construction enhancers are promising concepts and techniques that can promote the sustainable construction of DMUII projects. Findings indicate that research into construction enhancement techniques associated with DMUIIs is currently limited. This chapter provides an overview of related studies of enhancement techniques and proposes a process for tailoring existing NCDOT programs to enhance the construction of DMUII projects.

The identification and utilization of enhancers, such as CRs, M&P, automation, and 3D/4D modeling, can significantly improve the overall performance of transportation infrastructure projects. These enhancers have the potential to enhance constructability, reduce construction time and costs, improve site planning and safety, minimize errors, and optimize project coordination. Overall, the integration of these enhancement techniques can contribute to the reduction of construction inhibitors, improve construction processes, and promote sustainable practices for the construction of DMUII projects. The exploration of programs and tools for enhanced project performance in projects that have a DMUII design has highlighted the importance of incorporating effective techniques to improve project efficiency.

In the context of the NCDOT, several programs already have been implemented to enhance project performance, such as the CR program, the CLEAR program, and the ORD program. The CR program, managed by the VMO, has been valuable in incorporating construction knowledge into the design process. Recent improvements, including the development of a checklist, have enhanced the effectiveness of CRs. The CR checklist can be enhanced by adding a category that specifically addresses common inhibitors for projects that have a DMUII design. The CLEAR program, which includes a knowledge-sharing database, has been instrumental in capturing lessons learned and best practices from various NCDOT projects. To improve the capabilities of this program to include projects that have a DMUII design, the lessons learned online form should be amended to include DMUII project type identification. Lastly, the ORD program is focused on transitioning NCDOT's design operations to 3D modeling and can also benefit projects that have a DMUII design. The ORD program is currently in the planning/testing/training phase and the implementation plan is primarily aimed at the creation of 3D models. Features such as visualization, clash detection, design coordination, and sequencing of work could be utilized in the ORD program to evaluate and facilitate constructability and improve project outcomes for DMUII projects also.

Incorporating these enhancement techniques into existing NCDOT programs and tools will contribute to the success and efficiency of projects that have a DMUII design. These programs, directly and indirectly, utilize enhancement techniques identified by stakeholders, such as CRs, M&P, automation, and 3D/4D modeling. By addressing project constraints, sharing knowledge and lessons learned, and utilizing advanced modeling capabilities, the NCDOT can enhance its project management practices and achieve better outcomes in the delivery of transportation projects, including DMUII projects.

CONCLUSIONS AND FUTURE WORK

The purpose of the research is to (1) provide valuable insights that are related to the identification of construction inhibitors, (2) determine the performance of projects with diverse, modern, and unconventional intersections and interchanges (DMUII) design compared to projects with conventional intersection and interchange (CII), and (3) identify enhancement techniques to improve constructability for DMUIIs.

This research focused on identifying and understanding the inhibitors that affect projects that have a DMUII design through the use of interviews, surveys, and field observations. A total of 18 inhibitors were identified, including utilities, business impact, public acceptance, safety concerns, space constraints, and environmental issues. The field study of three projects that have a DMUII design in North Carolina revealed material delivery issues, space constraints, and utility problems as the most frequent inhibitors that affect construction.

Compared the overall project performance of projects that have DMUII and CII designs using claims and supplemental agreement data from North Carolina Department of Transportation (NCDOT) projects. Findings reveal that the most common inhibitors for projects that have a DMUII design are utilities, contract changes, signal and signage, traffic control, and material estimate change. Findings also emphasize the importance of not generalizing inhibitors to all DMUII designs. Chapter 4 examined and compared the cost and schedule performance of projects that have DMUII and CII designs. The analysis results show that projects that have CII designs exhibited the largest cost variation and that schedule variations were most prominent in projects with DDI design.

In addition, this research evaluated roadway congestion operations in work zone traffic control (WZTC) scenarios and compared the effectiveness of WZTC measures in a DDI and CII projects. The CII project performed better in terms of travel time but faced challenges in roadway operations and incurred higher user costs compared to the DDI project. The evaluation highlighted the benefits of DMUIIs in optimizing traffic flow, reducing delays, and minimizing road user impact.

This work also focused on identifying construction enhancers for DMUII projects, such as constructability reviews, modularization and prefabrication, automation, and 3D/4D modeling. These enhancers have the potential to improve constructability, reduce construction time and costs, enhance safety, and optimize project coordination. Existing NCDOT programs, including its Constructability Review program, CLEAR (Communicate Lessons, Exchange Advice, and Record) program, and OpenRoads Designers (ORD) initiative, were examined for their potential to enhance DMUII project performance. Strategies to implement changes that better capture enhancement techniques for DMUII projects were recommended. Incorporating these enhancement techniques into existing NCDOT programs and tools can improve project efficiency and outcomes.

Overall, these research findings provide valuable findings that can guide transportation agencies in identifying and mitigating construction inhibitors, promoting efficient resource allocation, and adopting sustainable practices in the construction of DMUII projects.

Contributions

The contributions that result from this research are organized based on academic contributions and industry contributions. The academic contributions describe advances in academic knowledge that result from this work. The industry contributions describe ways that this research aids transportation infrastructure stakeholders in the construction of DMUII projects.

Academic Contributions

- Conducted a systematic and comprehensive analysis of the construction inhibitors that affect projects with DMUII designs.
- Performed thorough analysis of construction enhancers that have the potential to improve the construction of projects with DMUII designs.
- Identified variations in cost, schedule, and roadway operation measures between projects with DMUII and CII designs that prove the potential of a larger, multistate effort along similar lines.
- No prior work has been done addressing the impact of the cost of WZTC, claim, and supplemental agreements on projects with DMUII designs.
- Provided objective and quantitative insights into the effectiveness and efficiency of different design approaches by comparing CII and DMUII cost and schedule data.
- Utilized chi-square tests to evaluate the relevance and significance of construction inhibitors based on interviews and surveys, claims data, and supplemental agreement data, ultimately enhancing the understanding and management of construction projects.

Industry Contributions

- Provided transportation infrastructure stakeholders with a comprehensive list of the most common inhibitors that affect projects with DMUII designs.
- Offered meaningful results and guidance to assist stakeholders in evaluating the presence of potential inhibitors during the construction of projects with DMUII designs.
- Determined and quantified differences in project performance between projects with CII and DMUII designs.
- Develop a detour analysis method that could be adopted by NCDOT Traffic Management Unit.
- Identified stakeholders who require additional training to become familiar with the design and construction practices of projects that have DMUII designs. Construction engineers are less familiar with DMUII designs, highlighting the need to prioritize training for this group.
- Developed an implementation plan to support the NCDOT in incorporating enhancement techniques on already established programs that can aid to identify and mitigate constructability inhibitors in projects with DMUII designs.

Limitations

The limitations associated with this research include that the sample size for some of the projects with DMUII designs was small (e.g., one Continuous Flow Intersection and three Quadrant

Roadways projects), which prevents generalization of the findings related to inhibitors that affected the projects. In addition, the findings in Chapter 5 are limited to a single DDI and CII project. Further studies with larger sample sizes and a variety of DMUII types are recommended to reinforce the findings. These additional efforts should focus on exploring DMUII WZTC performance based on design type. Future research also could include projects that were not affected by COVID-19 restrictions.

Future Work

This work has led to several recommendations for ways to enhance the construction of DMUIIs and opens the door for future research studies. First, further research is needed to explore ways to use ORD to facilitate and detect constructability issues and reduce the level of risks due to uncertainties (e.g., the location of utilities). The concept of constructability and how it will be incorporated into ORD is fuzzy. Also, ways that ORD can help with constructability assessment need to be identified. Integrating all of these efforts will be key to improving construction in general, but the greatest benefits will involve DMUIIs because DMUII designs are relatively new and many construction uncertainties surrounding DMUIIs will need to be identified and mitigated.

In addition to identifying enhancement techniques, determining ways to measure the impact of each technique is likewise important. Tracking the impact of constructability reviews, modularization and prefabrication, automation, 3D modeling, and staging and sequencing for projects with DMUII designs is of special interest because knowing which enhancer is more effective for a particular DMUII design will allow practitioners to allocate resources to those enhancers. Therefore, developing performance metrics is important because these tools will aid in the representation, organization, and determination of the success of a project. With respect to DMUIIs, the performance metrics can be applied to evaluate the performance of key areas (American Society of Quality 2021). These metrics will aid the NCDOT in reducing the need for complex measurements and being able to use a single value that can be tracked, managed, and improved consistently throughout all NCDOT Divisions.

Lastly, to comprehensively address the variations in cost, schedule, and roadway operation measures between DMUII and CII designs, a national (multistate) data collection effort should be considered. Such efforts would enable us to gather data from various regions and states, encompassing diverse geographical, climatic, and demographic conditions. By collecting this extensive dataset, we can better understand how different inhibitors impact the performance and efficiency of DMUII and CII designs in real-world scenarios. Also, since this project could not provide any guidance on Echelon Interchanges, if any future work is built, it is recommended to assess their constructability.

Through this nationwide data collection effort, we can identify key patterns and trends that may emerge, shedding light on the strengths and weaknesses of both DMUII and CII approaches. This will allow policy, engineers, and decision-makers to make informed choices when selecting the most suitable design for specific projects in different locations. Moreover, this collaborative data collection effort will foster knowledge sharing among states, promoting best practices and innovative solutions for tackling transportation challenges.

By undertaking this ambitious data collection effort, we can proactively address potential inhibitors, helping ensure that future transportation projects are not only efficient but also cost-effective.

In addition, it is recommended to conduct a public perception assessment for DMUIIs. What we discovered early in the project was that public perception and opposition is a major inhibitor. Unfortunately, a detail assessment of tis inhibitor indicated that it is outside the scope of this project because our focus was related to construction inhibitors only. There is anecdotal evidence that pre-construction diminishes post-construction when drivers become familiar with the new intersection design. For example, DDIs appear to be quickly accepted by users one thy are built similarly, 400 RCIs have been built in NC in which 80 reside in division 3 alone. Reports from division 3 indicate a positive acceptance of this RCIs. Demonstrating that widespread implementation promotes familiarity and reduces anxiety and opposition. On the other hand, despite their regular use, roundabouts appear to be continuously challenging for users and to drawn negative reviews. In summary, we recommend a study to carefully evaluate public perception of DMUIIs. This could involve pre-construction, post construction, survey, and assessment.

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APPENDICES

Appendix A

Interview Questionnaire

Respondent Background

1. Please provide the following information:
   Name: | Email:
   Last name: | Phone:
   Company name: | Job title:

2. What is your current job function? Specify

3. How many years of experience do you have in your current line of work?
   a) Less than 2 years
   b) 3-5 years
   c) 6-9 years
   d) More than 10 years

AIIs General Questions and Issues Identification

4. Have you been involved in the construction of any projects that included a DMUII (show image of projects of interest)?
   a) None
   b) I have been involved in 1 project
   c) I have been involved in 2 projects
   d) I have been involved in more than 3 projects

   Please provide the # or location of the most challenging projects:

To consultants only

4. How many AII projects have you contributed to or been a part of in design or pre-construction?
   a) None
   b) I have been involved in 1 project
   c) I have been involved in 2 projects
   d) I have been involved in more than 3 projects

   Please provide the # or location of the most challenging projects: ________________

Ask questions 5-11 for each project mentioned in question 4

5. What type of AII project was (*Name the project(s) mentioned in #4*)?
   a) Diverging Diamond Interchanges
   b) Grade-Separated Quadrant Intersection
   c) Echelon Intersection
   d) Reduced Conflict Intersection
   e) Continuous Flow Intersection
   f) Other, specify

6. How was your experience participating in or being on the project team of (*Name the project mentioned in #4*)?
   a) Favorable, everything went smoothly
   b) The project presented issues but we were able to manage them
   c) There were many setbacks and the project was a problem project

7. What type of contract was used in (*Name the project(s) mentioned in #4*)?
   a) Design Build (DB)
   b) Design Bid Build (DBB)
   c) Construction Manager/General Contractor (CM/GC)
   d) Other, specify

8. Do you believe the type of contract (DB vs DBB) has an impact on AIIs? Please explain
   a) Yes
   b) No

9. How was your experience participating in or being on the project team of (*Name(s) the DMUII project(s) mentioned in #4 or 5*)?
    a) Favorable, everything went smoothly
    b) The project presented issues but we were able to manage them
    c) There were many setbacks and the project was a problem project

    Specify ____________________

Constructability

10. In (*Name the project(s) mentioned in #4*) did you experience any of the following issues? (Mark all that apply)
    a) Utilities
    b) Safety for workers
    c) Safety for drivers
    d) Construction sequencing
    e) Traffic control during construction (work zone control)
    f) Space constraints
    g) Site access
    h) Right-of-Way
    i) Bridge construction
    j) Wall construction
    k) Geotechnical issues
    l) Environmental concerns
    m) Water drainage during construction
    n) Multimodal transit (bicycles, pedestrians, buses, train) accommodation
    o) Public acceptance
    p) Business impact
    q) High bids
    r) Other, specify ______________

    Describe each issue ____

11. In what project phase did you experience the issue(s)? (Ask based on the issue (s) identified in #9) Beginning of construction
    a) Planning/ Environmental
    b) Design
    c) Pre Bid
    d) Middle of construction
    e) End of construction
    f) Throughout the construction of the project

12. Have you previously participated in a constructability review (formal or informal) of an AII project?
    a) Yes
       Which project(s) ____________________
    b) No

13. What type of review was it?
    a) Formal
    b) Informal

14. In which project development stage was the constructability review performed?
    a) Planning
    b) Design
    c) Pre-Bid meeting
    d) Construction

15. How is the construction of an AII design different from a conventional intersection or interchange?

16. Comment on the constructability of a tightly constrained vs an unconstrained site

Enhancers

17. Do you believe constructability reviews are beneficial in AII designs and construction?
    a) Yes
    b) No
    c) None

    Please comment ____________________________

18. Do you believe modularization and prefabrication would be beneficial for AII projects?
    a) Yes
    b) No
    c) None

    Please comment ____________________________

19. Do you believe automation (i.e. use of robots to automate paving operations, excavation, or installation of material) would be beneficial in AII designs and construction?
    a) Yes
    b) No
    c) None

    Please comment ____________________________

20. Do you think BIM or 3D modeling will be beneficial for AII design and construction?
    a) Yes
    b) No
    c) None

    Please comment ____________________________

21. Do you believe staging (where you put things and when) is beneficial to AII projects?
    a) Yes
    b) No
    c) None

    Please comment ____________________________

22. Are there any setbacks (disadvantages) to any of these enhancers?
    a) Constructability reviews ______________________________
    b) Modularization and prefabrication _________________________
    c) Automation ____
    d) BIM and 3D modeling _______________________________
    e) Staging ____

23. Is there any additional enhancer that needs to be considered? That is what else might improve AII constructability?

24. What business/construction process changes are needed for improving AII s designs and construction?

Appendix B

Survey Questionnaire

1. Please provide the following information:
   - Name:
   - Last name:
   - Agency name:
   - Email:
   - Phone:

2. How many years of experience do you have in your current line of work?
   a) Less than 2 years
   b) 3-5 years
   c) 6-9 years
   d) More than 10 years

3. What is your primary job function? (mark all that apply)
   a) Project manager
   b) Designer/planner
   c) Construction Engineer
   d) Superintendent
   e) Roadway Engineer
   f) Structural Engineer
   g) Project Engineer
   h) Traffic Engineer
   i) Other:____________

4. Have you participated in or contributed to a project that had any of the following types of intersections and interchanges? (mark all that apply)
   a) Diverging Diamond Interchange
   b) Grade-Separated Quadrant Intersection
   c) Echelon Intersection
   d) Reduced Conflict Intersection
   e) Continuous Flow Intersection
   f) Other:_______________

5. Do you believe the type of contract (Design Build vs Design Bid Build) has an impact on the success of AIIs?
   c) Yes - Design Build is preferred
   d) Yes - Design Bid Build is preferred
   e) No preferences
   f) Other:_________________________

6. Which of the following issues do you believe has the biggest impact on large and complex transportation construction projects? (Mark all that apply)
   a) Utilities
   b) Safety for workers
   c) Safety for drivers
   d) Construction sequencing
   e) Traffic control during construction (work zone control)
   f) Space constraints
   g) Site access
   h) Right-of-Way
   i) Bridge construction
   j) Wall construction
   k) Geotechnical issues
   l) Environmental concerns
   m) Water drainage during construction
   n) Multimodal transit (bicycles, pedestrians, buses, train) accommodation
   o) Public acceptance
   p) Business impact
   q) High bids
   r) Other, specify_______________

   Describe each issue ____

7. Are the following enhancers beneficial for the success of large and complex projects? In other words, do these techniques improve the constructability of a project?

	Yes	No	Don't know
BIM/ 3D Modeling	☐	☐	☐
Constructability Reviews	☐	☐	☐
Modularization and Prefabrication	☐	☐	☐
Automation (i.e. use of robots to automate paving operations, excavation, or installation of material)	☐	☐	☐
Staging/Phasing	☐	☐	☐

8. Please identify any other concepts, techniques, practices, or technologies that you think are effective at enhancing constructability

9. Please describe any inhibitors that could reduce the benefit of the enhancers listed above in question 7. Identify in question 10 that are missing (others).

	Requires a learning curve	Time consuming	Lack of accuracy	Costly	None	Other
BIM/ 3D Modeling	☐	☐	☐	☐	☐	☐
Constructability Reviews	☐	☐	☐	☐	☐	☐
Modularization and Prefabrication	☐	☐	☐	☐	☐	☐
Automation	☐	☐	☐	☐	☐	☐
Staging/Phasing	☐	☐	☐	☐	☐	☐
Enhancer identified in question 8	☐	☐	☐	☐	☐	☐

10. If you respond "others" in question 9, please specify the inhibitor.

11. Comment on the challenges and constructability of a tightly constrained vs unconstrained site.

Appendix C

Inhibitors on Alternative Intersections

Does your project have any alternative intersection or interchange designs?

☐ Yes ☐ No

* If answer was no, there is no need to use this form

Does your project have any of the following alternative intersection or interchange designs? If so, go to their respective list of inhibitors. Otherwise proceed to the following section.

- ☐ Continuous Flow Intersection
- ☐ Diverging Diamon Interchange
- ☐ Reduced Conflict Intersection
- ☐ Quadrant Roadway
- ☐ Turbine Interchange

Checklist – Any Design

Identify if any of the following inhibitors are present:

- ☐ Utilities
- ☐ Contract changes
- ☐ Signal and signage
- ☐ Traffic control
- ☐ Material estimate change
- ☐ Right of way
- ☐ Construction sequencing
- ☐ Safety for workers
- ☐ Space constraints
- ☐ Safety for drivers
- ☐ Geotechnical issues
- ☐ Environmental concerns
- ☐ Design changes
- ☐ Multimodal transit accommodation
- ☐ Site access
- ☐ Water drainage during construction
- ☐ Bridge construction
- ☐ Public acceptance
- ☐ Wall construction
- ☐ Design errors
- ☐ Business impact
- ☐ Schedule change
- ☐ Weather impact
- ☐ Standards and specifications
- ☐ High bids
- ☐ Design specifications
- ☐ Permit acquisition
- ☐ Pavement markings
- ☐ Contract errors
- ☐ Inspection approval
- ☐ Equipment and labor estimate change
- ☐ Safety for public
- ☐ Work zone traffic control
- ☐ Delays on material delivery
- ☐ Material safety
- ☐ Water drainage
- ☐ Driver's expectation
- ☐ Railroads
- ☐ Schedule requirements

Continuous Flow Intersection

Identify if any of the following inhibitors are present:

- ☐ Signals and signage
- ☐ Material estimate change
- ☐ Utilities
- ☐ Weather impact
- ☐ Contract changes
- ☐ Inspection approval

Diverging Diamon Interchange

Identify if any of the following inhibitors are present:

- ☐ Environmental concerns
- ☐ Site access
- ☐ Safety for public
- ☐ Pavement markings
- ☐ Equipment and labor estimate change
- ☐ Utilities
- ☐ Right of way
- ☐ Design errors
- ☐ Contract errors
- ☐ Geotechnical issues
- ☐ Wall construction
- ☐ Permit acquisition
- ☐ Space constraint
- ☐ Safety for drivers
- ☐ Water drainage
- ☐ Contract changes
- ☐ Inspection approval
- ☐ Weather impact
- ☐ Material delivery
- ☐ Material safety
- ☐ Design changes
- ☐ Schedule changes
- ☐ Construction sequencing
- ☐ Business Impact
- ☐ Multimodal transit accommodation
- ☐ Water drainage during construction
- ☐ Design specifications
- ☐ Material estimate change
- ☐ Traffic control
- ☐ Standards and specifications
- ☐ Signals and signage
- ☐ Safety of workers
- ☐ Bridge construction

Reduced Conflict Intersection

Identify if any of the following inhibitors are present:

- ☐ Utilities
- ☐ Safety for public
- ☐ Signals and signage
- ☐ Bridge construction
- ☐ Environmental concerns
- ☐ Design errors
- ☐ Site access
- ☐ Weather impact
- ☐ Right of way
- ☐ Geotechnical issues
- ☐ Multimodal transit accommodations
- ☐ Schedule changes
- ☐ Material estimate change
- ☐ Traffic control
- ☐ Design changes
- ☐ Pavement markings
- ☐ Contract changes
- ☐ Design specifications

Turbine Interchange

Identify if any of the following inhibitors are present:

- ☐ Environmental concerns
- ☐ Permit acquisition
- ☐ Utilities
- ☐ Traffic control
- ☐ Signals and signage
- ☐ Material estimate change
- ☐ Geotechnical issues
- ☐ Site access
- ☐ Space constraint

Quadrant Roadway

Identify if any of the following inhibitors are present:

- ☐ Contract changes
- ☐ Bridge construction
- ☐ Multimodal transit accommodations
- ☐ Contract errors
- ☐ Safety for public
- ☐ Wall construction
- ☐ Utilities
- ☐ Safety for drivers
- ☐ Signals and signage
- ☐ Design changes
- ☐ Schedule changes
- ☐ Traffic control
- ☐ Environmental concerns
- ☐ Design errors
- ☐ Right of way
- ☐ Site access
- ☐ Safety of workers
- ☐ Geotechnical issues
- ☐ Work Zone Traffic Control
- ☐ Design specifications
- ☐ Standards and specifications
- ☐ Material estimate change

Appendix D

AADT and Road User Cost for DDI Project

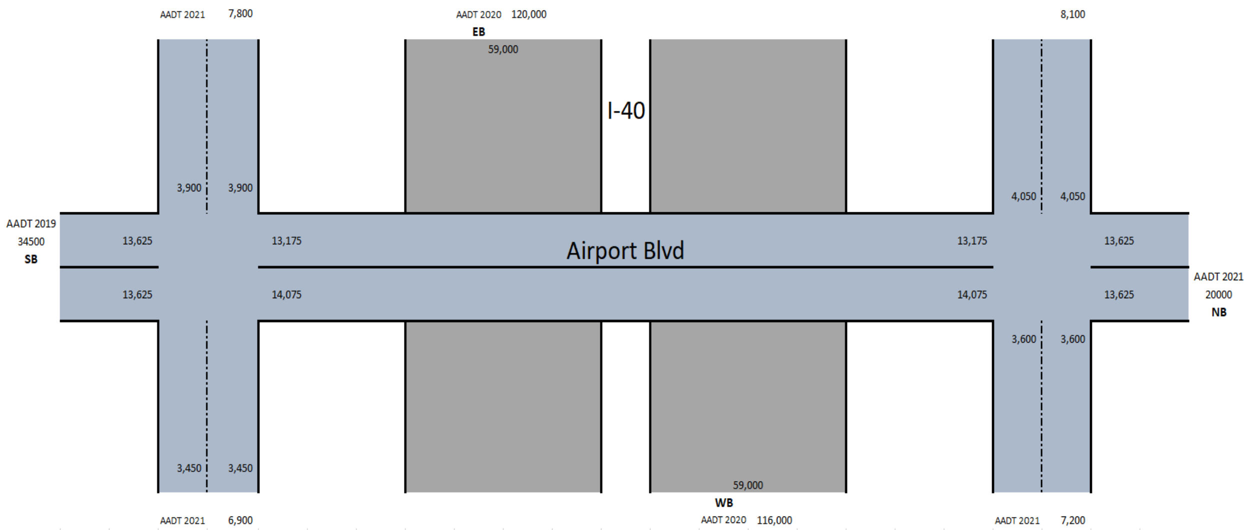

Figure D.1 AADT in I-5700 Project at Airport Boulevard (No Closure)

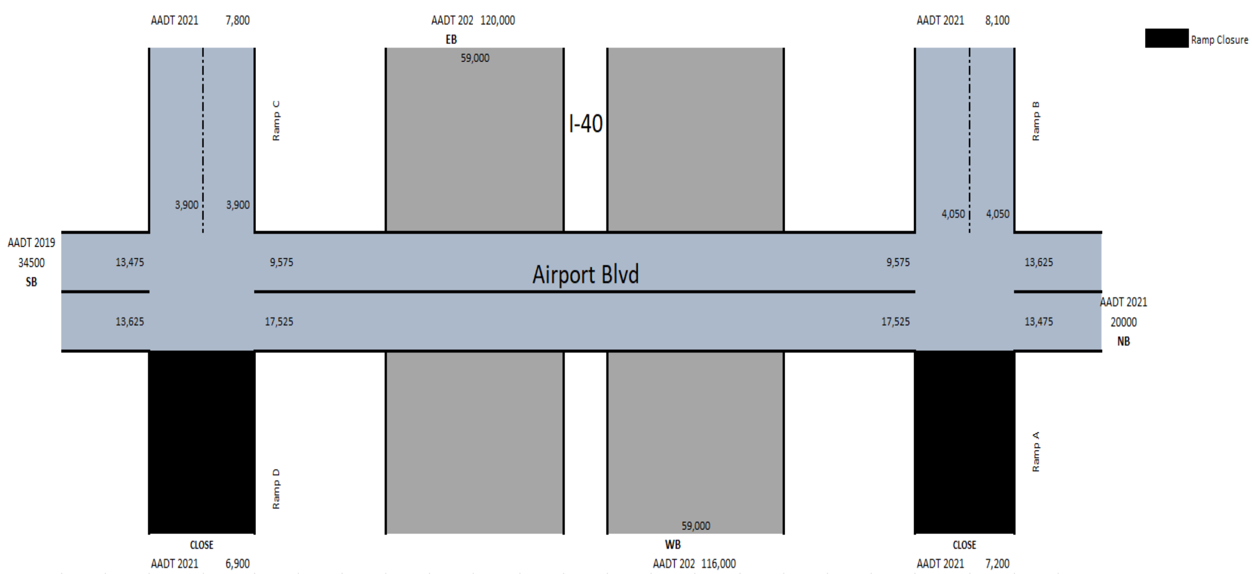

Figure D.2 AADT in I-5700 Project at Airport Boulevard (Closure Ramp A&D)

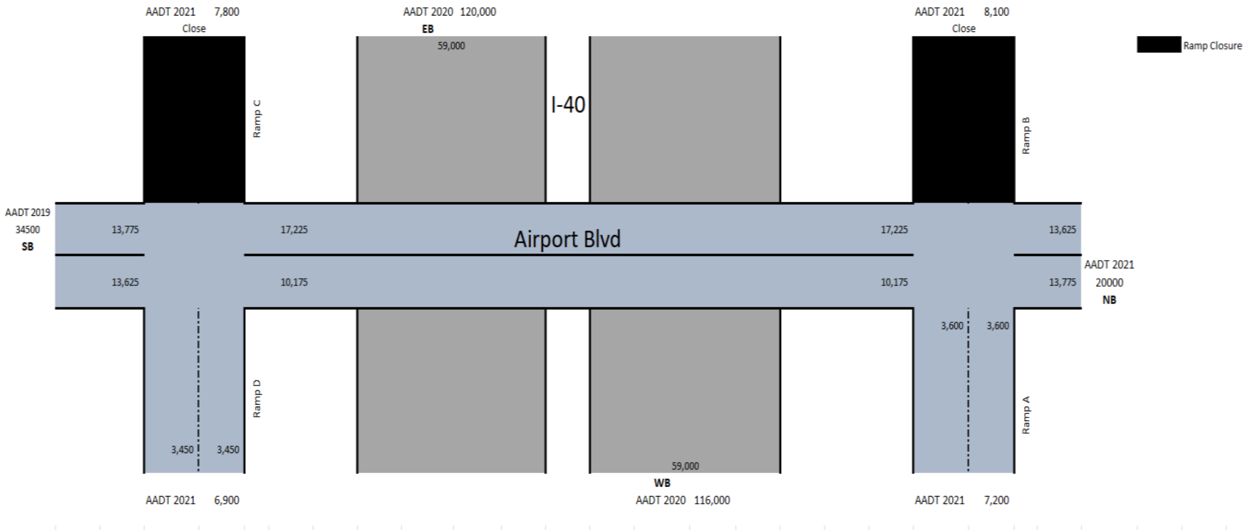

Figure D.3 AADT in I-5700 Project at Airport Boulevard (Closure Ramp B&C)

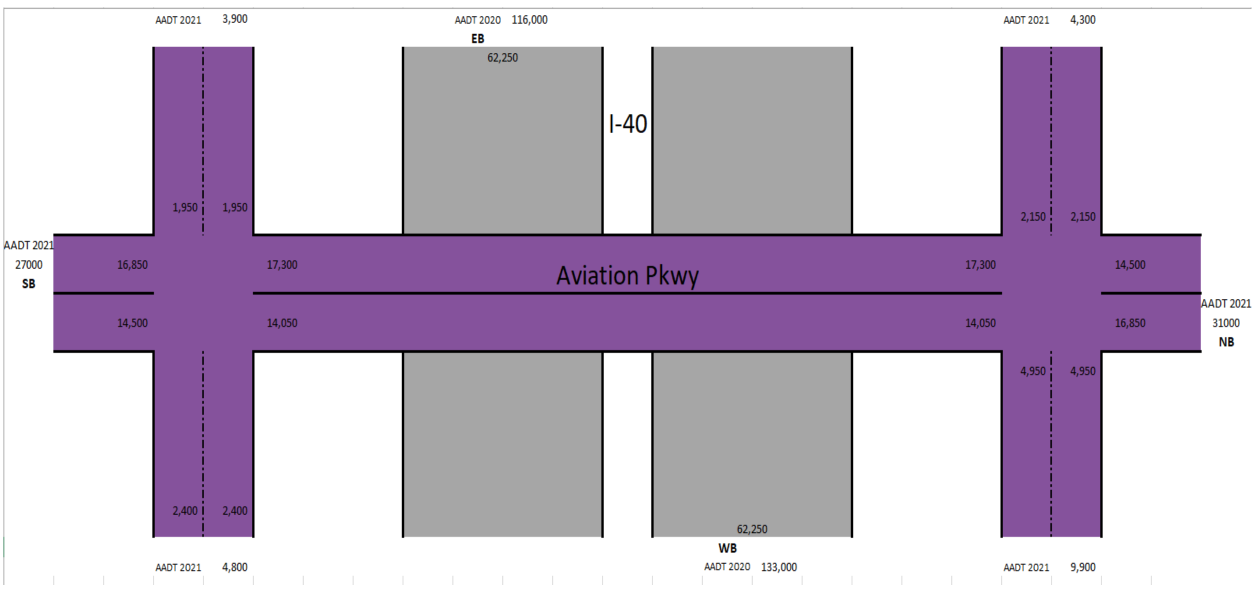

Figure D.4 AADT of Detour in I-5700 Project (No Closure)

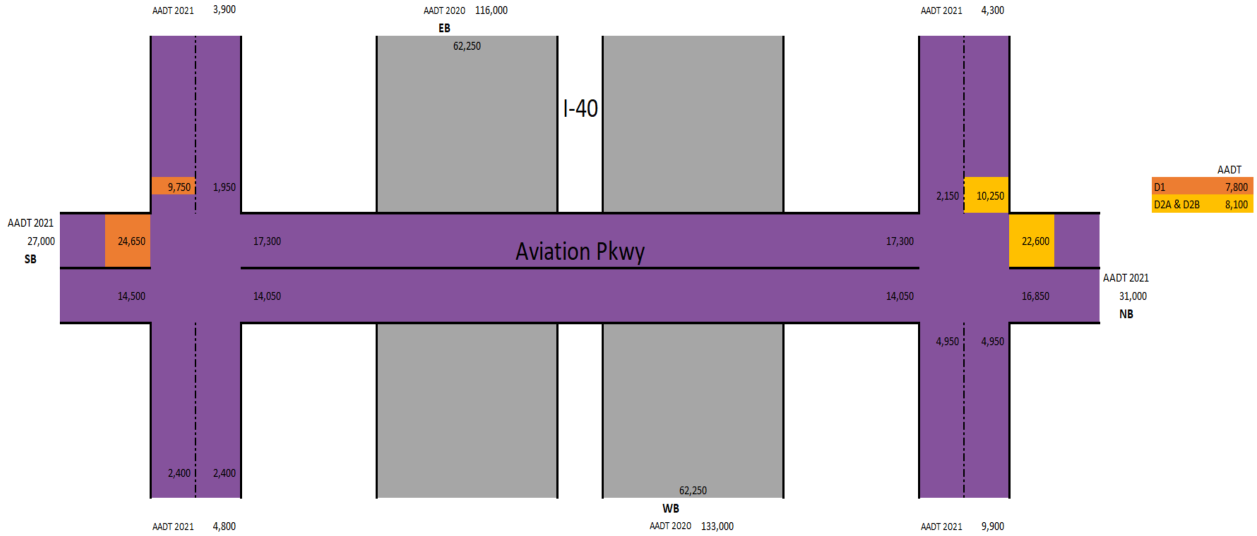

Figure D.5 AADT of Detour in I-5700 Project (Detour D, D2A, and D2B traffic)

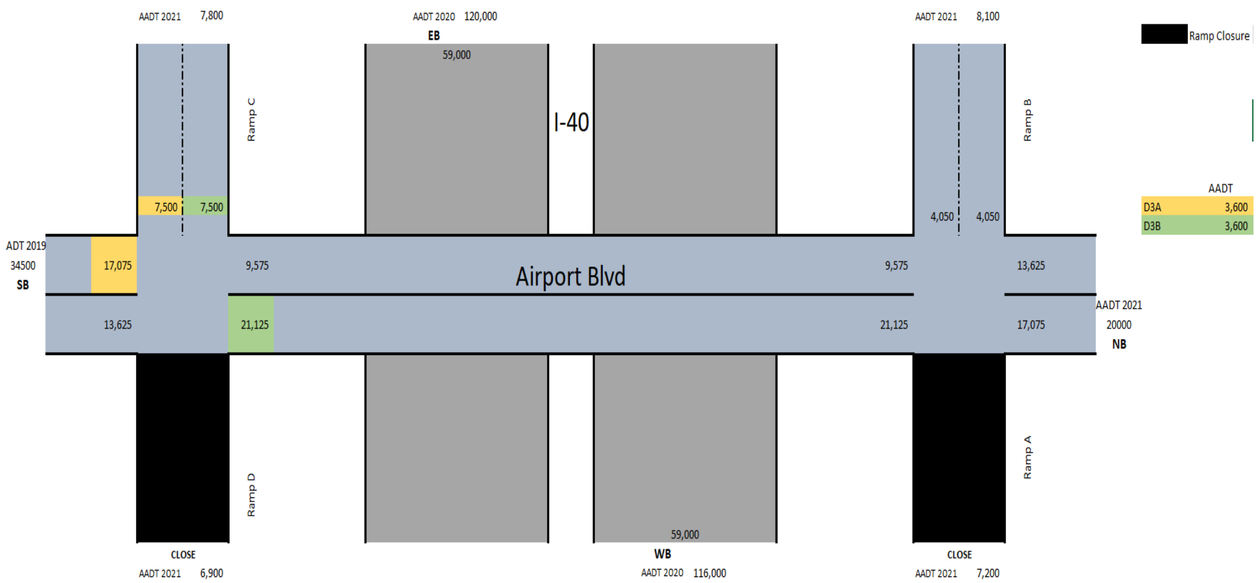

Figure D.6 AADT of Detour in I-5700 Project (Detour D3A and D3B traffic)

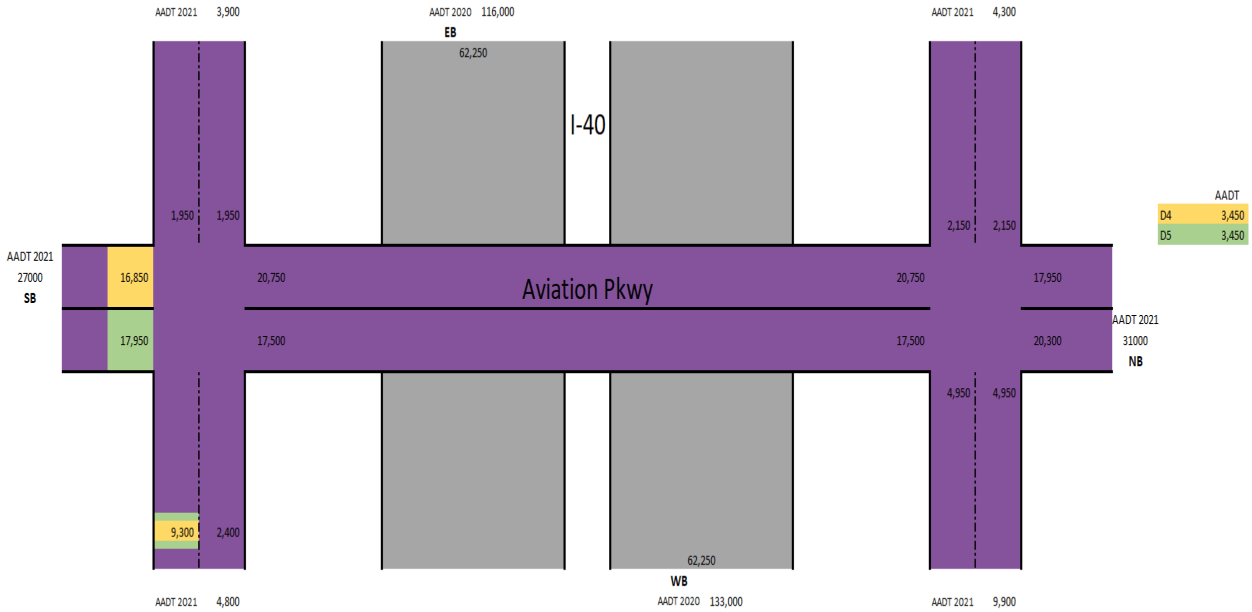

Figure D.7 AADT of Detour in I-5700 Project (Detour D4 and D5 traffic)

Table D.1 Road User Cost Data Input in I-5700 Project

Route	AADT	AADT Cars	AADT Trucks	Length (mile)			Additional Distance Travel due to Detour (mile)	Speed Limit (mile/hr.)			% Vehicles Using Detour
				Route	Work Zone	Detour		Route	Work Zone	Detour	
1	4,050	3,858	181	1.03	0.2	3.67	2.64	45	45	55	100%
2	13,625	12,979	610	0.38	0.2	0	0	45	45	55	0
3	3,600	3,429	161	0.54	0.2	4.6	4.06	45	45	55	100%
5	3,450	3,287	154	1.92	0.2	4.65	2.73	45	45	55	100%
6	13,625	12,979	610	0.36	0.2	0	0	45	45	55	0
7	3,900	3,715	174	0.87	0.2	6.08	5.21	45	45	55	100%
9	3,600	3,429	161	0.4	0.3	5.24	4.84	45	45	55	100%
10	3,900	3,715	174	0.59	0.3	5.75	5.16	45	45	55	100%
11	4,050	3,858	181	1.54	0.1	3.4	1.86	45	45	55	100%
12	3,450	3,287	154	1.68	0.1	4.71	3.03	45	45	55	100%

Table D.2 Detour Delay Cost in I-5700 Project

Route	Value of Time ($/hr.)		Travel Time along Route (min)	Travel Time along Detour Route (min)	Detour Delay Time (min)	Detour Delay Cost per Vehicle		Total Detour Delay Cost	
	Car	Truck				Cars	Trucks	Cars	Trucks
1	$12.50	$50.00	1.37	4.00	2.63	$0.55	$2.19	$2,114.16	$397.15
2	$12.50	$50.00	0.51	0.00	0.00	$0.00	$0.00	$0.00	$0.00
3	$12.50	$50.00	0.72	5.02	4.30	$0.90	$3.58	$3,070.89	$576.88
5	$12.50	$50.00	2.56	5.07	2.51	$0.52	$2.09	$1,720.45	$323.19
6	$12.50	$50.00	0.48	0.00	0.00	$0.00	$0.00	$0.00	$0.00
7	$12.50	$50.00	1.16	6.63	5.47	$1.14	$4.56	$4,235.89	$795.73
9	$12.50	$50.00	0.53	5.72	5.18	$1.08	$4.32	$3,703.08	$695.64
10	$12.50	$50.00	0.79	6.27	5.49	$1.14	$4.57	$4,246.21	$797.67
11	$12.50	$50.00	2.05	3.71	1.66	$0.34	$1.38	$1,330.85	$250.01
12	$12.50	$50.00	2.24	5.14	2.90	$0.60	$2.42	$1,984.36	$372.77

Table D.3 Vehicle Operating Cost in I-5700 Project

Route	Vehicle Operating Costs ($/mile)		Additional Miles due to detour (veh-miles)		Total Additional Vehicle Operating Costs	
	Car	Truck	Car	Truck	Car	Truck
1	$0.20	$0.50	10185	478	$2,037.07	$239.17
2	$0.20	$0.50	0	0	$0.00	$0.00
3	$0.20	$0.50	13923	654	$2,784.69	$326.95
5	$0.20	$0.50	8972	421	$1,794.44	$210.68
6	$0.20	$0.50	0	0	$0.00	$0.00
7	$0.20	$0.50	19356	909	$3,871.24	$454.52
9	$0.20	$0.50	16598	780	$3,319.68	$389.76
10	$0.20	$0.50	19170	900	$3,834.09	$450.16
11	$0.20	$0.50	7176	337	$1,435.21	$168.51
12	$0.20	$0.50	9958	468	$1,991.63	$233.84

Table D.4 Road User Cost Total in I-5700 Project

Route	Detour Delay Cost	Vehicle Operating Costs	Road User Cost per Day
1	$2,511.31	$2,276.25	$4,787.56
2	$0.00	$0.00	$0.00
3	$3,647.77	$3,111.64	$6,759.40
5	$2,043.64	$2,005.13	$4,048.77
6	$0.00	$0.00	$0.00
7	$5,031.63	$4,325.76	$9,357.39
9	$4,398.72	$3,709.44	$8,108.16
10	$5,043.89	$4,284.25	$9,328.13
11	$1,580.85	$1,603.72	$3,184.57
12	$2,357.14	$2,225.47	$4,582.61
Total (Daily Cost)	**$26,614.95**	**$23,541.64**	**$50,156.59**

Table D.5 Passenger Vehicle Operating Cost in I-5700 Project

Average Passenger Vehicle Operating Cost	Cost/mile	Source
Fuel	$0.110	AAA 2020 Your Driving Costs
Maintenance, repairs, tires	$0.090	
Total	**$0.200**	

Table D.6 Truck Operating Cost in I-5700 Project

Average Truck Operating Cost	Cost/mile	Source
Fuel	$0.308	ATRI Operational Cost of Trucking 2020
Repair and maintenance	$0.148	
Tires	$0.043	
Total	**$0.499**	

Appendix E

AADT and Road User Cost for Conventional Project

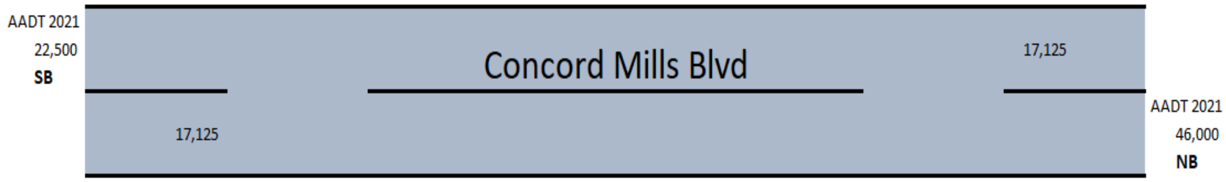

Figure E.1 AADT in U-5806 Project (Concord Mills Boulevard)

Table E.1 Road User Cost Data Input in U-5806 Project

Route	AADT	Adjusted AADT (Table D.2)	AADT Cars	AADT Trucks	Length (mile)			Additional Distance Travel due to Detour (mile)	Speed Limit (mile/hr.)		Vehicles Using Detour
					Route	Work Zone	Detour		Route	Work Zone	
2	17,125	3,117	2,969	139	0.55	0.55	0	0	45	35	0%
6	17,125	3,117	2,969	139	0.55	0.55	0	0	45	35	0%

Table E.2 Hourly AADT Calculations in U-5806 Project

Hour	Hourly-AADT	HDF
12:00 - 1:00 AM	127	0.74%
1:00 - 2:00 AM	80	0.47%
2:00 - 3:00 AM	70	0.41%
3:00 - 4:00 AM	86	0.50%
4:00 - 5:00 AM	144	0.84%
5:00 - 6:00 AM	377	2.20%
6:00 - 7:00 AM	1,029	6.01%
7:00 - 8:00 AM	1,572	9.18%
8:00 - 9:00 AM	1,413	8.25%
9:00 - 10:00 AM	1,041	6.08%
10:00 - 11:00 AM	885	5.17%
11:00 - 12:00 AM	891	5.20%
12:00 - 1:00 PM	921	5.38%
1:00 - 2:00 PM	944	5.51%
2:00 - 3:00 PM	971	5.67%
3:00 - 4:00 PM	1,041	6.08%
4:00 - 5:00 PM	1,132	6.61%
5:00 - 6:00 PM	1,211	7.07%
6:00 - 7:00 PM	957	5.59%
7:00 - 8:00 PM	676	3.95%
8:00 - 9:00 PM	531	3.10%
9:00 - 10:00 PM	450	2.63%
10:00 - 11:00 PM	341	1.99%
11:00 - 12:00 PM	235	1.37%
Total	**17125**	**100%**
Adjusted AADT (7:00 pm to 6:00 am)		**3,116.75**

*Values to calculate adjusted AADT are highlighted in grey

Table E.3 Work Zone Delay Cost in U-5806 Project

Route	Value of Time ($/hr.)		Travel Time along Route (min)	Travel Time at Work Zone Speed (min)	Work Zone Delay Time (min/veh.)	Work Zone Delay Cost per Vehicle		Total Work Zone Delay Cost	
	Car	Truck				Car	Truck	Car	Truck
2	$12.75	$50.00	0.73	0.94	0.21	$0.04	$0.17	$132.19	$24.35
6	$12.75	$50.00	0.73	0.94	0.21	$0.04	$0.17	$132.19	$24.35

Table E.4 Road User Cost Vehicle Operating Cost in U-5806 Project

Route	Vehicle Operating Costs ($/mile)		Additional Miles from Work Zone (veh-miles)		Total Additional Vehicle Operating Costs ($)	
	Car	Truck	Car	Truck	Car	Truck
2	$0.20	$0.50	0	0	$0.00	$0.00
6	$0.20	$0.50	0	0	$0.00	$0.00

Table E.5 Road User Cost Total in U-5806 Project

Route	Detour Delay Cost	Vehicle Operating Costs	Road User Cost per Day
2	$342.11	$0	$342.11
6	$342.11	$0	$342.11
Total (Daily Cost)	**$684.22**	$0	**$684.22**

Table E.6 Passenger Vehicle Operating Cost in U-5806 Project

Average Passenger Vehicle Operating Cost	Cost/Mile	Source
Fuel	$0.111	AAA 2018 Your Driving Costs
Maintenance, repairs, and tires	$0.082	
Total	**$0.193**	

Table E.7 Truck Operating Cost in U-5806 Project

Average Truck Operating Cost	Cost/Mile	Source
Fuel	$0.433	ATRI Operational Cost of Trucking 2019
Repair and maintenance	$0.171	
Tires	$0.038	
Total	**$0.642**	