Managed Freeway Before Study

NCDOT Project 2024-01
FHWA/NC/2024-01
March 2026

Shoaib Samandar
Guangchuan Yang
Abdullah Al Farabi
Nagui Rouphail
Christopher M. Cunningham
Thomas Chase
Institute for Transportation Research and Education (ITRE)
North Carolina State University

ITRE
Institute for Transportation Research and Education

STATE OF NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
RESEARCH & DEVELOPMENT

Managed Freeway Before Study

FINAL REPORT

Submitted to:
North Carolina Department of Transportation
Research and Development Unit
(Research Project No. RP2024-01)

Submitted by

Shoaib Samandar
Institute for Transportation Research and Education (ITRE)
North Carolina State University
909 Capability Drive
Research Building IV, Room 3402
Raleigh, NC 27606
N.C. State University's Centennial Campus
919.515.2011
smsamand@ncsu.edu

ITRE

March 2026

1. Report No. **FHWA/NC/2024-01**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Managed Freeway Before Study**		5. Report Date **March 01, 2026**
		6. Performing Organization Code
7. Author(s) **Shoaib Samandar** **Guangchuan Yang** **Abdullah Al Farabi** **Nagui Rouphail** **Christopher M. Cunningham** **Thomas Chase**		8. Performing Organization Report No.
9. Performing Organization Name and Address **Institute for Transportation Research and Education** **North Carolina State University** **Centennial Campus Box 8601** **Raleigh, NC**		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address **North Carolina Department of Transportation** **Research and Analysis Group** **104 Fayetteville Street** **Raleigh, North Carolina 27601**		13. Type of Report and Period Covered **Final Report** **August 2023 – March 2026**
		14. Sponsoring Agency Code **RP2024-01**
Supplementary Notes:		

16. **Abstract**

The North Carolina Department of Transportation (NCDOT) is pursuing managed freeway strategies to address growing congestion on the I-40 corridor in the Raleigh-Durham metropolitan area. This study developed a comprehensive before–after analysis framework integrating a state-of-the-practice review, microsimulation modeling, and benefit–cost analysis (BCA) to evaluate the operational, safety, and economic performance of four managed freeway technologies: Coordinated Adaptive Ramp Metering (CARM), Variable Speed Limits (VSL), Queue Warning Systems (QWS), and Lane Use Control Signals (LUCS). A calibrated VISSIM microsimulation model of a 20+ mile segment on Eastbound I-40 was used to evaluate technology scenarios under projected 2035 demand conditions. CARM delivered the greatest operational improvements, reducing total system delay by approximately 38% and increasing throughput by 6.6% relative to the 2035 baseline. The VSL-only scenario provided limited mobility benefits, while the combined VSL + CARM strategy reduced delay by 29% and increased throughput by 5.3%. QWS and LUCS were evaluated through literature synthesis, as their primary safety benefits cannot be adequately captured by simulation alone. The BCA results demonstrate strong economic justification, with a 10-year benefit–cost ratio of 14.4 under conservative assumptions and 30.0 under favorable assumptions when all strategies are deployed together. The study also produced a transferable spreadsheet-based BCA tool for NCDOT practitioners and a phased implementation plan for statewide scaling. Findings support the deployment of managed freeway technologies on the I-40 corridor and provide a replicable methodology for future NCDOT managed freeway investments.

17. Key Words **Managed Freeway, Benefit-Cost Analysis, Coordinated Adaptive Ramp Metering, Variable Speed Limit, Microsimulation**	18. Distribution Statement		
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 71	22. Price $238,456

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

Disclaimer

Acknowledgments

The research team thanks the North Carolina Department of Transportation (NCDOT) for supporting and funding this project. We are particularly grateful to the Steering and Implementation Committee (StIC) members and key stakeholders for the exceptional guidance and support they provided throughout this project:

Jennifer Portanova (Chair)
Braden Walker
Thomas Chase
David Keilson
Andrew Skuce
Brian Mayhew
Courtney Weeter
Nathan Webster
Jennifer Hernandez
Natasha Henderson
Jaehoon Kim (RDO Project Manager)

Executive Summary

This report presents the findings of NCDOT Research Project #2024-001, which developed and applied a comprehensive before–after analysis framework for evaluating managed freeway strategies on the I-40 corridor in the Raleigh-Durham metropolitan area. As NCDOT advances two pilot managed freeway projects—I-6001 (I-40 from I-440 to US 64/264) and I-6006 (I-40 from SR 54 to I-440)—there is a critical need for an evidence-based methodology to quantify the operational, safety, and economic benefits of these investments prior to deployment. In this report, economic benefits refer to the monetized mobility benefits (travel-time and delay savings, valued using Value of Time) and safety benefits (crash reductions, valued using NCDOT unit crash costs) that form the basis of the Benefit–Cost Analysis. This study addresses that need by integrating a state-of-the-practice literature review, microsimulation modeling, and benefit–cost analysis (BCA) to evaluate four managed freeway technologies: Coordinated Adaptive Ramp Metering (CARM), Variable Speed Limits (VSL), Queue Warning Systems (QWS), and Lane Use Control Signals (LUCS).

The state-of-the-practice review confirmed that managed freeway implementation remains limited in the United States, with only one pilot deployment of a fully integrated system to date. Nonetheless, individual Active Traffic Management (ATM) strategies have been deployed in various states that include, Virginia, Minnesota, Washington, and Colorado with documented operational and safety benefits. International experience from agencies such as VicRoads in Australia and the UK Highways Agency provided valuable design and operational benchmarks that directly informed the analytical framework developed in this study.

A calibrated PTV VISSIM microsimulation model was developed for a 20-mile segment on Eastbound I-40 and was used to evaluate four scenarios under projected 2035 demand conditions derived from the North Carolina Statewide Travel Model (NCSTM). The analysis focused on the PM peak period (3:00–7:00 PM) under recurring congestion conditions. Among the strategies modeled, CARM delivered the largest operational improvements, reducing total system delay by approximately 38% and increasing corridor throughput by about 6.6% relative to the 2035 no-build baseline. The VSL-only scenario provided limited operational benefits and slightly worsened congestion, consistent with its primary role in safety-oriented speed harmonization rather than demand management. The combined VSL + CARM strategy offered a balanced improvement, reducing total delay by approximately 29% while increasing throughput by roughly 5.3%. Benefits were then extrapolated to all daytime hours and both directions of the I-40 segment. Queue Warning and LUCS were evaluated through a comprehensive literature synthesis rather than simulation, as the research team determined that their primary safety benefits cannot be adequately captured by microsimulation models alone.

The BCA framework integrated mobility benefits (travel time savings from simulation), safety benefits (crash reductions estimated using North Carolina–specific Safety Performance Functions and literature-derived Crash Modification Factors), and project costs (capital, operations, and maintenance) to produce scenario-based benefit–cost ratios. When all four strategies are implemented, the 10-year benefit, cost ratio is estimated at around 14:1 under conservative assumptions, demonstrating strong economic justification for the managed freeway investment. Among individual strategies, CARM emerges as the most cost-effective under conservative estimates with a 10-year B/C ratio of 18.8, followed by LUCS at 16.4 and

Queue Warning at 8.7. VSL does not appear to be an investment priority under conservative assumptions due to its potential to increase travel time, though it remains viable under favorable conditions.

In addition to the analytical findings, the research team developed a spreadsheet-based BCA calculator tool that allows NCDOT practitioners to estimate benefit–cost ratios for the I-40 managed freeway project under various strategy combinations and parameter assumptions. The tool is designed to be transferable to other managed freeway corridors across North Carolina by updating corridor-specific inputs such as traffic volumes, crash data, segment lengths, and cost estimates.

Based on the benefit–cost performance, the study recommends a phased deployment strategy beginning with CARM as the highest-priority technology, followed by Queue Warning, Lane Use Control Signals, and Variable Speed Limits. In the near term (Years 3–5), NCDOT should apply the BCA framework and tool to the I-6001 and I-6006 projects currently advancing through the project development process, finalize system architecture requirements, and align construction documents with the operational concepts evaluated in this research. Over the longer term (Years 5–10), NCDOT should pursue statewide scaling by identifying additional candidate corridors—such as I-77 in Charlotte or I-85 between Greensboro and Durham—through a screening process that considers recurring congestion severity, crash frequency, and existing ITS infrastructure. The study also recommends integrating managed freeway considerations into NCDOT's long-range transportation planning and Strategic Transportation Investments (STI) prioritization framework.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1 Background and Motivation

Freeway congestion poses a persistent and growing challenge for transportation agencies across the United States. As metropolitan areas continue to expand, the demand placed on aging highway infrastructure increasingly outpaces the physical capacity available during peak travel periods. Traditional approaches to congestion mitigation—primarily widening roadways and adding new lanes—are constrained by right-of-way limitations, environmental regulations, and escalating construction costs. In this context, managed freeway strategies emerges as a practical and cost-effective alternative for improving the operational efficiency and safety of existing freeway facilities without the need for major physical expansion.

Managed freeways employ an integrated suite of Active Traffic Management (ATM) technologies to dynamically monitor and regulate traffic flow in real time. These technologies include Coordinated Adaptive Ramp Metering (CARM), which controls the rate at which vehicles enter the freeway from on-ramps to prevent mainline flow breakdown; Variable Speed Limits (VSL), which dynamically adjust posted speed limits to harmonize speeds and reduce rear-end collision risk; Queue Warning Systems (QWS), which alert drivers to the presence of slow or stopped traffic downstream; and Lane Use Control Signals (LUCS), which manage lane assignments to optimize utilization and guide drivers around incidents or lane closures. When deployed in combination, these strategies can substantially reduce delay, improve safety, and enhance the reliability of freeway travel.

The North Carolina Department of Transportation (NCDOT) is advancing the implementation of managed freeways in the state, beginning with two pilot projects on the Interstate 40 (I-40) corridor in the Raleigh-Durham metropolitan area. Those projects are I-6006, covering I-40 from SR 54 to I-440, and project I-6001, covering I-40 from I-440 to US 64/264. The phased deployment of CARM, VSL, QWS, and LUCS on these corridors is expected to substantially improve travel times, reduce congestion-related crashes, and increase overall roadway efficiency. As one of the first fully integrated managed freeway programs in the southeastern United States, the I-40 initiative represents a transformative step in NCDOT's approach to traffic management, leveraging technology-driven solutions to address congestion on facilities where capacity expansion is either infeasible or insufficient on its own.

Internationally, managed freeway concepts have been implemented with demonstrated success in Australia (VicRoads), the United Kingdom (M42 Managed Motorways), and several U.S. states, including Colorado (CARM), Virginia (VSL, QWS, and LUCS), and Washington (VSL and LUCS). However, no U.S. corridor has yet deployed a full suite of integrated managed freeway strategies – combining CARM, VSL, QWS, and LUCS, as envisioned for the I-40 corridor in this project. This gap underscores the need for state-specific analytical tools that can assess the expected benefits and costs of managed freeway technologies prior to construction, enabling informed investment decisions and supporting the project development process.

1.2 Problem Statement

The I-40 corridor in the Raleigh-Durham metropolitan area is one of the most heavily traveled freeway facilities in North Carolina. The corridor serves as a critical east-west connector linking the Research Triangle region and carrying substantial commuter, commercial, and through traffic on a daily basis. Based on projected demand growth from the North Carolina Statewide Travel Model (NCSTM), the facility is expected to experience severe recurring congestion by the year 2035, if no appropriate mitigation measures are implemented. The approximately 20-mile eastbound segment of I-40 between NC 54 and the I-440 beltline, which includes 19 on-ramps and 16 off-ramps, is already subject to significant peak-period congestion, and forecasted volumes indicate that traffic conditions are likely to deteriorate substantially over the next decade.

While NCDOT has committed to deploying managed freeway technologies on this corridor, the agency lacked a systematic, transferable framework for evaluating the expected operational, safety, and economic impacts of these deployments prior to construction. Without such a framework, it is difficult to quantify the anticipated return on investment, prioritize the sequencing of technology deployments, or compare managed freeway strategies against traditional capacity improvements. This research was initiated to address that gap by developing a structured before-after analysis methodology and an accompanying benefit-cost analysis tool that NCDOT can apply to the I-40 projects and, ultimately, to future managed freeway corridors statewide.

1.3 Research Objectives

The primary objective of this research (NCDOT Research Project #2024-001) was to develop and apply and apply a comprehensive before-after analysis framework for evaluating managed freeway strategies on the I-40 corridor. The specific objectives of the study are as follows. First, to identify relevant technologies, performance measures, and lessons learned via a comprehensive review of the state of the art and practice in managed freeway implementation, both domestically and internationally, which could inform the North Carolina context. Second, to develop a structured before-after analysis framework integrating three complementary assessment components: microsimulation modeling for mobility evaluation, safety performance estimation using Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs), and a benefit-cost analysis (BCA) for economic evaluation. Third, to quantify the operational and mobility impacts of CARM, VSL, and combined CARM + VSL strategies on the I-40 corridor under projected future-year demand conditions through scenario-based microsimulation analysis. Fourth, to evaluate the economic feasibility of managed freeway investments by estimating benefit-cost ratios under varying strategy combinations and parameter assumptions, supported by a practitioner-oriented spreadsheet-based BCA tool. Fifth, to formulate deployment recommendations, strategy prioritization guidance, and a phased implementation plan for managed freeway technologies in North Carolina.

1.4 Scope and Limitations

The scope of this study encompasses the development and application of the before-after analysis framework to a 20-mile segment of eastbound I-40 in the Raleigh-Durham area. The microsimulation analysis covered the PM peak period (3:00 PM to 7:00 PM) under recurring congestion conditions using projected 2035 demand volumes. Four simulation-based scenarios were evaluated: 2035 Base (no managed freeway technologies), CARM, VSL only, and combined VSL + CARM. Queue Warning and Lane Use Control Signals were assessed through a comprehensive literature synthesis rather than simulation, as the research team determined that microsimulation modeling does not adequately capture the primary safety benefits of these technologies.

Several limitations should be noted. The simulation model represents one direction of travel (eastbound) during the PM peak period and does not explicitly account for non-recurring events such as incidents, adverse weather, or special events. However, the peak-period eastbound simulation results were extrapolated to full-day (24-hour) conditions and both directions of travel for the benefit-cost analysis. The Crash Modification Factors used in the safety analysis were derived from deployments in other jurisdictions and may not fully reflect North Carolina-specific conditions. Additionally, the BCA relies on projected demand volumes from the NCSTM, which introduces uncertainty associated with future growth assumptions. In Chapter 8, these limitations are discussed.

1.5 Organization of the Report

This report is organized into eight chapters. Following this introduction, Chapter 2 presents a literature review and state-of-the-practice summary covering managed freeway concepts, key managed freeway technologies, performance measures, and lessons learned from national and international deployments. Chapter 3 describes the analytical methodology, including the before-after framework structure, data sources, microsimulation modeling approach, and the managed freeway technology scenarios evaluated in this study. Chapter 4 presents the scenario analysis results, including simulation-based operational findings for the CARM, VSL, and combined strategies, as well as literature-based assessments for Queue Warning and Lane Use Control Signals. Chapter 5 documents the benefit-cost analysis framework and results, including estimated project costs, mobility and safety benefits, and scenario-based benefit-cost ratios. Chapter 6 provides recommendations for deployment, including strategy prioritization, corridor selection criteria, and technology integration considerations. Chapter 7 presents a phased implementation plan covering near-term project actions, long-term statewide scaling, data management, and stakeholder outreach. Finally, Chapter 8 summarizes the key findings, discusses study limitations, and offers recommendations for future research. Supporting technical details, including the CARM algorithm formulation, additional simulation results, the BCA methodology document, and related technical memoranda, are provided in the appendices.

Chapter 2. Literature Review and Current State of the Practice

A managed freeway is a relatively new concept encompassing operational strategies aimed at actively managing transportation demand and the efficiency of the transportation network. Technically, a managed freeway is a sub-category of Active Traffic Management (ATM). The Federal Highway Administration (FHWA) defines ATM as the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions (Sheehan et al., 2012). A managed freeway uses a combination of ATM strategies and intelligent transportation system (ITS) interventions to actively manage traffic flows, improve roadway efficiency and safety, control demand, and provide real-time information to road users. Typical interventions include coordinated adaptive ramp metering (CARM), variable speed limits (VSL), queue warning systems (QWS), dynamic lane use control (DLUC), and hard shoulder running (HSR).

Managed freeways were first implemented in the Netherlands and have been in operation in the United Kingdom since 2006 (van Vuren et al., 2012). Since these early deployments, agencies worldwide have realized numerous benefits, including decreases in primary and secondary incidents, increased throughput, improved speed uniformity, increased capacity through dynamic shoulder use, and greater trip reliability (van Vuren et al., 2012; Dutta et al., 2019). Despite these benefits, managed freeway implementation in the United States has been limited. As of December 2023, the National Operations Center of Excellence (NOCoE) documented 28 states that have deployed at least one ATM strategy (*Figure 1*), with notable applications in Centreville, VA; Minneapolis, MN; Seattle, WA; and Denver, CO.

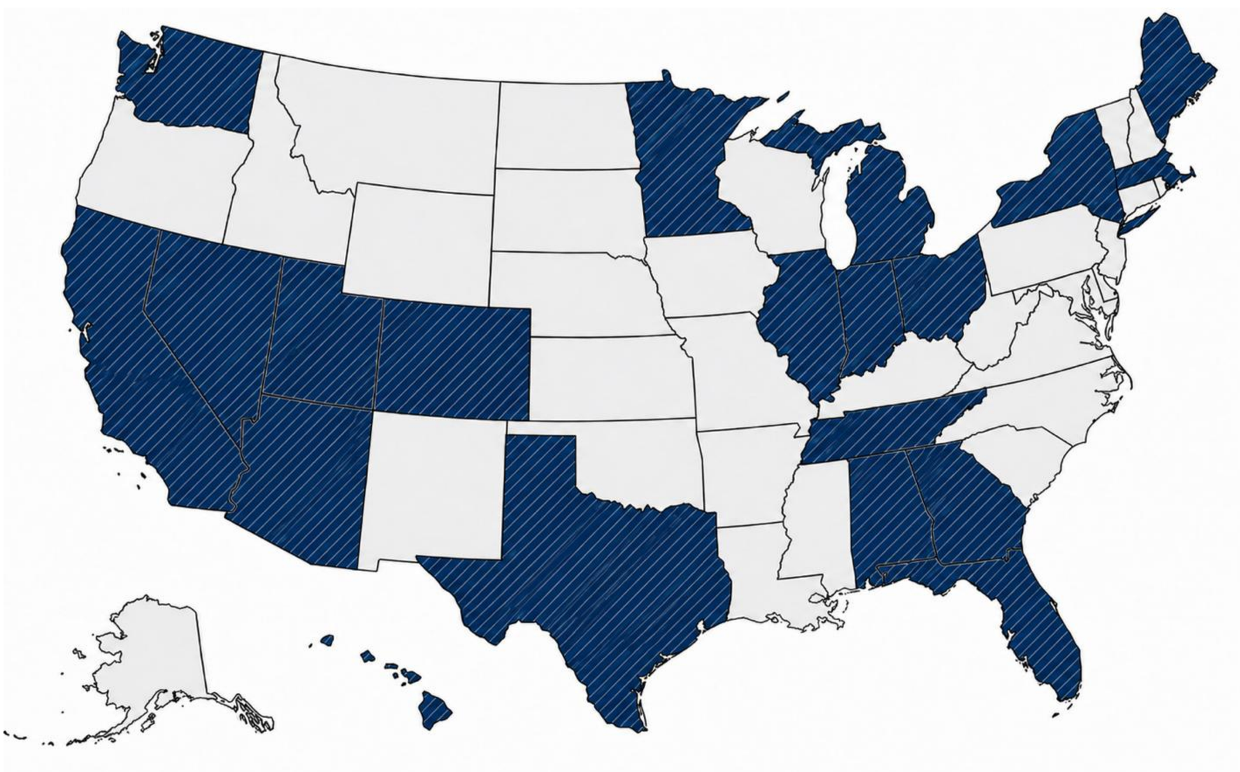


Figure 1: States with Active Traffic Management Deployment in the U.S.

NCDOT is spearheading the implementation of managed freeways in North Carolina, starting with two pilot projects, including the I-40 managed freeway system in the Raleigh-Durham Metropolitan Area. The phased deployment of CARM, QWS, dynamic speed advisories, and DLUC on the I-40 corridor is expected to substantially improve travel times, reduce congestion, and increase roadway safety. The following subsections provide an overview of the four key technologies relevant to this study, lessons learned from early adopters and identified research gaps. A detailed literature review is provided in Appendix A.

2.1 Overview of Key Managed Freeway Technologies

Coordinated Adaptive Ramp Metering (CARM). Ramp meters regulate the rate at which vehicles enter the freeway to address recurring congestion and improve merge-point safety. Under a CARM approach, metering rates are calculated in real time based on conditions across the entire covered network. A study in Minnesota found average benefit-cost ratios of approximately 20:1 for ramp metering (MnDOT, 2001). ALINEA is the most widely deployed local ramp metering strategy due to its simplicity and low implementation costs (Papageorgiou et al., 1991; 1997), while coordinated algorithms such as zone-based metering, fuzzy logic, SWARM, and HERO have been widely used in practice. A before-after safety evaluation on I-80 in California found a CMF of 0.95 for fatal and injury crashes following CARM implementation (Molan et al., 2023).

Variable Speed Limits (VSL). VSL systems alert drivers of potential slowdowns by dynamically adjusting posted speed limits. Strategies range from reactive rule-based approaches that respond to preselected thresholds of traffic flow or speed, to proactive approaches that predict future conditions and issue remedial actions before breakdowns occur (Khondaker and Kattan, 2015; Hadiuzzaman et al., 2013). Research has demonstrated that speed harmonization can efficiently alleviate freeway congestion (Ma and Shladover, 2016). Avelar et al. (2021) reported a CMF of 0.89 for fatal and injury crashes following VSL deployment in Georgia, indicating an 11% reduction. Kwon and Park (2015) found that the I-35W advisory VSL system in Minneapolis reduced average maximum deceleration by 22% and improved travel time reliability by 24–32% during peak hours.

Queue Warning Systems (QWS). QWS provide advance notice to drivers of congested conditions downstream via variable message signs, enabling safer deceleration as drivers approach queued traffic. Hourdos et al. (2017) found that Minnesota's I-94 QWS resulted in a 22% decrease in crashes and a 54% decrease in near-crashes. Ullman et al. (2016) and Hsieh et al. (2017) reported a 44% reduction in crashes from combined back-of-queue warning and portable rumble strips at Texas work zones on I-35. Sakhare et al. (2022) found that hard braking events decreased by 80% when queue warning trucks were deployed in Indiana. In terms of operational effects, the literature indicates a modest delay reduction of 2–5% (Bashir, 2020), with most observed effects primarily related to safety rather than operational improvements.

Dynamic Lane Use Control (DLUC). DLUC systems use overhead dynamic message signs to manage lane usage upstream of closures or blockages, guiding traffic during incidents or construction. Human factors research has established that a downward diagonal yellow arrow is more effective than the yellow X for indicating downstream lane closure (Ullman et al., 1993; Finley et al., 2013; Chrysler et al., 2022). Dutta et al. (2017) reported a CMF of 0.94 for fatal and injury crashes following LUCS implementation on I-66 in Virginia. Currently, limited information exists regarding the operational performance of DLUC systems beyond safety, representing a notable gap in the literature.

2.2 Lessons Learned from Early Adopters

Several international and domestic deployments provide valuable lessons for NCDOT's I-40 implementation. The VicRoads M1 Managed Motorway in Melbourne, Australia, incorporating CARM at 62 ramps, VSL, and lane use control, yielded a 5–8% increase in throughput, 35–59% improvements in traffic speeds, and 150–500% improvements in travel time reliability during peak periods, with a 31% decline in crash rates over five years (Faulkner et al., 2014). VicRoads' iterative, route-based design process (Hall et al., 2019; Gaffney et al., 2019) served as a model for the systematic planning approach adopted in this study. The Birmingham M42 Managed Motorway in the United Kingdom demonstrated that combining VSL with HSR can yield a 7–9% increase in throughput, a 27% reduction in travel time variability, and 97% driver compliance at the 50-mph speed limit (Mott MacDonald, 2008). Microsimulation modeling by Millard and Unwin (2009) reported up to an 11% decrease in travel time and 13% increase in network throughput. Van Vuren et al. (2012) noted an additional 15% in wider economic benefits beyond traditional travel time savings. The VISSIM-based modeling approach adopted in the M42 evaluation directly informed the microsimulation methodology used in this study.

The Colorado Smart 25 pilot deployed the HERO-based CARM algorithm on 23 ramps of I-25 near Denver, achieving a 19% reduction in PM peak travel time, a 42.2% decrease in total delay, and a 14.3% decrease in congestion duration (WSP, 2023; CDOT, 2023). This HERO-based approach provided a direct reference point for the capacity-constrained CARM algorithm developed in this study. The Virginia I-66 ATM system, incorporating advisory VSL, LUCS, HSR, and QWS on a 12.4-mile corridor, demonstrated off-peak travel time improvements of 2–6% and a total crash rate reduction of 4.4% (Chun and Fontaine, 2017; Dutta et al., 2019). TheI-66 deployment provided critical empirical crash modification factors adopted in this study's benefit-cost analysis.

2.3 Performance Measures

The literature identifies several categories of performance measures for evaluating managed freeway systems: mobility (delay, throughput, travel time, speed), safety (crash frequency and rate, surrogate safety measures), reliability (travel time index, planning time index), and productivity (the product of vehicle throughput and average speed). The Colorado Smart 25 evaluation notably employed productivity alongside more traditional metrics (WSP, 2023). These measures—particularly delay, throughput, travel time, speed, productivity, and travel time index—were adopted in this study to quantify operational conditions under all managed freeway scenarios.

2.4 Identified Research Gaps and Implications for This Study

Despite growing interest in managed freeway systems, the literature review identified several research gaps relevant to North Carolina. First, there is limited research on the combined effects of multiple ATM strategies deployed simultaneously within an integrated managed freeway system in the U.S. context. This study addresses this gap by evaluating both individual strategies and multiple combined, including implementation of all four strategies or any combination, to assess their synergistic effects.

Second, the operational effects of queue warning systems remain poorly understood. A comprehensive review found that most QWS studies focused on work zone applications rather than managed freeways and that assessments have predominantly emphasized algorithm reliability over operational or safety performance (Silverstein et al., 2024). Challenges in calibrating driver behavior in response to warning messages further limit simulation-based QWS assessment. Consequently, the QWS evaluation in this study was grounded in a literature synthesis, presented in Appendix B, rather than simulation. Similarly, limited information on DLUC operational performance led to a literature-based approach for that technology.

Third, most managed freeway deployments in the literature are located in regions with different geometric, traffic, and institutional conditions than those in North Carolina. The I-40 corridor presents unique characteristics as a critical commuter and freight route in the Raleigh-Durham Metropolitan Area. This study develops a microsimulation model calibrated to I-40's specific conditions, ensuring locally relevant evaluation results.

Lastly, the literature lacks a comprehensive framework that integrates microsimulation-based operational analysis with benefit-cost analysis for managed freeway systems. This study addresses this gap by developing an integrated framework linking scenario-based microsimulation with a structured benefit-cost analysis methodology, providing NCDOT with a systematic tool for evaluating managed freeway investments on the I-40 corridor and future deployments statewide.

Chapter 3. Framework Development, Scenarios and Simulation

This chapter describes the analytical methodology developed to evaluate the operational, safety, and economic impacts of managed freeway technologies on congested freeway corridors in North Carolina. The methodology is structured around a before and after analysis framework that integrates three complementary assessment components: microsimulation modeling, safety performance estimation, and benefit–cost analysis (BCA). Together, these components provide a systematic and reproducible approach for quantifying the expected effects of managed freeway deployments prior to implementation.

The chapter is organized as follows. Section 3.1 presents the overall framework development, including the structure of the before–after analysis, the integration of mobility, safety, and economic performance measures, and the data sources that support each analytical component. Section 3.2 describes the microsimulation modeling approach, including the development of the study corridor testbed, the calibration and validation of the base-year model, and the configuration of future-year scenarios incorporating managed freeway technologies. Section 3.3 discusses the managed freeway technology scenarios analyzed in this study, including those evaluated through simulation and those assessed using findings from the published literature.

3.1 Framework Development

A central objective of this research was to develop a structured analytical framework capable of evaluating the anticipated impacts of managed freeway technologies in a before–after context. The term "before" refers to the projected future-year condition without any managed freeway technologies in place (i.e., the 2035 Base scenario), while the "after" condition represents the same future-year facility with one or more managed freeway strategies deployed. By comparing performance across these two conditions, the framework enables a rigorous assessment of the incremental benefits attributable to each technology or combination of technologies.

The framework is designed to be transferable across corridors and scalable to accommodate varying combinations of Active Traffic Management (ATM) strategies, including Coordinated Adaptive Ramp Metering (CARM), Variable Speed Limits (VSL), Queue Warning (QW), and Lane Use Control Signals (LUCS). While the current study applies the framework to a 20-mile segment of Eastbound I-40 in the Raleigh–Durham area, the underlying methodology is intended to serve as a reusable tool for NCDOT's future managed freeway projects, such as projects I-6001 and I-6006.

Framework Structure

Figure 2 presents an infographic illustrating the overall framework workflow, from mobility and safety, to model development through scenario analysis, performance measurement, and benefit–cost evaluation. The integration of these data sources and analytical methods within a unified framework enables a comprehensive, evidence-based evaluation of managed freeway strategies. The framework is designed not only to inform investment decisions for the I-40 corridor, but also to serve as a transferable methodology that NCDOT can apply to future managed freeway projects statewide. Figure 2 is organized into three interconnected assessment pillars: mobility analysis, safety analysis, and economic analysis. Each pillar draws on distinct data inputs and analytical methods, and their outputs converge in the benefit–cost analysis to produce a unified measure of project performance.

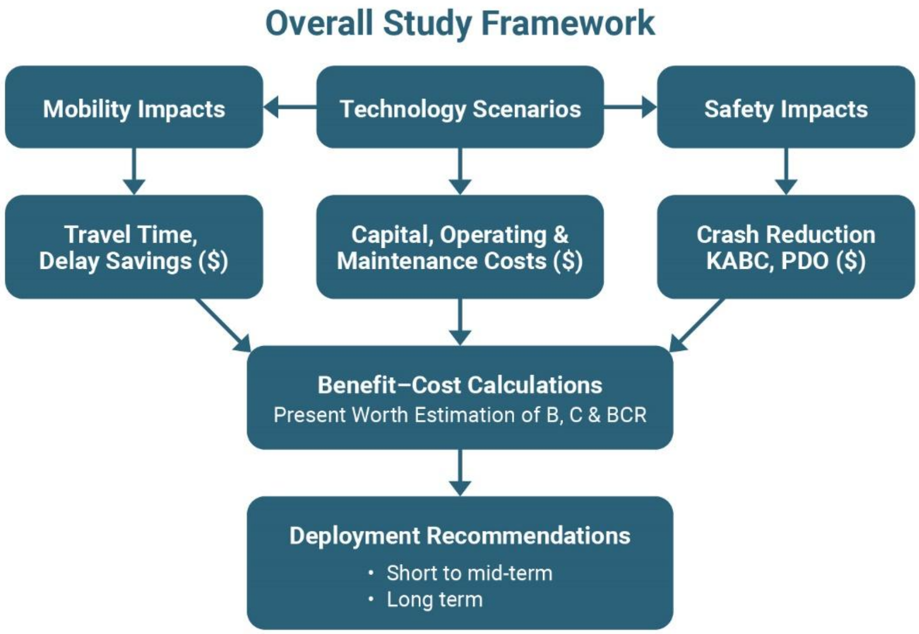


Figure 2: Overall Study Framework for the Managed Freeway Project

The **mobility impact assessment** component employs microsimulation modeling to estimate the operational performance of the I-40 corridor under both baseline and managed freeway conditions. A detailed microsimulation model of the study corridor was developed in PTV VISSIM and calibrated against field data for the 2022 base year. A corresponding 2035 future-year model was then constructed by incorporating NCDOT-projected infrastructure improvements and anticipated demand growth. The managed freeway technology scenarios—including CARM (with queue flushing), VSL, and the combined VSL + CARM strategy—were modeled directly in the simulation environment. Performance measures extracted from the simulation include Vehicle Hours of Delay (VHD), Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), throughput, average speed, latent demand, productivity, and Travel Time Index (TTI). These measures collectively characterize the operational state of the facility and enable direct comparison between scenarios. The mobility component of the framework is illustrated in Figure 3.

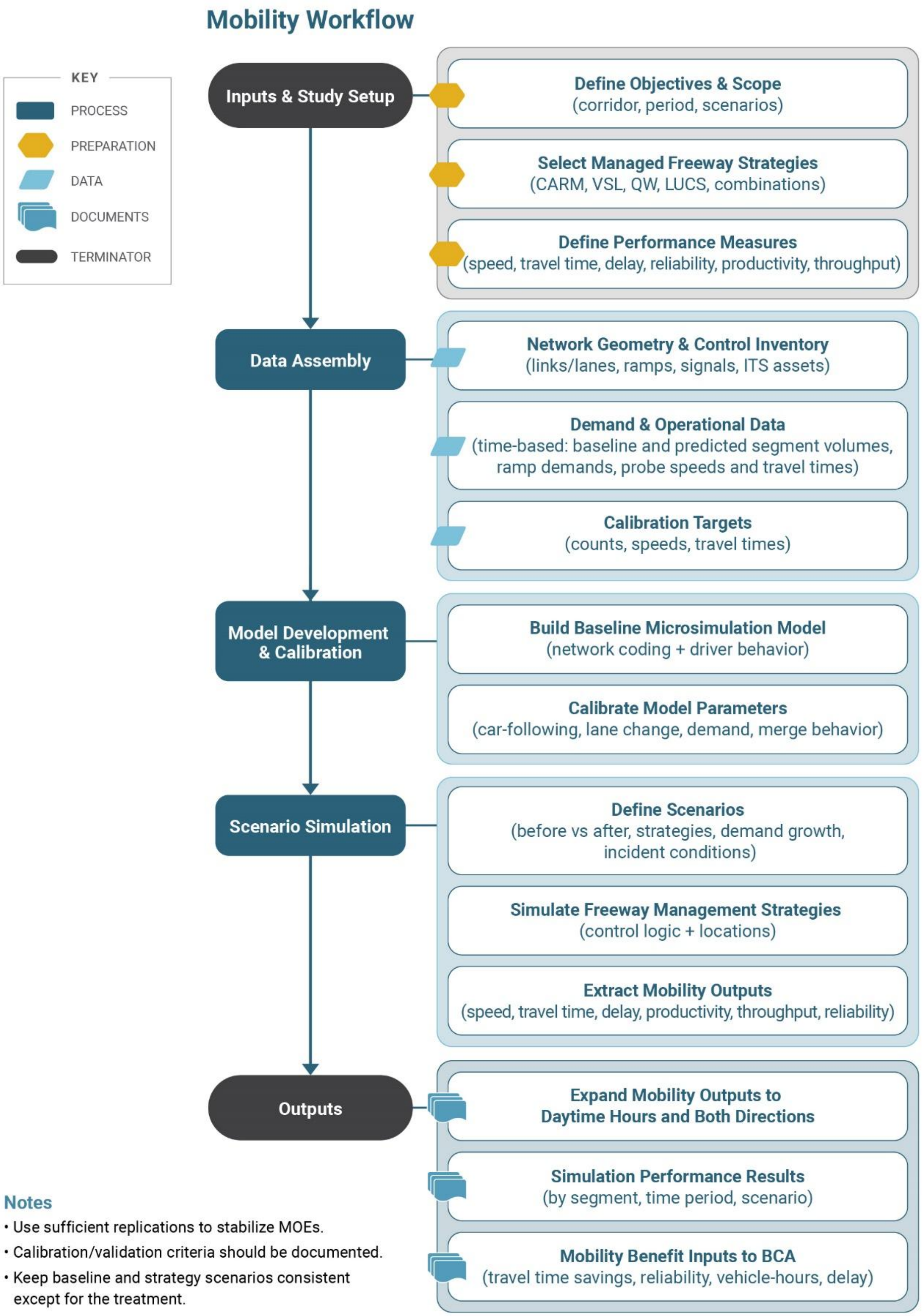


Figure 3: Workflow for Mobility Impact Assessment of Managed Freeways

The **safety impact assessment** component estimates the expected change in crash frequency resulting from the deployment of managed freeway technologies. Baseline crash predictions are generated using Safety Performance Functions (SPFs) developed specifically for North Carolina roadway facilities (Srinivasan and Carter, 2011), with Annual Average Daily Traffic (AADT) serving as the principal exposure variable. Crash Modification Factors (CMFs) derived from peer-reviewed literature are then applied to quantify the anticipated reduction (or increase) in crash frequency by severity category—specifically, Fatal and Injury (KABC) crashes and Property Damage Only (PDO) crashes—for each ATM strategy. Where simulation-based evaluation was not feasible (i.e., for QW and LUCS), safety benefits were estimated solely from literature-reported CMFs. The Safety component of the Framework is illustrated in Figure 4.

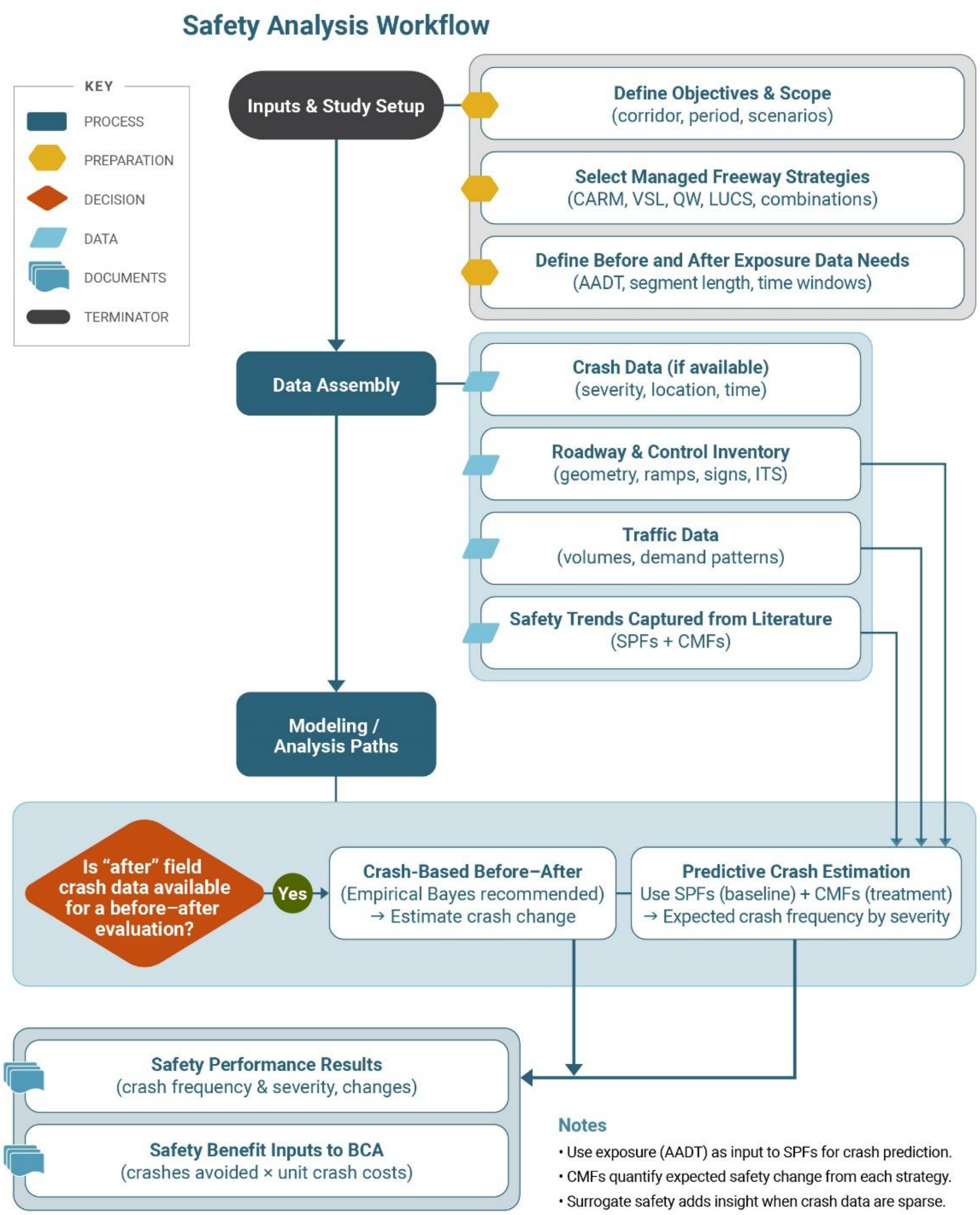


Figure 4: Workflow for Safety Impact Assessment of Managed Freeways

The **economic analysis** component synthesizes the mobility and safety results into a comprehensive Benefit–Cost Analysis (BCA). Mobility benefits are monetized by applying Value of Time (VOT) factors to the estimated travel time savings for passenger vehicles and freight. Safety benefits are monetized using NCDOT's standardized crash cost estimates by severity level (NCDOT, 2024). These monetized benefits are compared against the estimated project costs—including capital expenditures and ongoing operations and maintenance (O&M) costs—to compute a Benefit–Cost Ratio (BCR) for each technology scenario over both 5-year and 10-year analysis periods. A BCR greater than 1.0 indicates that the expected benefits exceed the costs, supporting the economic justification and investment prioritization of the project. The BCA framework encompassing the mobility and safety components is shown in Figure 5.

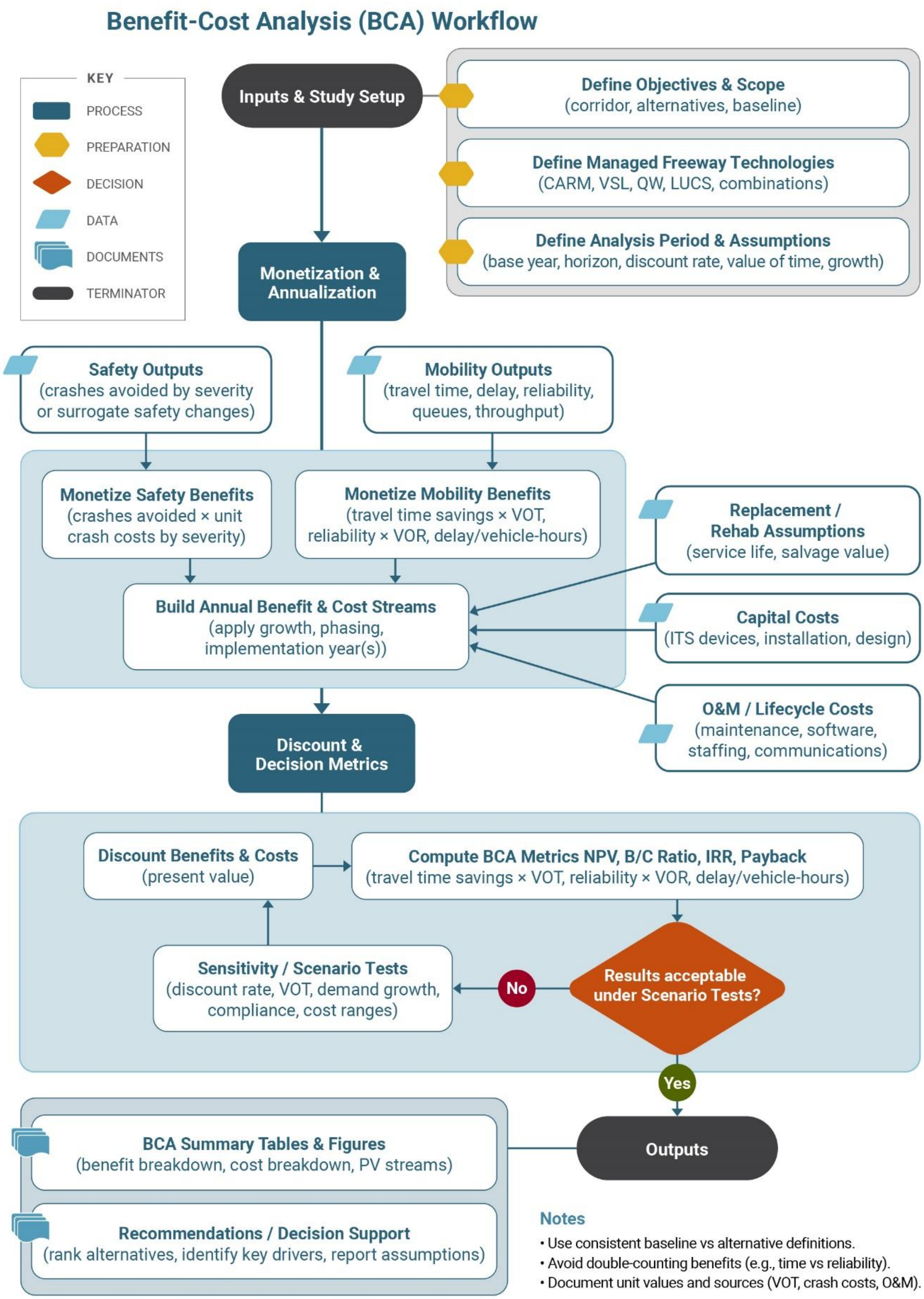


Figure 5: Workflow for BCA Assessment of Managed Freeways

Data Sources

The framework draws on multiple data sources to support the mobility, safety, and economic analysis components. Table 1 summarizes the primary data sources, their roles within the framework, and the analytical components they inform.

Table 1: Summary of Primary Data Sources Used in the Before–After Analysis Framework

Data Source	Description and Use	Framework Component(s)
NC Statewide Travel Model (NCSTM)	Provided 2035 traffic demand volumes and origin–destination patterns for the study corridor. These forecasts were used as the demand inputs for the 2035 future-year microsimulation model, reflecting anticipated growth in the study area.	Mobility (Microsimulation)
2022 Traffic Volume	NCDOT provided 2022 demand volumes for the I-40 corridor. Used as baseline demand inputs for the simulation model. These volumes were used with O&D patterns and other traffic parameters to code the 2022 base-year model.	Mobility (Microsimulation)
Probe-Based Travel Time and Speed Data	Weekday travel time and speed data from probe-based for October 2022. These data were used to calibrate the 2022 base-year microsimulation model, ensuring that simulated travel times and segment speeds matched observed field conditions.	Mobility (Simulation Model Calibration)
Annual Average Daily Traffic (AADT)	Baseline (2022) AADTs for each interchange were extracted from the NCDOT AADT map. Future-year (2035) AADTs were estimated using a growth factor method (1.5% annual growth rate) applied to the baseline values. AADT serves as the principal exposure variable in the Safety Performance Functions used for crash prediction in the benefit–cost analysis.	Safety
Safety Literature (SPFs and CMFs)	Safety Performance Functions calibrated for North Carolina (Srinivasan and Carter, 2011; Saleem et al., 2021) were used to predict baseline crash frequencies. Crash Modification Factors for CARM, VSL, QW, and LUCS were sourced from peer-reviewed studies and authoritative agency reports to estimate the expected change in crash frequency following managed freeway technology deployment.	Safety
Cost Data	Capital cost estimates for managed freeway infrastructure (CARM, QW/VSL gantries, LUCS) were provided by NCDOT for project I-6006. Annual O&M cost estimates were obtained from the NCDOT Transportation Mobility and Safety Division. Standardized crash costs by severity were sourced from NCDOT (2024), and Value of Time parameters followed USDOT and FHWA guidance (NCDOT 2025).	Economic (BCA)

3.2 Managed Freeway Technologies and Associated Scenarios

Consistent with the project scope, the research team developed and evaluated a set of scenarios for the managed freeway technologies that are planned for NCDOT's managed freeway future projects. Among the technologies, five scenarios were evaluated using a microsimulation testbed of a real-world facility. Table 2 lists the associated scenarios along with a brief description.

Table 2: Managed Freeway Technology-Related Scenarios

Scenarios		Description
I.	**2022 Existing Conditions Model**	This scenario represents existing (2022) corridor conditions, including geometric and operational characteristics as of October 2022. The model was used to calibrate and validate the simulation and to develop future-year scenarios.
II.	**2035 Base**	This scenario builds on the calibrated 2022 model and reflects projected infrastructure conditions, without managed freeway control strategies.
III.	**2035 CARM (+Flush)**	This scenario evaluates the effects of CARM technology under 2035 conditions. The model incorporates: a. Projected Y2035 infrastructure changes. b. CARM-related ramp modifications (additional on-ramp lanes based on demand as per the project CONOPS) c. Ramp metering signals at on-ramps selected by NCDOT. d. A CARM controller based on a capacity-constrained mixed-integer linear programming (MILP) formulation. e. A queue flush override (manual override) mechanism was implemented to prevent queue spillback (Please see Appendix C for more details of the algorithm).
IV.	**2035 VSL**	This scenario analyzes Variable Speed Limits (VSL) under 2035 conditions. The model incorporates 2035 projected infrastructure changes and VSL control at selected key locations. VSL logic follows (Allaby et al., 2007), including detector-based VSL and transition speed limit logic (More details in Appendix C).
V.	**2035 VSL + CARM (+Flush)**	This simulation scenario analyzes the combined effects of CARM and VSL technology for the year 2035. The model includes projected infrastructure changes by 2035. CARM-related changes (e.g. additional on-ramp lanes based on on-ramp demand as per CONOPS document, metering lights) and VSLs at multiple key locations.
VI.	**QWS**	The effects of QW were extracted from a literature review.
VII.	**LUCS**	The effects of LUCS were extracted from a literature review.

3.3 Microsimulation Modeling Approach

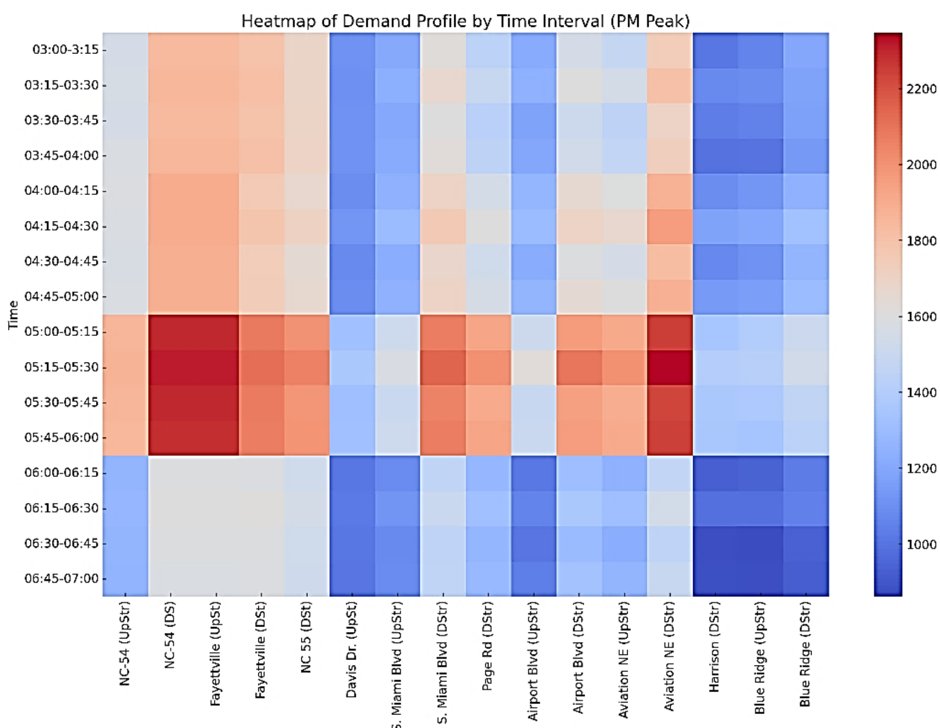
Description of the Study Corridor

A 20.5 mile-long freeway facility represents the implementation testbed for the proposed managed freeway related technology deployments. Specifically, a congested portion of Eastbound I-40 in North Carolina represents the study site. Based on projected demands in 2035, the facility is expected to experience severe recurring congestion in the next decade if no appropriate mitigation measures are taken. As part of the North

Carolina Department of Transportation (NCDOT) strategic planning efforts, an operational analysis of this freeway facility performance in the year 2035 (with CARM along with on-ramp flushing algorithm, VSL, QW) was carried out by the research team.

The freeway corridor includes nineteen on-ramps and sixteen off-ramps. The corridor's western-most point begins just west of NC 54 and the eastern-most point ends just east of the I-440 beltline. Figure 6.a depicts the corridor location and Figure 6.b shows a heat map of the projected facility segment demands during the 2035 PM peak period (3-7 pm in 15-minute intervals) in units of vehicles/hr./lane.

(a): Study Location



(b): Projected Demand

Figure 6: Test Study Location (a) and Projected Per Lane Demand Heat Map (b)

In the actual simulation runs, additional time periods were simulated beyond 7:00 pm as a clearance period to ensure all vehicles arriving within the 4-hour block (03:00 p.m. to 07:00 p.m.) are released from the network. This ensures the proper estimation of the system performance measures. Figure 6.b clearly shows that the highest demands were projected to occur at the 5-6 pm peak hour. For context, the peak capacity for a basic freeway segment hovers around 2,300-2,400 passenger car/hr./lane in the peak 15 min, according to the Highway Capacity Manual (TRB, 2022).

Note that number of on-ramp lanes for future 2035 scenarios were determined based on CONOPS documents. A summary of details is presented in **Table 3**. Also, a minimum metering rate of 400 vph and a maximum metering rate is set to on-ramp capacity (around 1500 vph on average) for each on-ramp. Demand values can be understood from Figure 6.

Table 3: On-ramp Details

On-ramp Name	NC-54	Hope Valley Road	Fayetteville Road	NC-55	885-N	885-S	Davis Dr.	Miami Dr.	Page Road	I540-S	I540-N	Airport Blvd	Aviation Pkwy-1	Aviation Pkwy-2	Harrison Av.	I440-N	Edwards Mill	Blue Ridge Road
# of storage lanes	2	2	2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
Appr. length (m)	290	250	120	273	450	552	440	338	220	478	460	477	274	420	428	800	388	405
Metering condition	metered	un-metered	metered	metered	un-metered	un-metered	metered	metered	metered	un-metered	un-metered	metered	un-metered	metered	metered	un-metered	un-metered	metered
Cluster No.	1	1	1	2	2	2	2	2	3	3	3	3	3	3	3	-	-	-

Software Platform Selection

PTV **VISSIM** (PTV AG, Karlsruhe, 2024) was selected as the most appropriate micro-simulation platform. This decision was driven by VISSIM's demonstrated ability to model the dynamic and complex interactions inherent in managed freeway systems with a high level of fidelity. In particular, VISSIM provides a robust and reliable environment for simulating advanced freeway management strategies such as **CARM and VSL**, enabling detailed assessment of their impact on traffic operations, safety, and efficiency.

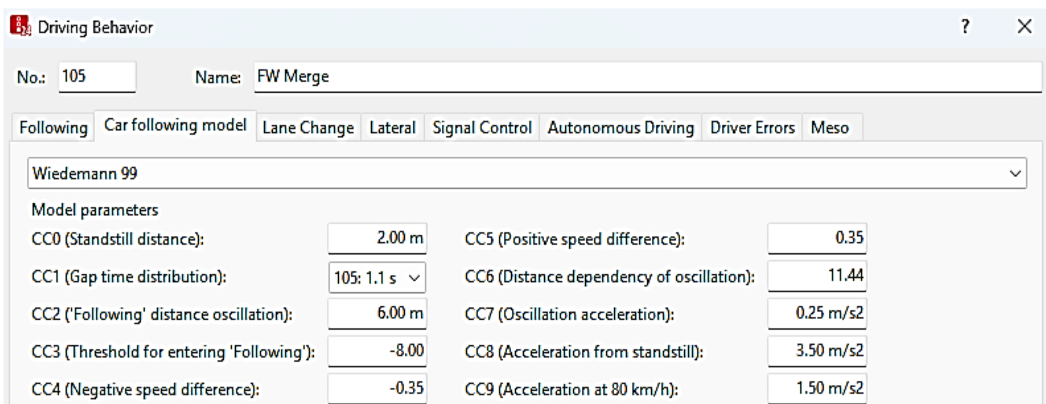
The selection of VISSIM is further supported by its extensive use in prior managed freeway and ITS studies worldwide, with numerous documented applications validating its accuracy and real-world relevance (Farabi et al., 2024; Gomes et al., 2004; Yang et al., 2013). Equally important was the strong technical support offered by the software developers, along with comprehensive documentation that facilitates proper model calibration, validation, and implementation of advanced control strategies.

In this study, two versions of VISSIM (PTV VISSIM 2021 and PTV VISSIM 2024) were used. The initial studies used VISSIM 2021 but due to the need for accurate modeling of VSL and to facilitate the use of VISSIM attribute modifications, VISSIM version 2024 was selected. Scenario I to Scenario IV were run in VISSIM 2024.

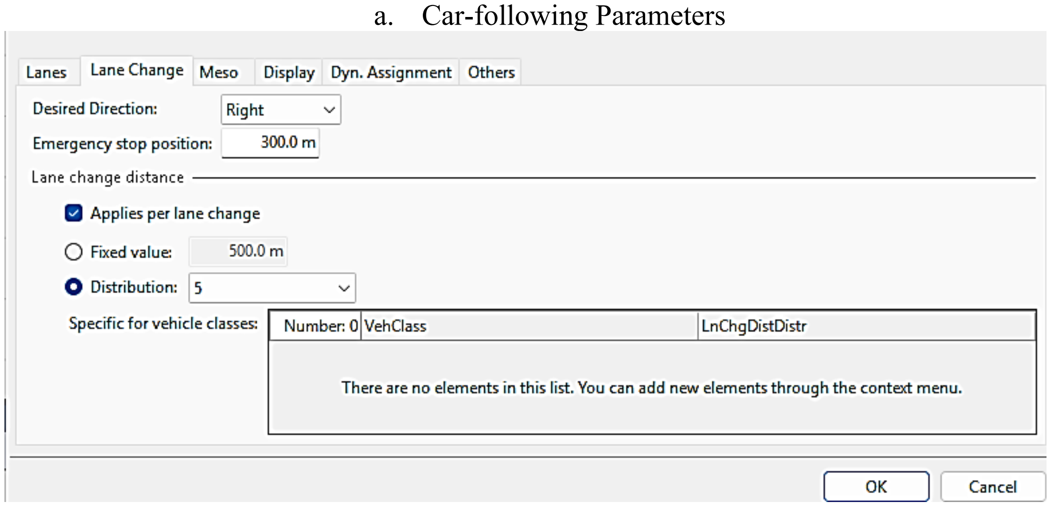
Base-year Model Development, Calibration, and Validation

The initial phase focused on coding the geometric network elements (e.g. mainline links, on-ramps links, and connectors) along with 2022 demand volume-inputs, desired speed distributions, and other required traffic parameters for the EB I-40 facility. Next, the model was calibrated to replicate the observed traffic operations. The calibration process included weekday crash-free speed and travel time field data during the simulated PM peak period. NCDOT provided demand volumes, travel time, and weekday speed data for October 2022. In addition, incidents data that occurred during the study month within the corridor were also provided by NCDOT. Using the incident dataset, the research team conducted data cleaning, filtering, and processing to ensure that only crash-free weekday data were used for model calibration.

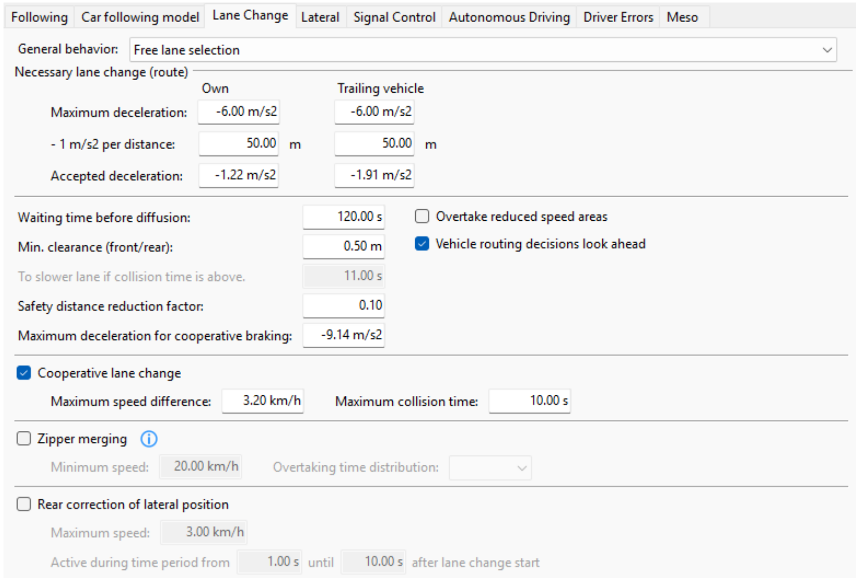
During calibration, various simulation parameters (e.g., car-following, lane changing) were adjusted to reproduce the field metrics. More specifically, driving behavior parameters: look ahead distance, Widemann 99 parameters, necessary lane change (route), minimum clearance, waiting time before diffusion, and lateral parameters were calibrated along with desired lane change direction and lane change distribution distance. Figure 7 shows typical calibration parameters from VISSIM simulation software.



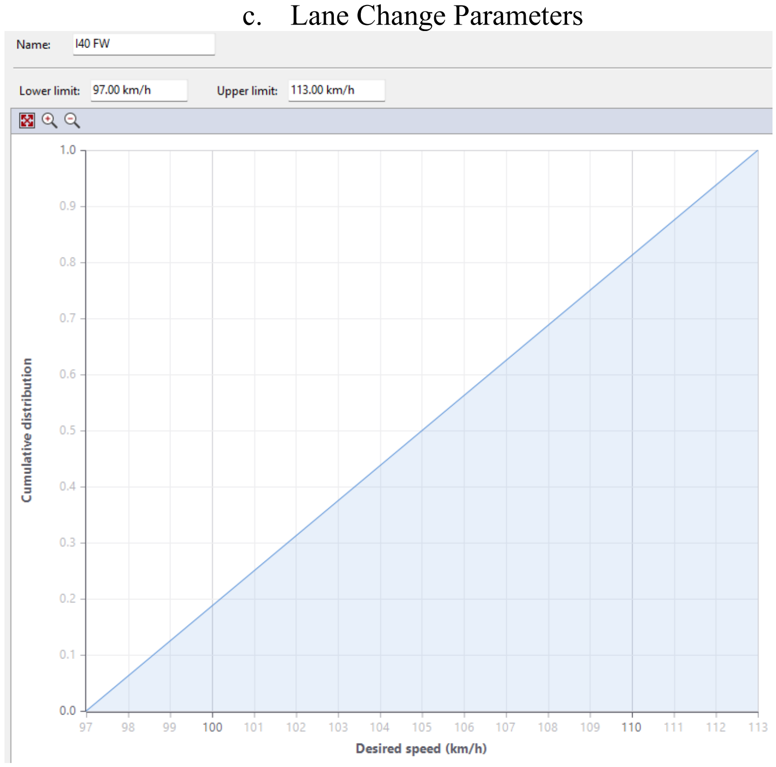
a. Car-following Parameters



b. Lane Change Distance



c. Lane Change Parameters

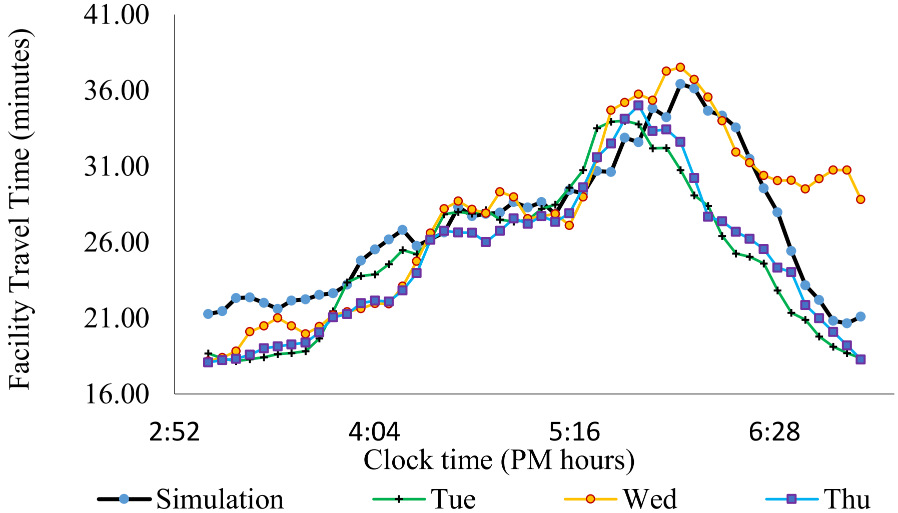


d. Desired Speed Distribution

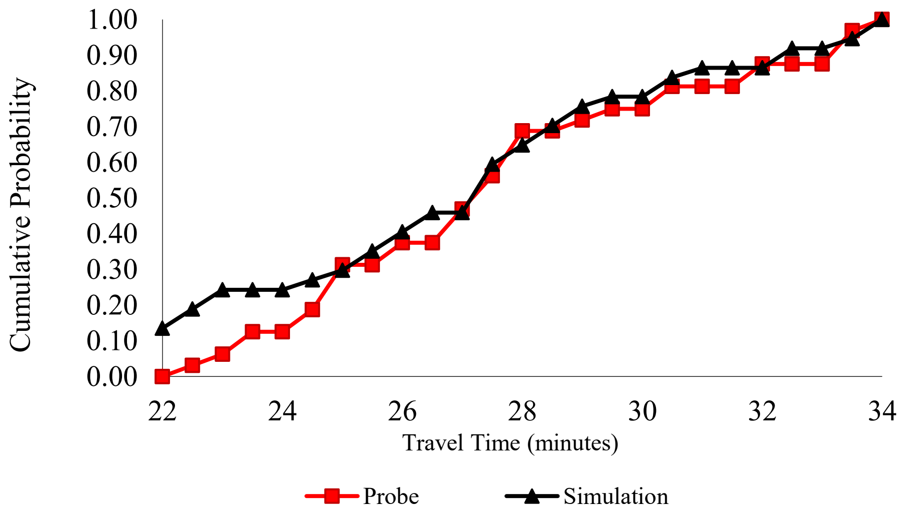
Figure 7: Typical Calibration Parameters for VISSIM

Figure 8.a depicts the 2022 system travel time comparisons against probe data from three weekdays. A Two-sample K-S test (D = 0.18 < $D_{critical}$ = 0.28) of the cumulative travel time distribution shows that the model faithfully represented field travel time conditions at the 95% confidence level, as illustrated in Figure 8.b. The 2022 calibrated simulation model served as the basis for designing a simulation model for 2035.

Leveraging the 2022 simulation model, a base model for the year 2035 was coded by incorporating NCDOT-projected infrastructure improvements and anticipated demand volumes for 2035. Also, based on the on-ramp demands and NCDOT capital improvement plans, ramp metering signals were placed at the NCDOT-selected on-ramp locations for two scenarios as discussed later.



a. Travel time profiles: Simulation vs. Probe based for 2022 base year



b. K-S test Comparing simulation and probe corridor travel time distributions

Figure 8: Simulation Model Calibration Results for 2022 Baseline

In addition, average speeds across segments and time periods on the facility were compared between simulation and field (

Figure 9.a and

Figure 9.b). The speed profiles of simulation during the peak analysis period shows reasonable closeness to the field observations. However, there are discrepancies between probe-data measured speed and simulation speed. It could be for the following reasons: The simulation used stochastic vehicle inputs at the entry points but the exact temporal distribution of demand is not known. NCDOT-provided volume input (the number of vehicles that were able to pass a given location) may not represent the inherent true demand and therefore, simulation modeling might differ from the actual field condition. Also, simulation modeling may not always capture real-world disturbances (e.g. heavy weaving, lane-change frictions). Still, the model

calibration results produced a good-enough realistic simulation model that can be used to build future year scenarios and compare future performance among different scenarios. The next section discusses simulation results for different managed freeway technology implementations.

Segment No.	1	2	3	4	5	6	7	8	9	10	11	12	13	15	16	17
Segment Name	West of NC54	NC54 to NC751	NC751 to Fayetteville	Fayetteville Rd. to NC55	NC55 to I-885	I-885 TO Davis Dr.	Davis to Miami	Miami to Page	Page Rd. to I-540	I-540 to Airp. Blvd	Airp. Blvd to Avia. Pkwy	Aviation Pkwy to Harrison Ave.	N. Harrison to Wade Ave.	I-40 EB and WB Ramps to EM	Edwards Mill to Blue Ridge	Blue Ridge to I-440
03:00-3:15	70	65	62	63	64	63	61	60	64	65	65	65	68	65	57	46
03:15-03:30	70	66	62	61	61	58	56	55	64	64	61	62	68	64	54	41
03:30-03:45	71	63	62	61	58	54	50	50	63	64	60	62	66	61	52	40
03:45-04:00	71	64	59	56	54	47	43	43	63	63	56	58	63	57	46	35
04:00-04:15	68	59	55	52	52	47	41	41	63	60	55	55	59	55	45	36
04:15-04:30	66	58	49	46	48	37	32	35	59	53	49	53	60	53	37	29
04:30-04:45	64	52	46	43	46	36	34	38	56	52	50	55	57	54	41	31
04:45-05:00	63	54	48	43	47	39	36	38	55	49	46	51	56	53	42	31
05:00-05:15	66	56	49	46	49	40	37	40	54	45	41	50	54	52	42	32
05:15-05:30	66	57	51	47	48	35	30	33	48	35	30	43	45	40	31	28
05:30-05:45	67	60	53	48	46	32	28	31	44	29	29	42	40	37	33	30
05:45-06:00	68	62	55	50	48	41	34	35	44	31	30	41	45	39	38	34
06:00-06:15	68	63	56	52	50	53	47	46	48	35	33	46	52	45	44	36
06:15-06:30	68	63	56	56	54	59	57	56	56	42	41	50	53	46	46	40
06:30-06:45	69	65	60	56	59	64	60	59	61	54	50	54	58	50	47	43
06:45-07:00	70	66	60	59	61	64	61	61	68	58	52	57	60	54	50	47

a. Average Segment Speed (mph) from Probe/Field Data

03:00-3:15	63	62	62	60	59	54	51	48	59	57	62	63	61	48	51	41
03:15-03:30	62	55	63	58	48	61	57	48	61	57	63	63	63	48	50	43
03:30-03:45	59	47	61	52	54	53	40	41	56	55	61	64	62	51	51	37
03:45-04:00	58	48	61	42	52	41	29	29	58	46	48	63	60	51	51	41
04:00-04:15	64	57	62	48	45	31	26	42	44	54	51	62	59	48	50	42
04:15-04:30	63	51	57	47	46	22	22	41	53	53	55	62	57	38	48	39
04:30-04:45	64	58	41	39	47	22	31	52	47	51	47	63	60	48	51	40
04:45-05:00	64	61	48	51	41	33	54	53	43	50	45	60	59	49	50	41
05:00-05:15	64	60	62	55	53	52	56	51	53	46	44	51	40	41	49	37
05:15-05:30	64	62	63	57	40	58	59	44	55	47	57	25	30	45	42	27
05:30-05:45	64	63	62	58	53	57	62	57	51	54	53	19	34	44	35	22
05:45-06:00	64	62	61	60	57	62	63	62	58	57	48	22	35	39	47	27
06:00-06:15	64	64	62	61	60	61	62	53	61	54	63	24	32	25	49	42
06:15-06:30	64	64	64	62	63	63	64	61	63	59	64	27	34	34	50	43
06:30-06:45	64	64	64	63	61	62	63	63	63	60	64	58	63	52	52	43
06:45-07:00	64	64	64	63	64	64	64	64	64	63	64	64	64	53	53	43

b. Average Segment Speed (mph) from Simulation

Figure 9: Comparison of Time-Dependent Segment Speeds: Field vs. Simulation

3.4 Scenario Analysis and Results

Among the identified scenarios, five involved simulation experiments while QW and LUCS were analyzed based on information gleaned from the literature review. The simulation-based scenarios—2022 base year, 2035 Base, CARM (+Queue Flush Override), VSL, and VSL + CARM (+Queue Flush Override)—were tested in the calibrated VISSIM model during the PM peak period (3:00 PM to 7:00 PM). An hour of warm-up period and multiple hours of cool-down period were added to the analysis period to ensure correctness of simulation performance and to confirm that no unmet demand exists at the end of the cool-down period.

Several performance measures were analyzed for each of the scenarios. The following performance measures were used to quantify operational conditions under all scenarios:

Delay: Delay is the additional travel time experienced by a vehicle compared to a reference free-flow or uncongested travel time. It is typically reported as seconds or minutes per vehicle or vehicle-hours over a system. The simulation model directly reports this value. Besides, the simulation system directly tracks and provides the latent delay which refers to delays of vehicles that could not enter into the system due to queue back-ups at the entry points. However, it is important to note that simulation runs did not anticipate or report potential delays caused by crashes (non-recurring). The reported delay savings should be interpreted as the operational benefit associated with recurring congestion only.

Throughput: Throughput is the total number of vehicles that successfully pass through the system during a specified time period. This vehicle count includes all exiting vehicles (all off-ramps, mainline exits, any other exits due to roadway splits). It is commonly reported in vehicles or vehicles per hour.

Travel Time: Travel time is the elapsed time required for a vehicle to traverse the system.

Speed: Speed represents the average rate of vehicle motion over a roadway segment, typically computed as the ratio of distance traveled to travel time. It is reported as space-mean speed and expressed in miles per hour (mph) or kilometers per hour (km/h).

Productivity: Productivity refers to the efficiency with which a transportation facility converts available infrastructure and time into vehicle or person movement. It is calculated as $\sum speed_i * Throughput_i$ where i is one segment of the facility.

Latent Demand: Latent demand represents the unserved or suppressed vehicle demand that exists but cannot enter the facility due to capacity constraints, congestion, or operational limitations.

Travel Time Index (TTI): The Travel Time Index is the ratio of observed (or peak-period) travel time to free-flow travel time for a given roadway segment or corridor. A TTI greater than 1.0 indicates some congestion and quantifies the reliability and severity of travel time degradation.

These defined performance measures are reported for the facility and across all scenarios

3.4.1 2035 Base Line Condition

The 2035 Base scenario represents future-year conditions without the implementation of any managed freeway technologies. This scenario serves as the reference case against which all treatment scenarios are compared. Table 4 summarizes the 15-minute interval performance measures for the eastbound I-40 corridor during the PM peak period (3:00–7:00 PM) under 2035 baseline demand conditions. Table 4 indicates a progressively worsening congestion pattern during the PM peak under the 2035 base scenario. Beginning at 3:00 p.m., average delay already exceeds 175 s/veh and increases steadily to a peak of approximately 465 s/veh by 6:15–6:30 p.m., reflecting severe breakdown conditions.

Table 4: Peak Period Performance Measures for 2035 Base Scenario

Time Period (PM)	Avg. Delay/ veh (sec)	Avg. # of Stops	Avg. Speed (mph)	Average Mainline Travel Time (sec)	Latent Demand (vehs)	15 min Period Throughput (vehs)	System Produc-tivity	Travel Time Index
03:00-03:15	176	14	34	1,810	248	4,487	1,007,405	1.57
03:15-03:30	202	15	31	2,043	303	4,595	901,857	1.77
03:30-03:45	225	15	29	2,257	613	4,616	839,395	1.95
03:45-04:00	238	18	28	2,461	945	4,691	834,755	2.13
04:00-04:15	250	20	27	2,659	1258	4,773	774,201	2.30
04:15-04:30	266	20	25	2,844	1570	4,733	696,150	2.46
04:30-04:45	302	22	22	3,031	1881	4,580	643,070	2.62
04:45-05:00	323	24	21	3,175	2193	4,605	620,974	2.75
05:00-05:15	352	26	19	3,366	2826	4,702	585,620	2.91
05:15-05:30	386	29	17	3,545	4144	4,567	544,365	3.07
05:30-05:45	412	31	15	3,800	5304	4,675	503,020	3.29
05:45-06:00	436	33	14	4,165	6780	4,595	494,744	3.61
06:00-06:15	460	38	13	4,237	6716	4,403	479,385	3.67
06:15-06:30	464	39	13	4,580	7232	4,396	503,871	3.97
06:30-06:45	449	37	14	4,605	7412	4,345	508,473	3.99

06:45-07:00	424	34	16	4,703	7607	4,429	529,100	4.07

This deterioration is accompanied by a sharp rise in the average number of stops from about 14 stops per vehicle in the early peak to nearly 39 stops during the most congested intervals—signaling frequent stop-and-go traffic and unstable flow. Correspondingly, average speeds decline continuously from roughly 34 mph to nearly 13 mph, indicating a transition to heavily congested operations. Average mainline travel time follows a similar trend, increasing from about 30 to nearly 78 minutes at the end of 07:00 PM. Latent demand (vehicles unable to enter the system) grows rapidly throughout the peak, exceeding 7,000 vehicles in the late PM period, suggesting that unmet demand and queue spillback constrain system performance. The worsening condition can also be understood when average segment speed is observed (Figure 10). Significant drops in speed, especially on segments 1-7 are indicative of severe levels of congestion.

Time Period	1	2	3	4	5	6	7	8	9	10	11	12	13	15	16	17
03:00-03:15	63	54	13	12	23	63	61	49	58	56	61	63	59	55	55	55
03:15-03:30	63	21	9	12	23	63	50	34	56	55	59	63	45	55	55	55
03:30-03:45	61	13	9	12	23	64	32	29	57	54	60	63	38	55	55	54
03:45-04:00	53	11	9	12	22	63	37	29	55	56	60	63	38	55	55	47
04:00-04:15	29	10	9	12	24	62	22	26	54	55	57	63	35	54	55	49
04:15-04:30	20	10	9	12	24	44	14	24	53	55	58	63	26	54	55	52
04:30-04:45	15	10	9	12	23	28	14	24	55	56	59	53	20	55	55	54
04:45-05:00	12	10	9	12	23	22	14	25	55	56	57	46	18	54	55	54
05:00-05:15	12	10	9	12	23	19	13	23	50	54	55	36	17	55	56	53
05:15-05:30	11	10	9	12	25	16	12	22	49	53	46	26	17	54	55	45
05:30-05:45	11	10	9	12	17	13	11	21	49	55	51	18	17	55	56	36
05:45-06:00	11	10	9	11	9	8	13	23	50	55	53	14	17	54	56	39
06:00-06:15	11	10	8	9	7	8	15	27	56	57	44	12	17	54	55	48
06:15-06:30	9	8	7	9	10	11	17	28	57	57	58	12	17	55	55	54
06:30-06:45	8	7	7	9	13	13	17	26	55	58	62	13	17	55	55	55
06:45-07:00	8	8	8	10	15	13	18	27	57	57	62	14	17	56	55	55

Figure 10: Baseline Scenario Time Dependent Projected Segment Speed (mph) in 2035 Year

3.4.2 Managed Freeway Technology Scenarios

The effects of implementing managed freeway technologies on the congested facility in the 2035-year scenario can be seen in Table 5. The facility-wide performance measures for some key measures are shown.

Table 5 shows that the 2035 Base scenario experiences severe congestion, reflected by the highest total system delay (30,522 veh.h), and substantial unmet demand remaining at the end of the analysis period (8,050 vehicles). Implementing CARM (+FLUSH) results in significant performance improvements across all scenarios, reducing total delay by approximately 38% relative to the base case while simultaneously increasing total throughput to 77,998 vehicles and lowering unmet demand to 2,617 vehicles.

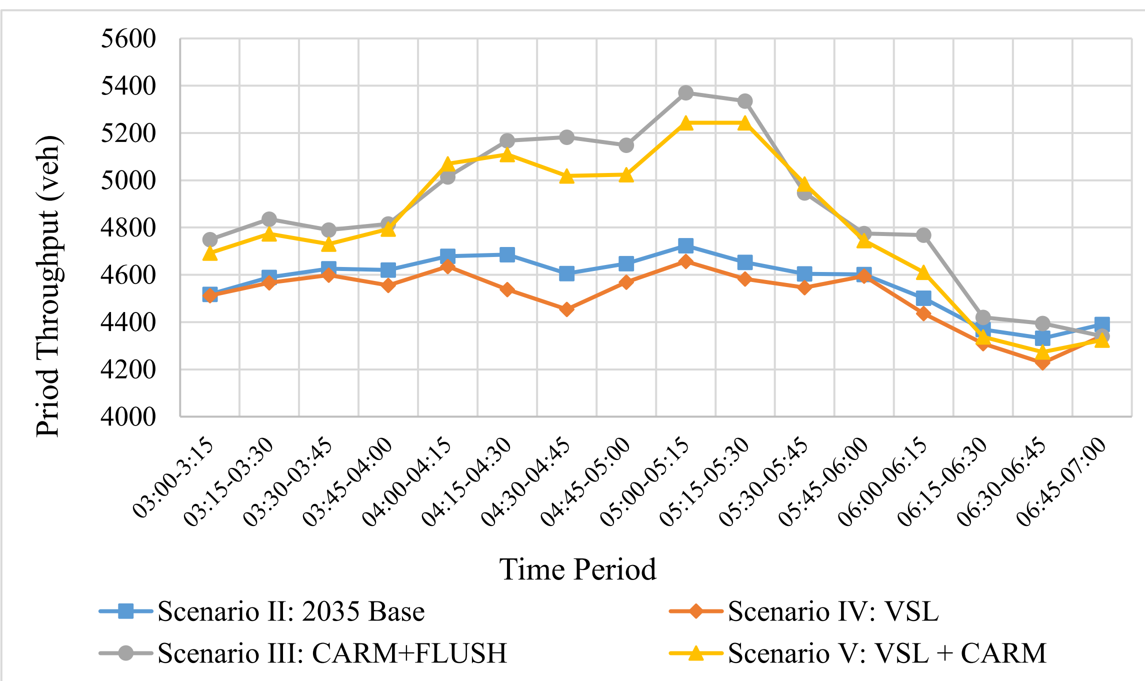
The VSL-only scenario does not yield noticeable congestion relief; instead, it slightly increases total delay and unmet demand compared to the base case, indicating limited effectiveness when applied in isolation under heavily congested conditions. By contrast, the combined VSL + CARM strategy still improves system performance, achieving a 29% reduction in total delay and a 61% reduction in unmet demand relative to the base scenario, while maintaining high throughput.

Table 5: Facility-wide Performance by Scenario

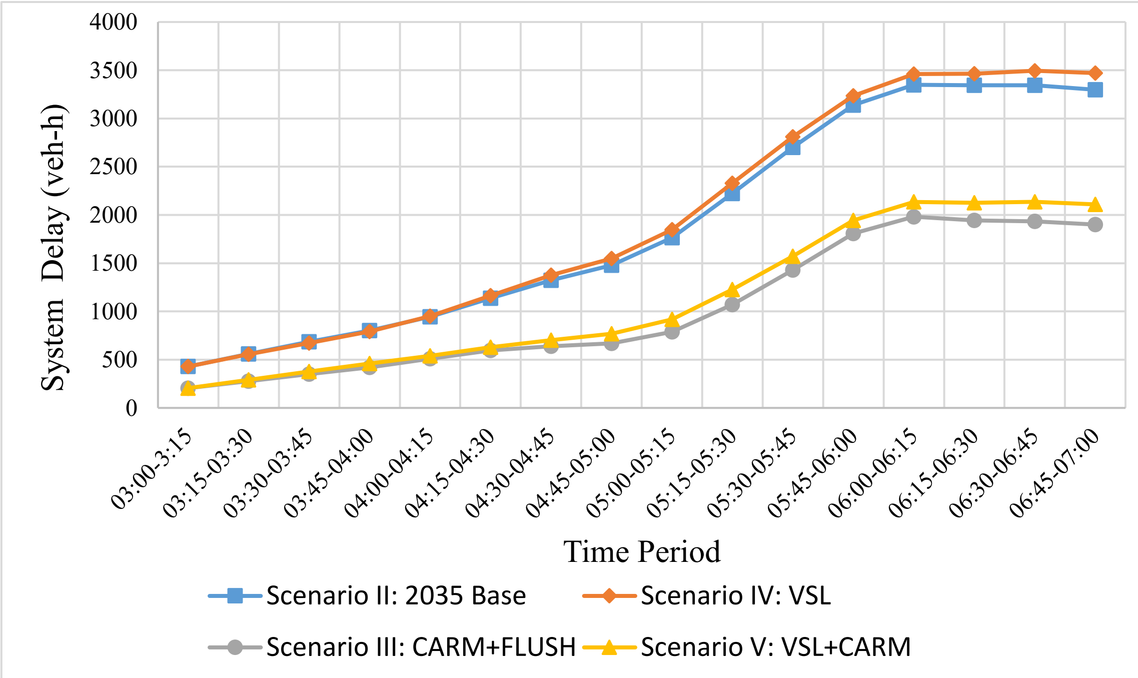
Scenario	Total Delay (In System + Latent Delay) (veh-h)	VMT (veh-miles)	VHT (veh-h)	Unmet Demand at 07:00 p.m. (veh)	Total Through-put Across 4 hrs. (veh)
II: 2035 Base	30,522	443,097	23,515	8,050	73,145
III: CARM (+FLUSH)	18,926	463,946	18,521	2,617	77,998
IV: VSL ONLY	31,605	435,130	24,097	9,004	72,123
V: VSL + CARM (+FLUSH)	21,672	455,734	19,877	3,165	76,976

Overall, the results demonstrate that demand-responsive ramp metering strategies, particularly when combined with queue-flushing logic, are critical for mitigating congestion and improving freeway efficiency in the 2035 managed freeway environment, whereas standalone VSL strategy cannot perform well under heavy demand levels.

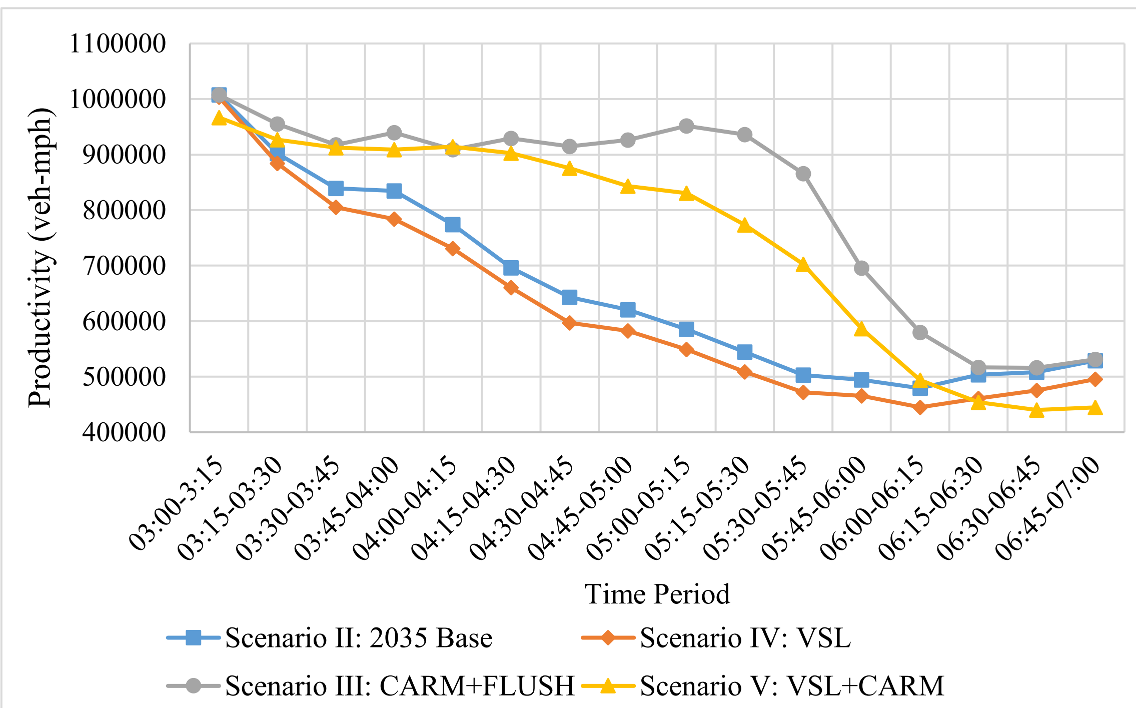
In addition, throughput values (Figure 11.a) and total delay (Figure 11.b) during the peak period also shows clearly that scenario III (CARM + Flush) can relieve the congested condition when compared to 2035 Base scenario.



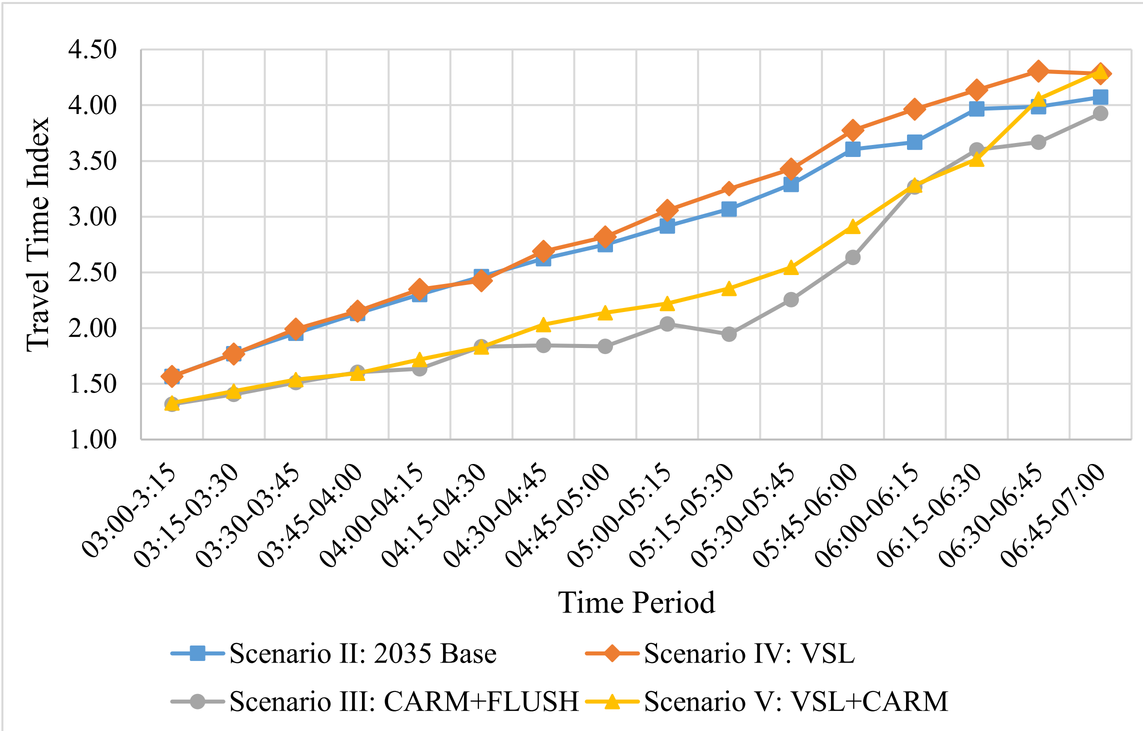
a. System Throughput Volume in Each 15 Minute Period



b. System Delay (veh-hours) in Each 15 Minute Period



c. Productivity in Each 15 Minute Period (Total Network)



d. Travel Time Index in Each 15 Minute Period

Figure 11: System Throughput, Delay, Productivity, and TTI by 15min Period

Two other key performance measures: productivity and travel time index (TTI) are also explored. Figure 11.c shows that the productivity is low when VSL is in operation. VSL, with its focus on safety, could not provide operational benefits based on our simulation experiments. However, CARM (+Flush) provides maximum productivity and CARM (+Flush) with VSL increases significantly high productivity as well. A similar performance trend (lower index) can be observed in Figure 11.d.

Speed distributions provide insights into the safety benefits. In the speed distributions shown in Figure 12, the 2035 Base scenario tends to produce a bimodal speed distribution profile where significant portions of speed fall around 10 mph and 50 mph. VSL speeds have dropped to a peak near 50 mph highlighting improvements in speed variations. However, CARM (+Flush) and CARM (+Flush) + VSL reduced the initial 10 mph peak significantly and improved the high-speed distribution from 50 mph to 60 mph.

Thus far, the performance measures have shown the effects of managed freeway technologies on the overall facility. It is equally important, however, to investigate those same effects segment-wise. Average speed values by segment under CARM (+Flush) are shown in Figure 13.a; VSL impacts are shown in Figure 13.b.

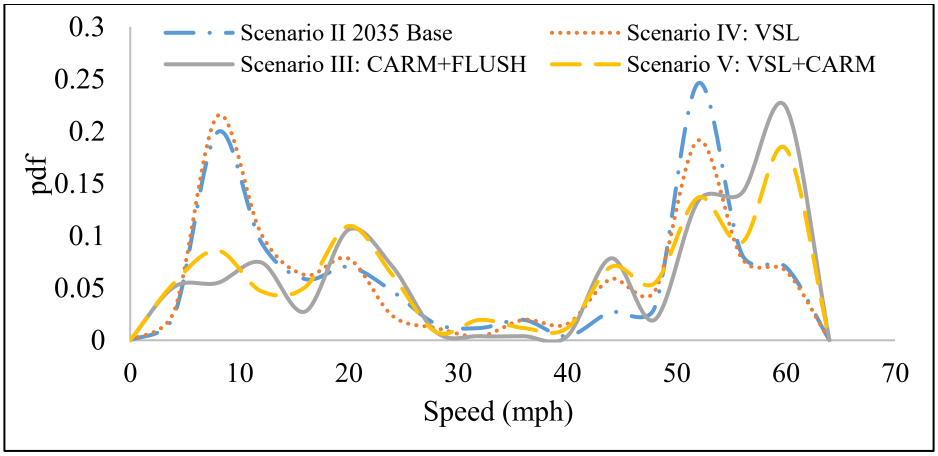


Figure 12: Probability Distribution Functions of Speed across Scenarios

TIME (PM)	1	2	3	4	5	6	7	8	9	10	11	12	13	15	16	17
03:00-03:15	63	60	63	25	23	63	23	26	55	54	59	63	63	55	56	46
03:15-03:30	62	59	63	22	26	45	13	24	54	56	59	63	62	41	55	46
03:30-03:45	63	62	63	22	25	26	12	23	56	56	63	64	63	44	55	46
03:45-04:00	63	58	61	20	27	20	14	24	56	57	61	63	62	55	56	46
04:00-04:15	62	57	63	19	27	16	12	21	53	56	62	64	63	53	55	46
04:15-04:30	63	58	62	20	25	13	12	21	54	56	61	63	62	51	55	45
04:30-04:45	61	56	63	22	29	10	11	22	53	59	62	63	63	52	55	46
04:45-05:00	62	56	62	24	28	9	12	23	54	56	62	63	63	54	55	46
05:00-05:15	60	54	63	25	26	8	12	22	54	55	59	63	62	50	55	46
05:15-05:30	55	51	63	20	26	8	11	22	46	55	59	63	62	39	55	44
05:30-05:45	60	47	54	17	26	7	9	19	52	55	59	63	59	12	56	47
05:45-06:00	56	53	22	13	27	6	10	22	51	55	59	62	21	6	57	47
06:00-06:15	64	54	14	13	23	5	10	23	55	58	61	35	12	7	57	46
06:15-06:30	64	32	11	13	19	4	13	22	57	58	62	27	11	6	57	47
06:30-06:45	64	21	10	13	22	5	14	24	56	58	63	22	12	7	56	47
06:45-07:00	64	21	10	13	24	7	14	25	56	57	61	24	13	6	57	47

a. Time Dependent Projected Segment Speed Profiles under CARM (+Flush)

TIME (PM)	1	2	3	4	5	6	7	8	9	10	11	12	13	15	16	17
03:00-03:15	63	54	13	12	23	63	61	49	58	56	61	63	59	55	55	55
03:15-03:30	63	21	9	12	23	63	50	34	56	55	59	63	45	55	55	55
03:30-03:45	61	13	9	12	23	64	32	29	57	54	60	63	38	55	55	54
03:45-04:00	53	11	9	12	22	63	37	29	55	56	60	63	38	55	55	47
04:00-04:15	29	10	9	12	24	62	22	26	54	55	57	63	35	54	55	49
04:15-04:30	20	10	9	12	24	44	14	24	53	55	58	63	26	54	55	52
04:30-04:45	15	10	9	12	23	28	14	24	55	56	59	53	20	55	55	54
04:45-05:00	12	10	9	12	23	22	14	25	55	56	57	46	18	54	55	54
05:00-05:15	12	10	9	12	23	19	13	23	50	54	55	36	17	55	56	53
05:15-05:30	11	10	9	12	25	16	12	22	49	53	46	26	17	54	55	45
05:30-05:45	11	10	9	12	17	13	11	21	49	55	51	18	17	55	56	36
05:45-06:00	11	10	9	11	9	8	13	23	50	55	53	14	17	54	56	39
06:00-06:15	11	10	8	9	7	8	15	27	56	57	44	12	17	54	55	48
06:15-06:30	9	8	7	9	10	11	17	28	57	57	58	12	17	55	55	54
06:30-06:45	8	7	7	9	13	13	17	26	55	58	62	13	17	55	55	55
06:45-07:00	8	8	8	10	15	13	18	27	57	57	62	14	17	56	55	55

b. Time Dependent Projected Speed Profiles under VSL

Figure 13: Speed Heat Maps for Scenarios III and IV

Figure 13 confirms that the test facility, even under managed freeway technologies, will continue to experience severe congestion in several locations. When compared to the 2035 Base scenario (Figure 10) significant speed improvements occurred in segment 1-3, 9-12 using CARM (+FLUSH) mechanism. However, segments 4-8 still experience significant speed drops. This is due to the presence of heavy input demand from an unmetered system interchange (on I-885) which makes these segments experience unavoidable congestion. Note that the VSL Scenario IV does not improve the speed profile while producing lower speeds compared to 2035 Base.

4.2 Summary of Simulation Results on Mobility Impacts

The simulation results revealed clear differences in the operational effectiveness of the evaluated managed freeway technologies under 2035 demand conditions. Relative to the 2035 Base scenario, which exhibited severe congestion with a total system delay of 30,522 veh-h and 8,050 vehicles of unmet demand by the end of the PM peak, the CARM (+FLUSH) strategy delivered the largest operational benefits. Specifically, CARM+FLUSH reduces total delay by approximately 38%, decreases unmet demand by nearly 67%, and increases total throughput by about 6.6%, demonstrating its effectiveness in directly regulating freeway entry flows and preventing mainline breakdown.

By contrast, VSL–only provided limited operational benefits and yielded slightly worse congestion, increasing total delay by approximately 4% and unmet demand by about 12% relative to the base case, while reducing throughput by nearly 1.4%. These results are consistent with the primary role of VSL in improving safety and speed harmonization rather than managing demand or increasing effective capacity.

The combined VSL + CARM (+FLUSH) strategy offered a balanced improvement, reducing total delay by approximately 29% and unmet demand by about 61%, while increasing throughput by roughly 5.3% compared to the base scenario. Although its operational benefits are somewhat lower than those of CARM+FLUSH alone, the combined strategy provides a promising compromise when both operational efficiency and safety are both considered. Nevertheless, the interaction between ramp metering and speed control suggests the need for further research to identify optimal coordination policies and evaluate long-term impacts under mixed traffic and incident-prone conditions. Note that simulation modeling (both metered and unmetered scenarios) only included freeway system (e.g. mainline, on-ramps, and off-ramps) only and did not consider arterial operation that feeds traffic into the freeway. Rather, a stochastic variable vehicle input was provided at each entry point (e.g. on-ramps, upstream end of the mainline) that serves as a reasonable demand fluctuations observed in real-world. While this ensures a valid comparison among scenarios, a more accurate scenario testing should include arterial operation as well.

Another important aspect of this research is that CARM algorithm was coded externally and interacts with VISSIM simulation via COM programming. On the other hand, VSL logic is directly coded inside VISSIM using attribute modification programing. Therefore, any CARM framework can be implemented through COM programming but VSL would require modifying the attribute programming logic inside VISSIM.

Chapter 4. Benefit–Cost Analysis Framework and Results

4.1 Overview

The Benefit–Cost Analysis (BCA) framework provides an overview of the methods and data sources used to evaluate the economic efficiency of the proposed managed freeway project. This abbreviated framework outlines the key components and methodologies used to estimate project costs, mobility benefits, safety benefits, and ultimately the overall benefit–cost ratio (BCR). A comprehensive BCA framework, along with detailed analysis results, is presented in Appendix D. A benefit-cost ratio (BCR) is the ratio of the present-value benefits of a project to the implementation costs of the project (BCR = Benefits/Costs). If the ratio is greater than 1.0, then the project is considered economically justified. When multiple alternative solutions exist, countermeasures that produce the highest BCR for a specific site are the most desirable.

Project costs include both capital and ongoing operations and maintenance (O&M) expenses over the analysis period. Mobility benefits are estimated using traffic simulation and operational performance data from literature review to quantify savings in travel time, delay, and network efficiencies. The value of time (VOT) is applied to monetize these travel time savings for different user groups (e.g., passenger vehicles, freight), supported by relevant traffic data inputs such as peak hour traffic volume and Annual Average Daily Traffic (AADT). Safety benefits are derived from expected crash reductions using available AADT, Safety Performance Functions (SPFs), Crash Modification Factors (CMFs), and unit crash costs by severity level. These estimates reflect anticipated improvements in safety performance following project implementation. Finally, the BCR integrates all three components: costs, mobility benefits, and safety benefits, to provide a comprehensive measure of project performance.

4.2 Estimated Project Costs

This research adopted the civil costs for I-40 between SR54 and I-440 in Raleigh-Durham area (i.e., NCDOT project I-6006), which was estimated by WSP using the NCDOT Design Estimate Work Sheets *(WSP, 2024)*.

The research team obtained the annual O&M cost estimates from the NCDOT Transportation Mobility and Safety Division, as shown in Table 6. In practice, instead of applying monetized values directly, a rule-of-thumb is to approximate operating costs as a percentage of capital costs. The combined capital cost for the three ATM strategies is estimated at approximately $112 million with an annual O&M cost of approximately $2.7 million, representing 2.4 percent of the capital cost. Among the strategies, Lane Use Control Signals exhibit the highest O&M cost intensity, with annual O&M costs account for 3.12 percent of the capital cost. The Queue Warning and Dynamic Speed Advisory and Coordinated Adaptive Ramp Metering strategies demonstrate comparatively lower O&M ratios of 2.8 percent and 1.4 percent, respectively.

Table 6: Estimated Annual O&M Costs for the Study Corridor

ATM Strategy	Capital Cost	Annual O&M Cost	O&M Cost as a % of Capital Cost
CARM	$43,909,500	$625,000	**1.4%**
QW and VSL	$20,020,000	$560,000	**2.8%**
LUCS	$48,093,750	$1,500,000	**3.12%**
Total	**$112,023,250**	**$2,685,000**	**2.4%**

4.3 Estimated Project Benefits

4.3.1 Mobility Benefits

Table 7 presents the network performance metrics derived from VISSIM microsimulation modeling conducted for the Year 2035 baseline (no treatments) and three alternative operational improvement scenarios: CARM, VSL, and VSL + CARM. The results, obtained from model outputs, include Vehicle Hours of Delay (VHD), Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), and Throughput, which collectively reflect the efficiency and capacity of the transportation network under each scenario. Overall, the CARM and VSL+CARM scenarios demonstrate substantial reductions in delay (−38.0% and −29.0%, respectively) and notable increases in throughput, indicating enhanced traffic operations relative to the baseline. In contrast, the VSL-only scenario yields limited performance improvements. Vehicle Hours Traveled (VHT) was the selected performance metric for mobility benefits.

Table 7: Freeway-wide Operational Performance in representative PM peak period (3-7 PM)

Scenario	VHD (veh-hr)	VMT (veh.mile)	VHT (veh-hr)	Throughput (veh)
I: 2022 Existing Conditions	2,616	396,509	8,759	65,985
II: 2035 Base	30,522	443,097	23,515	73,145
III: 2035 CARM	18,926 (-38.0%)	463,946 (+4.7%)	18,521 (-21.2%)	77,998 (+6.6%)
IV: 2035 VSL	31,605 (+3.6%)	435,130 (-1.8%)	24,097 (+2.5%)	72,123 (-1.4%)
V: 2035 VSL + CARM	21,672 (-29.0%)	455,734 (+2.9%)	19,877 (-15.5%)	76,976 (+5.2%)

To ensure that the estimated project benefits represent system wide impacts, the 4-hr peak-period results are extrapolated to future year daily, annual and bi-directional conditions. The initial benefit estimates, typically derived from traffic simulation or performance data during the peak analysis period in one direction, are adjusted to account for both directions of travel and for all weekdays of the year. This extrapolation process incorporates factors such as the proportion of daily traffic represented by the peak hours (K-factor), directional traffic splits (D-factor), and the number of effective analysis days per year (N-factor). By applying these adjustments, the analysis provides a more comprehensive representation of the project's total annual mobility and safety benefits across the full facility.

K-factor - Percentage of I-40 Eastbound corridor, day-time traffic volume (6 am to 8 pm) which occurs during the simulated PM peak 4-hours (K=0.338 for the study freeway corridor) based on available 2035 hourly demand volumes

D-factor - Percentage of I-40 Eastbound corridor, day-time traffic volume (6 am to 8 pm) of bi-directional traffic flow traveling on the corridor (D=0.491 for the study freeway corridor)

N-factor – Number of weekdays per year benefits occur (N= 250 days per year)

O-factor – Weighted average vehicle occupancy per trip (O= 1.5 occupants per vehicle)

EB PM Peak Period VHT Savings = VHT Base (2025) – VHT Treatment (2035)

Corridor Annual Benefits = (Simulated EB Peak Period VHT Savings × N × O) / (K × D)

The input values of time align with current NCDOT benefit-cost analysis guidance and ensure consistency in evaluating the economic impacts of proposed transportation investments *(NCDOT, 2025)*. The value of time is estimated to be $21.10 per hour for passenger vehicles and $35.70 per hour for trucks.

4.3.2 Safety Benefits

The NCDOT Transportation Mobility and Safety Division adopts the recommendation of FHWA's Crash Costs for Highway Safety Analysis *(Harmon et al., 2018)*. The average costs per crash in North Carolina are estimated as $495,000 per injury (KABC) crash and $15,100 per PDO crash (*NCDOT, 2024*).

5.3.2.1. Predicting Baseline Number of Crashes

The baseline number of crashes for the analysis is estimated using the Safety Performance Function (SPF) developed specifically for roadway facilities in North Carolina *(Srinivasan and Carter, 2011)*. This SPF provides a predictive relationship between crash frequency and key roadway and traffic characteristics such as segment length, traffic volume, and facility type, depicted as follows:

$$Y = L \times (Annual\ Factor) \times exp\{\alpha + \beta \times \ln AADT\} = L \times (Annual\ Factor) \times e^{\alpha} \times AADT^{\beta}$$

- Y is the predicted number of crashes per year for a segment with length L (in miles)
- α is the intercept; $\alpha = -15.3488$ for KABC crashes, and $\alpha = -17.0107$ for PDO crash for the study freeway corridor
- β is the coefficient for $\ln AADT$; $\beta = 1.5478$ for KABC crashes, and $\beta = 1.7596$ for PDO crash for the study freeway corridor
- $Annual\ Factor$ is a multiplier applied to the SPF-predicted number of crashes to align the model's predictions with observed crash data for a specific year; $Annual\ Factor = 1.06$ for the study freeway corridor *(Saleem et al., 2021)*.

The baseline SPF serves as the foundation for estimating expected crash occurrences under existing conditions, prior to the implementation of any proposed improvements. It is important to note that the SPFs are developed separately for two crash categories: Fatal and Injury (KABC) crashes, and Property Damage Only (PDO) crashes. Accordingly, the total number of baseline crashes are calculated as the sum of crashes predicated from the two SPFs within the study freeway segment.

5.3.2.2. Crash Modification Factors (CMFs) for Selected ATM Strategies

This section summarizes the Crash Modification Factors (CMFs) used to evaluate the safety impacts of the selected freeway ATM strategies, including CARM, VSL, QW, and LUCS. CMFs represent the expected change in crash frequency associated with the implementation of a specific treatment and are critical inputs for quantifying safety benefits in project evaluation and decision-making. The selected CMFs, as listed in Table 8, are based on peer-reviewed literature and authoritative agency reports that specific to safety performance outcomes on urban freeways.

Table 8: Summary of CMFs for Various ATM Treatments (Extracted from Literature Review)

<table>
<tr><th>Treatment</th><th>Crash Type</th><th>Crash Severity</th><th>CMF</th><th>Study Region / Source</th></tr>
<tr><td rowspan="2">CRAM</td><td rowspan="2">All</td><td>KABC</td><td>0.95</td><td rowspan="2">I-80 in the San Francisco Bay Area, California. (Molan et al., 2023)</td></tr>
<tr><td>PDO</td><td>1.12</td></tr>
<tr><td rowspan="2">VSL</td><td rowspan="2">All</td><td>KABC</td><td>0.89</td><td>Avelar et al., 2021</td></tr>
<tr><td>PDO</td><td>0.918</td><td>Chakraborty and Mahmud, 2024</td></tr>
<tr><td rowspan="2">QW</td><td rowspan="2">Rear-end</td><td>KABC</td><td>0.84</td><td rowspan="2">Elvik and Vaa, 2004</td></tr>
<tr><td>PDO</td><td>1.16</td></tr>
<tr><td rowspan="2">LUCS</td><td rowspan="2">All</td><td>All</td><td>0.96</td><td rowspan="2">I-66, VA. (Dutta et al., 2017)</td></tr>
<tr><td>KABC</td><td>0.94</td></tr>
</table>

5.3.2.3. Predicted Annual Number of Crashes with ATM Systems

The general form of the predictive model used to determine the predicted average crash frequency, $N_{predicted}$, is shown below:

$$N_{predicted} = N_{SPFx} \times (CMF_{1x} \times CMF_{1x} \times \ldots \times CMF_{yx}) \times C_x$$

Where,

$N_{predicted}$ = predicted average crash frequency for a specific year for site type x

N_{SPFx} = predicted average crash frequency determined under base conditions (no technology) of the SPF developed for site type x

CMF_{yx} = Crash Modification Factors specific to SPF for site type x

C_x = calibration factor to adjust SPF for local conditions for site type x

$$Combined\ CMF = CMF_{CARM} \times CMF_{VSL} \times CMF_{QW} \times CMF_{LUCS}$$

For fatal and injury (KABC) crashes, the combined CMF is calculated as follows:

$$CMF^{KABC} = CMF_{CARM}^{KABC} \times CMF_{VSL}^{KABC} \times CMF_{QW}^{KABC} \times CMF_{LUCS}^{KABC}$$
$$= 0.95 \times 0.89 \times 0.84 \times 0.94 = 0.668$$

For property damage only (PDO) crashes, the combined CMF is calculated as follows:

$$CMF^{PDO} = CMF_{CARM}^{PDO} \times CMF_{VSL}^{PDO} \times CMF_{QW}^{PDO} \times CMF_{LUCS}^{PDO}$$
$$= 1.12 \times 0.918 \times 1.16 \times 0.96 = 1.145$$

So, the predicted average crash frequency for the tested managed freeway scenario is:

$$N_{predicted} = N_{spfx}^{KABC} \times CMF^{KABC} \times C_x^{KABC} + N_{spfx}^{PDO} \times CMF^{PDO} \times C_x^{PDO}$$
$$= N_{spfx}^{KABC} \times 0.668 \times C_x^{KABC} + N_{spfx}^{PDO} \times 1.145 \times C_x^{PDO}$$

4.4 BCR Calculator for I-40 Case Study

The research team developed a spreadsheet tool to estimate the Benefit-Cost Ratios of the I-40 managed freeway project. The tool provides two levels of analysis: a conservative estimate based on the lower-bound values of key variables and a favorable estimate based on default parameter values. A comprehensive summary of the analysis procedure and parameters used in the B/C analysis is provided in Appendix D.

Based on North Carolina data, the estimated B/C ratios for the evaluated strategies are presented in Table 5-4. When all strategies are implemented, the 10-year B/C ratio is estimated at 14.4 under conservative assumptions and increases to 30.0 under favorable assumptions. Among the four strategies analyzed, CARM emerges as the most cost-effective option, yielding a 10-year B/C ratio of 18.8 even under conservative estimates. Under favorable estimates, queue warning appears to be the most cost-effective option with a 10-year B/C ratio of 45.2. In contrast, variable speed limits do not appear to be a priority under conservative assumptions, as prior research indicates that VSL implementation may increase travel time. However, VSL remains a viable investment under aggressive estimation parameters, despite underperforming relative to alternative deployment options.

Table 9: Estimated Benefit-Cost Ratios under Various Scenarios

B/C Ratios using Conservative Estimates

Analysis Period	CARM Only	QW Only	VSL Only	LUCS Only	All 4 Strategies
5 Year	10.8	5.3	<1	10.2	8.6
10 Year	18.8	8.7	<1	16.4	**14.4**
B/C Ratios using Favorable Estimates					
Analysis Period	**CARM Only**	**QW Only**	**VSL Only**	**LUCS Only**	**All Strategies**
5 Year	22.1	28.4	13.7	19.6	18.7
10 Year	37.0	45.2	21.8	30.6	**30.0**

Chapter 5. Recommendations for Deployment

This chapter presents recommendations for deploying the managed freeway strategies evaluated in this research. Drawing on the benefit–cost analysis results, simulation findings, and lessons learned from national and international implementations, these recommendations are intended to guide NCDOT in prioritizing strategy deployment, selecting suitable corridors, and establishing the technical and institutional foundations needed for successful implementation.

5.1 Strategy Prioritization Based on Benefit–Cost Performance

The benefit and cost analysis demonstrates that all four ATM strategies—Coordinated Adaptive Ramp Metering (CARM), Queue Warning (QW), Variable Speed Limits (VSL), and Lane Use Control Signals (LUCS)—are economically justified when deployed on the I-40 corridor, with a combined 10-year BCR ranging from 14.4 under conservative assumptions to 30.0 under favorable assumptions. However, the individual strategies differ substantially in their cost-effectiveness and operational contributions, which has direct implications for deployment sequencing.

CARM emerges as the highest-priority strategy for initial deployment. Even under the most conservative estimation parameters, CARM yields a 10-year BCR of 18.8, driven by substantial reductions in total VHT (approximately 21.2%) and increases in system throughput (approximately 6.6%). The simulation results confirm that CARM with queue flush override is the single most impactful strategy for managing recurring congestion, as it directly regulates on-ramp demand to prevent mainline flow breakdown while maximizing corridor throughput. CARM's relatively low annual operations and maintenance cost, approximately 1.4 percent of capital cost, further strengthens its position as the lead strategy.

Queue Warning should be considered the second deployment priority. Under conservative conditions, QW achieves 10-year BCR of 8.7, reflecting its comparatively modest capital investment ($20.0 million) and meaningful safety benefits, including a projected 16 percent reduction in rear-end fatal and injury crashes (CMF = 0.84). QW also provides significant traveler information benefits that complement CARM by alerting drivers to the presence of slow or stopped traffic downstream.

Lane Use Control Signals represent the third priority. LUCS deliver a strong 10-year BCR of 16.4 under conservative assumptions, contributing to both safety improvements (CMF = 0.94 for fatal and injury crashes) and enhanced lane utilization during peak periods. However, LUCS carry the highest capital cost among the strategies ($48.1 million) and the highest annual O&M costs at 3.12 percent of capital cost, which warrants careful phasing relative to available funding.

Variable Speed Limits are recommended as the final phase of deployment. While VSL provides documented safety benefits—an 11 percent reduction in fatal and injury crashes (CMF = 0.89)—its operational performance under conservative assumptions is limited, with simulation results indicating a potential increase in total delay of approximately 4 percent when deployed in isolation. VSL is most effective when combined with CARM, where the joint deployment achieves a balanced improvement in both safety and operations. Accordingly, VSL should be implemented after CARM is operational to allow coordinated speed management and ramp metering policies.

Table 10: Recommended Strategy Deployment Sequence

Priority	Strategy	Capital Cost	10-Yr BCR (Conservative)	Primary Benefit
1	**CARM**	$43.9M	18.8	Mobility
2	**Queue Warning**	$20.0M	8.7	Safety
3	**LUCS**	$48.1M	16.4	Safety / Operations
4	**VSL**	*	<1	Safety / Speed Harmonization

** VSL's incremental cost is included in the QW capital estimate.*

5.2 Criteria for Identifying Suitable Corridors

The managed freeway framework developed in this research is transferable to other NCDOT freeway corridors. Based on the I-40 case study and the state-of-the-practice review, the following criteria should be used to evaluate corridor suitability for managed freeway deployment:

- **Recurring congestion with demand-to-capacity ratios approaching or exceeding 1.0 during peak periods (or demand of about 2,200 pcph /lane).** Corridors experiencing regular flow breakdown and queuing are strong candidates for CARM and VSL, as these strategies directly address capacity utilization and speed harmonization.
- **Elevated crash rates, particularly rear-end and sideswipe collisions.** Corridors with crash frequencies significantly above the statewide average for similar facility types are well-suited for QW and LUCS deployment.
- **Sufficient ramp density and on-ramp demand.** CARM requires multiple closely spaced on-ramps with significant demand to justify the coordination overhead. TheI-40 corridor, with 19 on-ramps along approximately 20 miles, or using a criterion of ≥ one interchange per mile provides a reasonable benchmark.
- **Adequate ramp storage capacity.** Ramp metering effectiveness depends on the availability of sufficient queue storage to prevent spillback onto adjacent arterials. Corridors with short ramp lengths or constrained ramp geometry may require infrastructure modifications prior to CARM deployment.
- **Existing or planned ITS infrastructure.** Corridors with existing detection, communication, and dynamic message sign infrastructure reduce the marginal cost of managed freeway deployment and facilitate faster activation.

5.3 Integration with NCDOT's TMC and ITS Architecture

Successfully managed freeway deployment requires seamless integration with NCDOT's existing Transportation Management Center (TMC) operations and statewide ITS architecture. The experience from Colorado's I-25 CARM system, Virginia's I-66 ATM deployment, and other deployments listed in the literature review demonstrates that centralized, real-time monitoring and control are essential for effective strategy coordination. The following integration considerations are recommended:

The CARM algorithm should operate as a module within the TMC's existing Advanced Traffic Management System (ATMS), receiving real-time detector data (mainline and ramp volumes, speeds, and occupancies) and issuing metering rates to the coordinated ramp signal controllers. The system should support both automatic operation and manual operator override for incident management. Queue flush override logic, which was demonstrated in the microsimulation analysis to be critical for preventing ramp spillback, should be incorporated as an automated safeguard that activates when ramp queue detectors indicate occupancy above a predefined threshold. Similar to control at regular signalized corridors, CARM may operate in "free mode", i.e. local metering during off peak hours.

QW and VSL strategies rely on dynamic message signs and lane control signal gantries that must be connected to the TMC through reliable, high-bandwidth communication networks. Detector spacing of approximately one-half mile is recommended for queue detection accuracy, consistent with findings from the simulation-based queue warning analysis conducted as part of this research. All field devices should be integrated into NCDOT's existing device management and monitoring platform to enable real-time status reporting, fault detection, and maintenance scheduling.

5.4 Guidelines for Data Requirements and System Monitoring

A robust data collection and performance monitoring program is essential for both the initial calibration and ongoing evaluation of the managed freeway system. The following minimum data requirements are recommended for deployment:

- **Mainline detection:** Volume, speed, and occupancy data collected at intervals not exceeding one-half mile, with a data aggregation interval of 20 to 30 seconds to support real-time CARM optimization and queue detection.
- **Ramp detection:** Passage and presence detectors at each metered on-ramp, including advance/upstream queue detectors to support the queue flush override mechanism.
- **Performance measures:** The system should continuously track and report throughput, average speed, travel time, travel time reliability, total delay, and productivity for the managed corridor.
- **Safety monitoring:** Crash data should be collected, categorized and analyzed on an ongoing basis using the Safety Performance Functions and Crash Modification Factors established in this research to support before–after evaluations of each deployed strategy. Observed crash data should be compared against baseline conditions and the predicted values from the SPFs and CMFs to identify outlier conditions and trends and support reliable before–after evaluation.
- **Device health monitoring:** All field devices, including detectors, ramp meters, dynamic message signs, and lane control signal gantries, should be monitored for operational status. A preventive maintenance program with defined response time standards should be established to ensure system reliability.

NCDOT should plan for a phased activation approach, similar to the incremental activation strategy used on Colorado's I-25 CARM corridor, which allowed for an adjustment period for drivers and enabled system tuning. The phased activation should begin with CARM on the highest-demand segments, followed by QW and VSL deployment on segments with identified queuing and safety concerns, and conclude with LUCS installation on gantry-equipped segments. Performance should be assessed at each activation milestone against the measures of effectiveness established in this research—including travel time reliability, productivity, throughput, and crash frequency—to validate benefits and inform any necessary adjustments to algorithm parameters or operational policies prior to full-corridor deployment.

Chapter 6. Implementation Plan

This chapter presents a phased implementation plan for deploying managed freeway strategies across North Carolina. The plan is structured around near-term actions tied to the I-40 corridor projects currently in development, longer-term statewide scaling activities, and the supporting data management, performance tracking, and stakeholder outreach efforts needed to sustain these investments over time.

6.1 Short-Term Actions (Years 3–5)

The immediate priority is to apply the before–after analysis framework and benefit–cost analysis (BCA) tool developed in this study to the two managed freeway projects currently advancing through NCDOT's project development process: I-6001 (I-40 from I-440 to US 64/264) and I-6006 (I-40 from SR 54 to I-440 in the Raleigh-Durham area) – already completed under this research project. For each project, we recommend that NCDOT uses the BCA spreadsheet tool to generate corridor-specific benefit–cost ratios by inputting localized traffic volumes, crash data, and cost estimates. This step will confirm the economic viability of the planned Coordinated Adaptive Ramp Metering (CARM), Variable Speed Limit (VSL), Queue Warning (QW), and Lane Use Control Signal (LUCS) deployments, and will help prioritize phasing if budget constraints require a staged rollout. Concurrently, NCDOT should finalize system architecture requirements, detector placement plans, and communication infrastructure designs so that construction documents align with the operational concepts evaluated in this research.

6.2 Long-Term Actions (Years 5–10)

Following the initial deployments on the I-40 corridor, we recommend that NCDOT pursue statewide scaling by identifying additional candidate corridors through a screening process that considers recurring congestion severity, crash frequency, demand-to-capacity ratios, and the availability of existing ITS infrastructure. The BCA framework and spreadsheet tool are designed to be transferable; analysts can update the input parameters (e.g., AADT, segment lengths, ramp densities, crash rates) to evaluate managed freeway feasibility on other corridors such as I-77 in the Charlotte region or I-85 between Greensboro and Durham. Beyond individual project analysis, NCDOT should integrate managed freeway considerations into its long-range transportation planning and programming processes, including the Strategic Transportation Investments (STI) prioritization framework, so that managed freeway strategies are evaluated alongside traditional capacity improvements during project scoring and funding decisions.

6.3 Data Management and Performance Tracking

Robust data collection and performance monitoring are essential processes needed to validate the projected benefits identified in this study and to support adaptive management of the deployed systems. NCDOT should establish a structured before–after data collection protocol that captures detector-based traffic volumes, speeds, and occupancy at key mainline and ramp locations, as well as probe-based travel time and reliability data, for a minimum of 24 months before system activation and 24 months afterward. Crash data should be compiled on an annual basis to allow empirical Bayes safety evaluations. Performance metrics should align with those used in the microsimulation analysis—including total delay, unmet demand, throughput, vehicle-miles traveled (VMT), and vehicle-hours traveled (VHT)—so that field observations can be compared directly against simulation predictions. The research team recommends that NCDOT house these data sets within the TMC's existing data infrastructure and develop automated dashboards to track system performance over time, flag degradation, and inform periodic recalibration of control algorithms.

6.4 Outreach and Communication

Public awareness and stakeholder engagement will be critical to the success of managed freeway deployments, as driver compliance with ramp metering signals, variable speed limits, and queue warning messages directly influences system effectiveness. NCDOT should develop a communication plan that includes pre-deployment public information campaigns using variable message signs, social media, and local news outlets to educate motorists about the purpose and expected operation of the new systems. Coordination with local municipalities, MPOs, and emergency services is equally important to ensure that signal priority, incident management, and arterial diversion protocols are aligned with freeway operations. Finally, NCDOT should share performance results with peer DOTs and the broader transportation community through FHWA's Active Transportation and Demand Management (ATDM) program and relevant TRB committees, contributing to the growing national knowledge base on managed freeway effectiveness.

Chapter 7. Conclusions and Future Research Needs

7.1 Summary of Key Findings

This study developed and applied a comprehensive before–after analysis framework for evaluating managed freeway strategies on an I-40 corridor in the Raleigh-Durham metropolitan area. The research integrated a state-of-the-practice review, microsimulation modeling, and a benefit–cost analysis (BCA) to assess the potential of Coordinated Adaptive Ramp Metering (CARM), Variable Speed Limits (VSL), Queue Warning Systems (QWS), and Lane Use Control Signals (LUCS) for improving freeway operations, safety, and economic performance. Principal findings of this study are summarized below.

State-of-the-Practice Review. The literature review confirmed that managed freeway implementation remains limited in the United States, with only one pilot deployment of a fully integrated system to date. Nonetheless, individual Active Traffic Management (ATM) strategies—including adaptive ramp metering, dynamic speed limits, queue warning, and dynamic lane use control—have been deployed in various states with documented operational and safety benefits. International experience from agencies such as VicRoads (Australia) and the UK Highways Agency provided valuable design and operational benchmarks that informed the framework developed in this study.

Microsimulation Modeling. A (Year 2022) calibrated VISSIM microsimulation model was developed for a 20.5 mile section of I-40 in the Research Triangle Region. The model was used to evaluate four scenarios under projected 2035 demand conditions. The key operational findings are as follows: (a) CARM delivered the largest operational improvements, reducing total VHT by approximately 21.2%, and increasing total throughput by about 6.6% relative to the 2035 Baseline scenario; (b) the VSL-only scenario provided limited operational benefits and slightly worsened congestion, increasing total delay by approximately 4% consistent with the primary safety-oriented role of VSL in speed harmonization rather than demand management; and (c) the combined VSL + CARM strategy offered a balanced improvement, reducing total delay by approximately 29% , while increasing throughput by roughly 5.3%, representing a promising compromise between operational efficiency and safety. Queue Warning and LUCS were evaluated through comprehensive literature synthesis rather than simulation, as the research team determined that microsimulation modeling of operations is not a prudent evaluation platform for QWS and LUCS given that their primary safety function.

Benefit–Cost Analysis. The BCA framework incorporated mobility benefits (travel time savings), safety benefits (crash reduction using Crash Modification Factors and Safety Performance Functions), and project costs (capital, operations, and maintenance) to estimate scenario-based benefit–cost ratios. When all four strategies are implemented together, the 10-year B/C ratio is estimated at 14.4 under conservative assumptions and 30.0 under favorable assumptions, demonstrating strong economic justification for the managed freeway investment. Among individual strategies, CARM emerged as the most cost-effective under conservative estimates, yielding a 10-year B/C ratio of 18.8, while Queue Warning achieved an estimated B/C ratio of 8.7. VSL does not appear to be an investment priority under conservative assumptions due to its potential to increase travel time, though it remains viable under favorable conditions. The combined capital cost for the managed freeway technologies on the I-40 corridor is estimated at approximately $112 million, with annual operations and maintenance costs of approximately $2.7 million (2.4% of capital cost).

Analysis Tools. The research team developed a spreadsheet-based BCR calculator tool that allows NCDOT practitioners to estimate benefit–cost ratios for the I-40 managed freeway project under various strategy combinations and key parameter assumptions. The tool is designed to be transferable to other managed freeway corridors across North Carolina.

7.2 Study Limitations and Challenges

Several limitations should be considered when interpreting the findings of this study. First, the microsimulation analysis covered only the Eastbound section of the I-40 corridor during the PM peak period (3:00–7:00 PM) under recurring congestion conditions. A simple extrapolation of the mobility benefits to all daytime hours and both directions was carried out. In addition, the model does not explicitly capture non-recurring events such as incidents, adverse weather, or special events, which are known to contribute substantially to freeway congestion and which managed freeway technologies are specifically designed to address. Secondly, the CARM algorithm implemented in the simulation represents one specific capacity-constrained formulation with queue flushing logic; alternative ramp metering algorithms or parameter settings could yield different operational outcomes. Thirdly, the safety and operational benefits for QWS and LUCS were derived entirely from the published literature, as the research team determined that microsimulation modeling of these technologies would not adequately capture their primary safety functions. While the literature-based approach provides a defensible basis for the BCA, the estimated crash reduction benefits are inherently transferred from other jurisdictions and facility types and may not fully reflect North Carolina–specific conditions. Fourth, the BCA relies on projected 2035 demand volumes from the North Carolina Statewide Travel Model (NCSTM), which introduces uncertainty related to future growth assumptions. Finally, the interaction effects between simultaneously deployed technologies (e.g., VSL and CARM operating in parallel) require further investigation, as the combined scenario results suggest that coordination policies may influence overall system performance.

7.3 Recommendations for Future Research

The findings of this study have established a good foundation for continued research and development of managed freeway strategies in North Carolina. The following recommendations are offered as future research needs in this domain.

After-Period Validation. Once the I-40 managed freeway system is deployed, a rigorous after-period evaluation should be conducted using field-collected data to validate the simulation-based and literature-based benefit estimates developed in this study. The before and after analysis framework developed herein provides the structure for this validation. Empirical measurement of travel time savings, crash frequency reductions, and system reliability improvements will be essential for calibrating the BCA tool and informing future deployment decisions.

Coordination of Combined Strategies. The simulation results indicate that the interaction between ramp metering and variable speed limit control influences system performance. Future research should investigate optimal coordination policies between CARM and VSL, including the development of integrated control algorithms that dynamically adjust both ramp metering rates along with speed advisories based on real-time mainline conditions. This research should also explore the effects of technology interactions under incident and mixed-traffic scenarios.

Non-Recurring Congestion and Reliability Analysis. This study focused on recurring congestion under typical weekday conditions. Managed freeway strategies are expected to provide significant benefits during non-recurring events such as incidents and adverse weather. Future research should incorporate stochastic simulation approaches or scenario-based analyses that account for incident management, weather-responsive operations, and travel time reliability improvements to provide a more comprehensive assessment of managed freeway benefits.

Transferability and Statewide Scaling. The developed framework and BCA tool could be applied to other planned NCDOT managed freeway corridors, including the I-6001 and I-6006 projects, to test transferability and refine parameter assumptions. As the managed freeway program expands statewide, research should focus on developing corridor screening criteria, technology selection guidelines, and standardized performance monitoring protocols to support consistent evaluation across projects.

North Carolina–Specific Crash Modification Factors. The CMFs used in this study were derived from deployments in other states. As field data become available from NCDOT’s managed freeway deployments, North Carolina–specific CMFs should be developed through Empirical Bayes or full Bayes before–after safety evaluations. This will improve the accuracy of safety benefit estimates and strengthen the evidence base for future investment decisions.

Energy and Environmental Benefits. While the current BCA focuses on mobility and safety benefits, managed freeway strategies also have the potential to reduce vehicle energy and emissions through smoother traffic flow and reduced stop-and-go conditions. Future research should incorporate fuel use and emission modeling to quantify environmental co-benefits and provide a more holistic economic assessment of managed freeway investments.

Chapter 8. References

Allaby, P., Hellinga, B., Bullock, M. Variable speed limits: Safety and operational impacts of a candidate control strategy for freeway applications. *IEEE Transactions on Intelligent Transportation Systems,* Vol.8, 2007, pp.671–680. https://doi.org/10.1109/TITS.2007.908562

Avelar, R., E.S. Park, S. Ashraf, K. Dixon, M. Li, and B. Dadashova. *Development of Crash Modification Factors for Variable Speed Limits*. Report No. FHWA-HRT-21-053. Federal Highway Administration, Office of Safety Research and Development. McLean, Virginia, 2021.

Bashir, S. *Operation and Safety Performance Assessment of Queue Warning Applications on Signalized Intersections for Connected Freight Vehicles*. M.S. Thesis, University of Wyoming, Laramie, WY, 2020.

CDOT. *Smart 25 Pilot Project: Coordinated Ramp Metering System on I-25 from Ridgegate Parkway to University Boulevard*. Colorado Department of Transportation, Denver, CO. https://www.codot.gov/projects/smart25pilotproject. (Accessed December 14, 2023)

Chakraborty, M., Mahmud, M.S. Evaluation of the Safety Impacts of Regulatory Variable Speed Limits. *ITE Journal*, Vol.94, No.8, 2024, pp.41-46.

Chrysler, S., Fitzpatrick, K., Theiss, L., Fuhs, C. *Application of Dynamic Lane-Use Control: Proposed Practices*. NCHRP Research Report 1021, Transportation Research Board, Washington, D.C., 2022.

Chun, P., Fontaine, M.D. Evaluation of Operational Effects of I-66 Active Traffic Management System. *Transportation Research Record*, Vol.2616(1), 2017, 91-103.

Dutta, N., R. Venkatanarayana, and M.D. Fontaine. *Examining Driver Understanding and Effectiveness of Diagonal Yellow Arrow Lane-use Control Signal Indications*. The 96th Annual Meeting of the Transportation Research Board, Washington, D.C., 2017.

Dutta, N., Fontaine, M.D., Boateng, R.A., Campbell, M. *Evaluation of the impact of the I-66 active traffic management system: Phase II*. Virginia Transportation Research Council Rep. No. VTRC 19-R7, 2018. http://www.virginiadot.org/vtrc/main/online_reports/pdf/19-r7.pdf.

Dutta, N., Boateng, R.A., Fontaine, M.D. Safety and Operational Effects of the Interstate 66 Active Traffic Management System. *Journal of Transportation Engineering, Part A: Systems*, Vol.145(3), 2019, DOI: 10.1061/JTEPBS.0000220.

Elvik, R. and Vaa, T. *Handbook of Road Safety Measures*. Oxford, United Kingdom, Elsevier, (2004)

Farabi, A. Al, Mohebifard, R., Niroumand, R., Hajbabaie, A., Hadi, M., Elefteriadou, L. Integrated corridor management by cooperative traffic signal and ramp metering control. *Computer-Aided Civil and Infrastructure Engineering,* Vol.39, Issue 16, 2024, pp.2439 – 2456, https://doi.org/10.1111/mice.13199

Faulkner, L., Dekker, F., Gyles, D., Papamichail, I., Papageorgiou, M. Evaluation of HERO-coordinated ramp metering installation at M1 and M3 freeways in Queensland, Australia. *Transportation Research Record*, Vol.2470(1), 2014, pp.13-23.

Finley, M., J. Schroeder, K. Fitzpatrick, B. Kuhn, A. Nelson, and K. Turnbull. *Evaluation of International Applications of ATM Lane Control Signing for Use in the United States*. Report FHWA-HOP-13-021. Texas A&M Transportation Institute, College Station, TX, 2013.

Gaffney, J., Hall, M., Burley, M. *Manaegd Motorway Design Guide, Volume 2: Design Practice – Part 2: Network Optimisation Tools*. Vicroads, Victoria, 2019.

Gomes, G., May, A., Horowitz, R., 2004. *A microsimulation model of a congested freeway using VISSIM*. horowitz.me.berkeley.edu 2270, 71–81. https://doi.org/10.3141/1876-08

Hadiuzzaman M., Qiu T.Z., and Lu X.Y. 2013. Variable speed limit control design for relieving congestion caused by active bottlenecks. *Journal of Transportation Engineering*, 139: 358–370.

Hall, M., Frankllin, J., Gaffney, J. *Manaegd Motorway Design Guide, Volume 2: Design Practice – Part 1: Design Principles and Warrants*. Vicroads, Victoria, 2019.

Harmon, T., Bahar, G., Gross, F. *Crash Costs for Highway Safety Analysi*s. Report No. FHWA-SA-17-071, Federal Highway Administration, Washington, D.C., 2018. https://rosap.ntl.bts.gov/view/dot/42858

Hourdos, J. Liu, Z., Dirks, P., Liu, H.X., Huang, S., Sun, W., Xiao, L. *Development of a Queue Warning System Utilizing ATM Infrastructure System Development and Field Testing*. Report No. MN/RC 2017-20, Minnesota Department of Transportation, St. Paul, Minnesota, 2017.

Hsieh, E.Y., Ullman, G.L., Pesti, G., Brydia, R.E. Effectiveness of End-of-Queue Warning Systems and Portable Rumble Strips on Lane Closure Crashes. *Journal of Transportation Engineering, Part A: System*, Vol.143(11), 2017, DOI: 10.1061/JTEPBS.0000084

Khondaker, B., Kattan, L. Variable speed limit: A microscopic analysis in a connected vehicle environment. *Transportation Research Part C*, Vol.58, Part A, 2015, PP.146-159.

Kwon, E., Park, C. *Development of Active Traffic Management Strategies for Minnesota Freeway Corridors*. Report No. MN/RC 2015-26, Minnesota Department of Transportation, St. Paul, MN, 2015.

Ma, J., Li, X., Shladover, S., Rakha, H. A., Lu, X.-Y., Jagannathan, R., & Dailey, D. J. (2016). Freeway Speed Harmonization. *IEEE Transactions on Intelligent Vehicles*, Vol.1(1), pp.78–89. https://doi.org/10.1109/TIV.2016.2551540

Millard, M., and Unwin, P. *Evaluation of the Benefits of Active Traffic Management Schemes Using Microsimlation Programming*. In Proc. European Transport Conference, 2009

MnDOT. *Twin Cities Ramp Meter Evaluation – Final Report*. Minnesota Department of Transportation, 2001. https://rosap.ntl.bts.gov/view/dot/37866/dot_37866_DS1.pdf

Molan, A.M., Pande, A., Harvey, S.M. Before-After Safety Evaluation of Coordinated Ramp Metering System using Empirical Bayes Approach: A Case Study on I-80 in California. *Journal of Transportation Engineering, Part A: Systems*, Vol.149, Issue 11, https://doi.org/10.1061/JTEPBS.TEENG-7226

Mott MacDonald. *ATM Monitoring and Evaluation, 4-Lane Variable Mandatory Speed Limits 12 Month Report (Primary and Secondary Indicators)*. Department for Transport, London, July 2008.

NCDOT. *2024 Standardized Crash Cost Estimates for North Carolina*. North Carolina Department of Transportation, Raleigh, NC, 2024. https://connect.ncdot.gov/resources/safety/Documents/Crash%20Data%20and%20Information/2024%20Crash%20Costs.pdf

NCDOT. *Benefit-Cost Analysis*. Technical Memorandum, North Carolina Department of Transportation, Raleigh, NC, 2025. https://connect.ncdot.gov/resources/BUILD2025-EastSpencer/Documents/Benefit-Cost%20Analysis%20Narrative.pdf

Papageorgiou, M. , Hadj-Salem, H., Blosseville, J.M. ALINEA: A Local Feedback Control Law for On-ramp Metering. *Transportation Research Record*, No.1320, 1991, pp. 58–64.

Papageorgiou, M., Hadj-Salem, H., Middelham, F. ALINEA Local Ramp Metering – Summary of Field Results. *Transportation Research Record*, No.1603, 1997, pp.90-98.

PTV AG, Karlsruhe, G., 2021. PTV VISSIM 2021 User Manual 265–297.

Saleem, T., Srinivasan, R., Vann, M. *Updated and Regional Calibration Factors for Highway Safety Manual Crash Prediction Models (2016-2019)*. Report No. FHWA/NC/2020-27, North Carolina Department of Transportation, Raleigh, NC, 2021.

Sakhare, R.S., Mahlberg, J., Mathew, J.K., et al. *Impacts to Traffic Behaviour from Queue Warning Truck: Current Pilot Project*. Report No. FHWA/IN/JTRP-2022/26, Indiana Department of Transportation, Indianapolis, IN, 2022.

Sheehan, B., Hunt, J., Colyar, J., Jones, G. *ATDM Program Brief: Active Traffic Management*. Publication No. FHWA-HOP-13-003, Federal Highway Administration, Washington, D.C., 2012. https://ops.fhwa.dot.gov/publications/fhwahop13003/fhwahop13003.pdf

Silverstein, C., Asare, S., Gatiba, A., Thompson, K., Ali, A., Wang, P., Achour, M., Davis, A. *Analysis, Modeling, and Simulation (AMS) for Intelligent Transportation Systems (ITS) State of Practice*. Report No. FHWA-JPO-24-130, Federal Highway Administration, Washington, D.C., 2024.

Srinivasan, R., Carter, D. *Development of Safety Performance Functions for North Carolina*. Report No. FHWA/NC/2010-09, North Carolina Department of Transportation, Raleigh, NC, 2010.

TRB, 2022. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. The National Academies Press, Washington, DC. https://doi.org/10.17226/26432

Ullman, G.L., Iragavarapu, V., Brydia, R.E. Safety Effects of Portable End-of-Queue Warning System Deployments at Texas Work Zones. *Transportation Research Record*, No. 2555, 2016, pp. 46–52.

Ullman, G.L., Wiles, P.B. *Operation of Lane Control Signals for Freeway Traffic Management*. Report FHWA/TX-94/1298-2F, Texas Transportation Institute, College Station, TX, 1993.

van Vuren, T., Baker, J., Ogawa, J., et al. Managed Motorways: Modeling and Monitoring Their Effectiveness. *Transportation Research Record*, No.2278, 2012, pp. 85–94.

WSP. *Managed Motorways: Transporting Benefits from Melbourne to Denver*. Available: https://www.wsp.com/en-us/insights/managed-motorways-transporting-benefits-from-melbourne-to-denver (Accessed December 15, 2023)

WSP. *Raleigh-Durham Area Managed Freeways Feasibility Study*. North Carolina Department of Transportation, Raleigh, NC, 2024.

Yang, M., Wang, W., Wang, B., Han, J. Performance of the priority control strategies for bus rapid transit: comparative study from scenario microsimulation using VISSIM. *Discrete Dynamics in Nature and Society*, Hindawi, vol. 2013, pages 1-9. https://doi.org/10.1155/2013/398938

Chapter 9. List of Appendices

9.1 Appendix A: Detailed Literature Review of Managed Freeway Strategies

9.2 Appendix B: Queue Warning and Lane Use Control Literature Synthesis and Modeling Justification

9.3 Appendix C: CARM Control Algorithm and Queue Flush Override Logic

9.4 Appendix D: Benefit-Cost Analysis Methodology and Calculator Documentation

The appendices referenced above contain detailed supporting materials that supplement the findings and recommendations presented herein. In the interest of keeping this report concise, the full contents of these appendices are not reproduced within this volume. Rather, they are provided as a separate companion volume accompanying this report and should be referenced alongside the main report for a complete understanding of the research methodology, analytical frameworks, and technical documentation underlying this study.