RESEARCH & DEVELOPMENT

Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways Final Report

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Abstract:
In response to growing traffic congestion, the North Carolina Department of Transportation will install North Carolina's first ramp meters at four locations in the westbound direction of I-540 in Raleigh. The study outlined in this report addressed this need by developing a state-specific method that can be incorporated into NCDOT planning processes to evaluate any potential ramp metering projects in the future. The related frameworks of analysis were applied to the four westbound I-540 ramp meters to estimate the expected outcomes of the project. The I-540 analysis and frameworks resulting from this study focus on four major steps in the ramp metering process: 1) planning-level data collection, 2) planning-level analysis, 3) life cycle cost analysis, and 4) before-and-after installation evaluation. Ultimately, the research team found that westbound I-540 ramp meters will provide estimated benefits of between $28,234,500 and $73,410,500 over the next ten years. Although such future research is suggested, this study produces a sound foundation for evaluating ramp metering outcomes on which the state can build a ramp metering program that is both sustainable and efficient.

Key Words **Ramp Metering, Life Cycle Cost Analysis, Delay, Safety, Operations, Planning**	Distribution Statement

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Sean Epperson
Kelly Becker
Cheryl Evans
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Without the help of all the above individuals, the project would not be able to be completed in a successful and timely manner.

Executive Summary

In response to growing traffic congestion, the North Carolina Department of Transportation (NCDOT) will install North Carolina's first ramp meters at four locations in the westbound direction of I-540 in Raleigh. Ramp meters have been increasingly used across the United States to mitigate congestion by throttling incoming freeway traffic using an on-ramp signal. An Active Transportation Management (ATM) strategy, ramp metering has been deployed in more than 20 areas across the United States since its introduction in the early 1960s (USDOT, 2013; Zhang and Levison, 2010).

Although ramp metering is a tested and widely used treatment, there is no clear method for incorporating ramp metering strategies into agency planning processes. This is because the cost, service life, operating requirements, and outcomes of treatments in different areas can vary (FHWA, 2006; Fontaine and Miller, 2012). Therefore, a customized evaluation framework is needed to appropriately and accurately estimate the outcomes of ramp meters in North Carolina. The study outlined in this report addresses this need by developing a state-specific method that can be incorporated into NCDOT planning processes to evaluate any potential ramp metering projects in the future. The related frameworks of analysis were applied to the four westbound I-540 ramp meters to estimate the expected outcomes of the project.

The I-540 analysis and evaluation frameworks resulting from this study focus on four major steps in the ramp metering process: 1) planning-level data collection, 2) planning-level analysis, 3) life cycle cost analysis, and 4) before-and-after installation evaluation. Guidance for each of these steps is outlined in this report using I-540 as a case study. Ultimately, the research team found that the proposed westbound I-540 ramp meters will provide estimated benefits of between $28,234,500 and $73,410,500 over the next ten years.

While these results are empirically sound, the research team utilized ranges for the benefits associated with increased safety and decreases in user delay because of the limited information available regarding essential elements of ramp metering performance, including the parameters and algorithms that will be used for the ramp meters. In addition, there is currently a lack of existing data on the actual outcomes of North Carolina-specific ramp meters. As such, it is recommended that a post-installation evaluation of the actual outcomes of the I-540 facility be conducted, and that the methods and the values developed through this study outlined in this report be updated based on these real world findings.

Although such future research is suggested, this study produces a sound foundation for evaluating ramp metering outcomes in which North Carolina on which the state can build a ramp metering program that is both sustainable and efficient.

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1. Introduction

The U.S. Department of Transportation notes that the "need for effective and financially viable freeway management tools is unprecedented" (FHWA, 2014). This trend extends to North Carolina, where freeway congestion is growing, especially during morning and evening peak travel hours. However, both funding and right-of-way access restrict the state's ability to expand the highway system.

In such cases, innovative strategies like ramp metering can be implemented to reduce congestion by optimizing traffic flow, providing numerous benefits such as decreased delay and improved safety. After studying the potential impacts of ramp metering on more than 200 sites of congestion across the Triangle region (Durham, Raleigh, and Chapel Hill), the North Carolina Department of Transportation (NCDOT) has decided to install the state's first ramp meters along westbound I-540, an area experiencing a 3-9% annual increase in traffic during the morning peak period. These first ramps will be metered on the westbound on-ramp terminals of I-540 at Leesville Road, Creedmoor Road, Six Forks Road, and Falls of Neuse Road.

An Active Transportation Management (ATM) strategy, ramp metering throttles vehicles moving onto freeways using on-ramp signals. While the outcomes of ramp metering have been examined since the debut of the strategy, most report findings are not universally transferrable to projects in other regions due to the unique, area-specific impacts of ramp metering (USDOT, 2013; Zhang and Levison, 2010). As a result, the study outlined in this report is aimed at creating a framework to measure the impact of ramp meters in North Carolina and applying this approach to identify the potential impacts of the first four I-540 meters, which the NCDOT plans to install by early 2017. These frameworks can be applied both during planning phases to evaluate outcomes of potential ramp meters and after installation to evaluate actual post-implementation outcomes. Planning-level findings can help decision makers more accurately identify the short and long term outcomes of ramp meters based on measures of performance such as reduction in crashes and vehicle delay, while post-implementation studies can be used to develop optimal strategies for ramp metering in North Carolina.

2. Background

As North Carolina continues to rapidly grow in population, the state is challenged to implement low-cost and timely solutions that address increasing traffic. Mitigating traffic congestion is especially vital in higher-populated regions such as the Triangle area and the Charlotte metropolitan area, where more than two-thirds of the state's population growth is occurring (University of North Carolina, 2015). In preparation, the NCDOT began exploring the option of implementing ramp meters in highly congested areas.

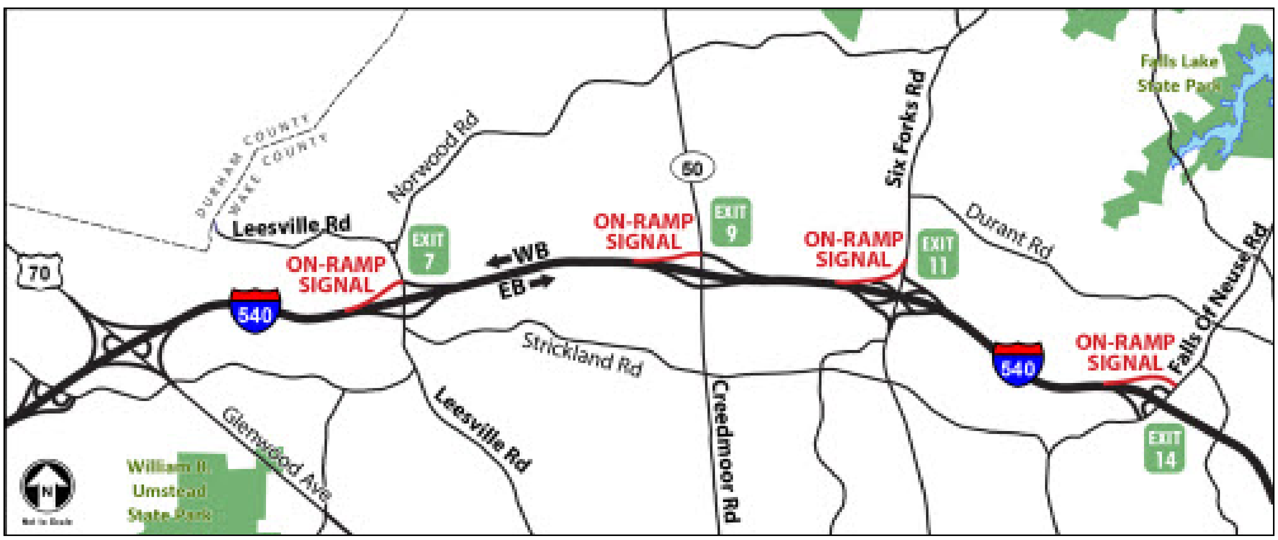
Ramp metering involves applying signal control devices to regulate the number of vehicles entering the freeway to improve traffic operations (FHWA, 2006). Instead of allowing traffic to flow freely from ramps, on-ramp signals meter ramp traffic during levels of high congestion by disrupting platoons of vehicles for smoother merging and increased freeway capacity (FHWA, 2006).

In 2013, the NCDOT in collaboration with Atkins Global, conducted an in-depth study of 208 candidate sites for ramp metering in Durham and Wake Counties, including sections of I-440, I-540, US 1, US 15-501, and NC 147 (Badgett, 2013). Using a four-step review process and a detailed evaluation, a smaller subset of 27 sites were selected for further analysis and were categorized into one of three groups based on their level of congestion, geometry, and proximity to other nearby sites (individual sites, multiple sites, or group sites) (Badgett, 2013). Based on this analysis, four sites along I-540 in the westbound direction were prioritized for North Carolina's first ramp metering installation locations:

- Falls of Neuse Road (Exit 14)
- Six Forks Road (Exit 11)
- Creedmoor Road (Exit 9)
- Leesville Road (Exit 7)

Shown in Exhibit 1, the four ramps will work in tandem as a system that is designed to alleviate congestion along the entire corridor. The NCDOT anticipates that these inaugural ramp meters will be operational in mid-2017, with construction beginning in early 2017.

Exhibit 1 First Four I-540 Westbound Ramp Meter Locations



Source: NCDOT, 2016

These first four sites will serve as a pilot for ramp metering in North Carolina, with the NCDOT evaluating the potential value of applying similar treatments in other parts of the Triangle region as well as the Charlotte metropolitan area. Public acceptance is a vital element of a successful ramp metering program. The experiences of other metropolitan areas show that citizen adoption of ramp meters can be expedited when transportation agencies share transparent educational materials and data about the treatments (WisDOT, 2006). Consequently, it is essential that a sound analysis of the outcomes of the first four North

Carolina treatments be conducted, as this evaluation will influence future state ramp metering plans and related communication with the public.

Although tested and widely used, there is no clear method for incorporating ramp metering strategies into agency planning processes. This is because the cost, service life, operating requirements, and outcomes of treatments in different areas can vary widely (FHWA, 2006; Fontaine and Miller, 2012). Therefore, a customized evaluation framework is needed to appropriately and accurately estimate and assess the outcomes of ramp meters in North Carolina.

2.1. Objectives and Scope

This research project is designed to estimate the outcomes of the first four ramp meters in North Carolina. In addition, because ramp metering outcomes can vary based on site-specific characteristics such as ramp spacing and ramp volumes (Fontaine and Miller, 2012), the research team sought to develop a state-specific method that can be incorporated into NCDOT planning processes to evaluate any potential ramp metering projects in the future. As such, the goals of this project include:

1) Identify appropriate measures for evaluating North Carolina ramp meter performance
2) Collect and analyze pre-implementation data collection related to performance measures for the first four I-540 sites earmarked for ramp metering;
3) Develop a state-specific evaluation methodology that can be used to evaluate future proposed NCDOT ramp metering projects, including a life cycle cost analysis methodology;
4) Conduct a life cycle cost analysis of the I-540 locations to identify the anticipated benefits of the project that can be compared to actual outcomes of the treatments.

Accordingly, this report focuses on four major deliverables:

1) Planning-level data collection method
2) Planning-level analysis method
3) Life cycle cost analysis method
4) Before-and-after evaluation guidance

For the purposes of this study, certain assumptions and decisions were made based on researcher expertise and sound literature:

- **System Coordination:** The first four I-540 sites will operate as a coordinated system of ramp meters instead of as isolated units. Ramp meters can operate as “local” stand alone units or multiple units can work in tandem as a coordinated “system-wide” network of meters. When used appropriately, the latter option can yield the most benefits (Bhargava, 2006; Fontaine and Miller, 2012). This assumption is made due to the nature of the I-540 site and discussions with the NCDOT.
- **Facilities Examined:** The safety and operational impacts of ramp metering were examined on the freeway mainline and ramps. However, similar to other ramp metering studies across the nation, the potential impacts to arterial roads were not evaluated due to the complexity of projecting related outcomes (MDOT, 2015). Furthermore, evaluations of the

impact of metering on adjacent streets in locations such as Denver, Detroit, Los Angeles, and Seattle have shown no significant impact to arterial streets due to diversions from metered freeways (WISDOT, 2006).

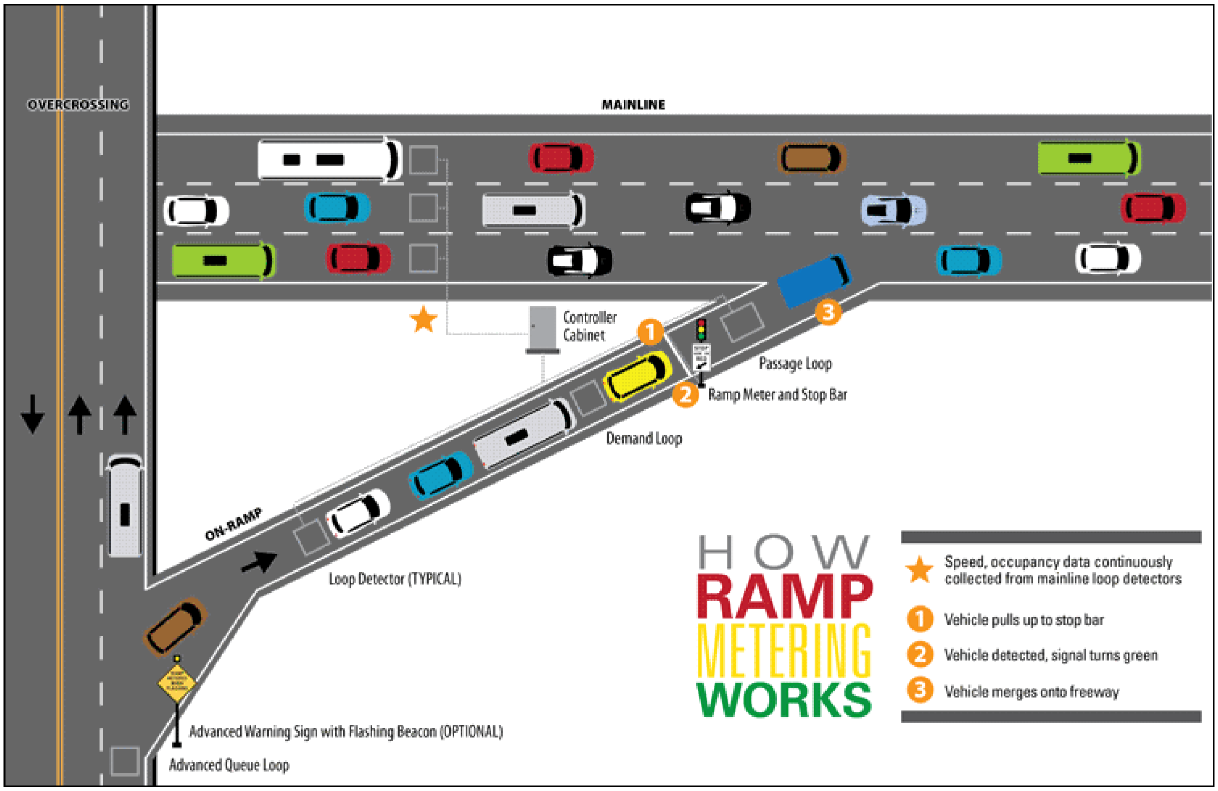
- **Impact Area**: Based on previous national studies and the research team's sensitivity testing for the westbound I-540 meters, data collection and analysis focused on the freeway segments and ramps between mile markers 14 (Falls of Neuse Rd) and 7 (Leesville Rd). These are the start and end points of the facility impact area for the before-and-after outcome analysis. This stretch of the freeway was selected because it contains the recurring queuing.
- **Temporal Boundaries**: Based on historic traffic data, 6 AM to 11AM on weekdays was selected as the timeframe of analysis. This is the most likely period of time that the westbound I-540 ramp meters will be activated frequently on a regular basis. The PM peak direction is eastbound and rarely experience notable congestion issues.

2.2. Ramp Metering Benefits and Evaluation

Since the introduction of ramp metering introduction in the early 1960s, the treatment has been deployed in more than 20 metropolitan areas across the United States to alleviate traffic congestion and to increase freeway capacity through the dynamic management of entrance ramp inflows (USDOT, 2013; Zhang and Levison, 2010; WisDOT, 2006). Ramp meters are designed to improve freeway traffic flows by breaking up platoons of vehicles merging from entrance ramps with the goal of improving roadway mobility and safety (Fontaine and Miller, 2012).

Exhibit 2 provides an example of how a ramp meter operates.

Exhibit 2 How Ramp Meters Work



Source: NCDOT, 2016

Ramp metering is a proactive approach to traffic management that allows transportation agencies to systematically control the traffic flows of freeway facilities and to adjust the parameters of these controls over time as volumes and traffic patterns change. Similar to traditional signalized systems, this treatment requires an investment in a traffic signal, controller, loop detectors, as well as advance warning signs. In recent years, the treatment has become increasingly popular because it can maximize freeway throughput and reduce travel time without the investment of large capital projects such as freeway expansion (Zhang, 2007; Fontaine and Miller, 2012; ADOT, 2013).

As previously referenced, there is not a one-size-fits-all framework for evaluating the outcomes associated with ramp meters. Both the evaluation method and the performance measures used to examine ramp metering outcomes can vary by location because each installation involves unique traffic challenges and facility parameters, such as metering algorithm choice. Systems of evaluation also vary due to differences in the priorities and resources of installing agencies. For example, some regions may prioritize safety outcomes over operational improvements, or may chose not to evaluate emissions outcomes due to the complexity involved (USDOT, 2013; Zhang and Levison, 2010).
Exhibit 3 outlines examples of the performance measures other areas of the U.S. have used to evaluate ramp metering and the quantifiable benefits that have attributed to the treatment.

Exhibit 3 Outcomes of Ramp Metering Across the United States

Are they effective?

The table below shows data from existing ramp meter deployments in other states:

Performance Measure	Location and Result
Travel time	**Atlanta** – 10% decrease in peak period **Houston** – 22% decrease in peak period **Arlington** – 10% decrease in peak period
Travel speed	**Milwaukee** – 35% increase in peak period **Portland** –155% increase in peak period **Detroit** – 8% increase **Los Angeles** – 15 mph increase
Crash rate	**Phoenix** – 16% decrease during metered hours **Milwaukee** – 15% decrease in peak period
Crash frequency	**Portland** – 43% decrease **Sacramento** – 50% decrease **Los Angeles** – 20% decrease
Driver hours saved	**Sacramento** – 50% decrease **Los Angeles** – 8,470 hours per day (# of hours x # of people)
Vehicle volume	**Milwaukee** – 22% increase in peak period **Sacramento** – 5% increase in peak period **Detroit** – 14% increase in volume **Los Angeles** – increase of 900 vehicles per day
Gallons of fuel saved	**Portland** – 700 gallons per weekday
Emissions reduction	**Minneapolis** – 1,160 tons annually
Benefit-Cost ratio	**Atlanta** – benefits were 4 times greater than the cost after 1 year, and 20 times greater after 5 years

Source: NCDOT, 2016

While ramp metering can offer numerous benefits to some roadway users, it can also increase costs to others (Zhang, 2007). For example, while congestion can be alleviated on the freeway, delays on arterial and local roads may increase due to traffic diversions (WisDOT, 2006; Zhang, 2007). Therefore, it is essential that agencies such as NCDOT develop frameworks of assessment that thoroughly evaluate ramp metering projects before and after installation to ensure that performance outcomes are accurately projected.

3. Methodology

As explained earlier, this study is aimed at establishing a method that can be used to evaluate ramp metering projects in North Carolina during the planning and operational phases of any ramp metering project. Therefore, three separate but related methods of analysis were developed, one for each step of the ramp metering evaluation process. These methods, which are described in the following sections, are 1) planning-level evaluation and data collection method, 2) planning-level analysis method, and 3) life cycle cost analysis method. Each of these methodological frameworks includes data currently accessible to the NCDOT and NC-specific parameters, where available and appropriate, with the goal of providing practitioners with robust means to evaluate NC ramp meters.

Throughout the explanations of the methodologies developed through this report, the first four westbound I-540 ramp meters are used as a case study. Following this analysis, guidance on how to transfer the planning methods to a post-implementation before-and-after evaluation is provided. It should be noted that the data available for specific sites may vary from that used for this case study. Therefore, planners may need to adapt their data collection approaches accordingly to fit the data available for a given site.

3.1. Planning-Level Data Collection

Two major measures of effectiveness (MOEs) are selected for analysis of the impacts of ramp meters on travel times. The first MOE is the route travel time, which is the sum of all travel times for segments that make up the route. This measure is calculated for each time period of the day (i.e. 15 minute travel time data results in a route travel time for each 15 minutes of the day). This data is used for the analysis of the average travel time as well as time of day or reliability analysis of travel times. The second MOE is route vehicle hours of delay (VHD), which is the sum of VHD for segments that make up the route. A segment's VHD is the product of the delay and volume for a given time period. This measure is typically totaled to an annual value for a segment or route.

Exhibit 4 shows the average weekday travel time for the study route during the AM period. As mentioned, this analysis can be repeated for a subset of the year, or in a reliability context. It is important to remember that when comparing before and after travel times, they should be for the same time of day. In order to develop VHD for the route, additional work was needed to estimate volumes where no sensors are located as detailed in Appendix 1. Exhibit 5 shows the multipliers for the amount of traffic in each month compared to AADT data, which was used in addition to 5 minute volume estimates to create the volume portion of VHD.

Exhibit 6 shows the distribution of VHD by month and time of day for 2014, with clear spring and fall peaks. The total VHD for the route in 2014 was approximately 569,000 vehicle-hours of delay.

Traffic data available in the Triangle region includes point sensors maintained by HERE, Probe-based travel times and speeds from INRIX and HERE, as well as AADT counted by NCDOT. The probe data is available from INRIX until April 2016, at which point data is only available from HERE. It is important for the analyst to identify sensor and segment locations carefully, as they are defined differently across the data providers. The method presented can be replicated to asses post-implementation outcomes with these data sources, but each of the monthly and time of day profiles must be updated with new data prior to analysis. The analysis must also account for changes in travel time and VHD that are not solely be due to the presence of ramp meters, as the traffic in this region is rapidly growing.

Exhibit 4 Annual Average Weekday Route Travel Times in 2014

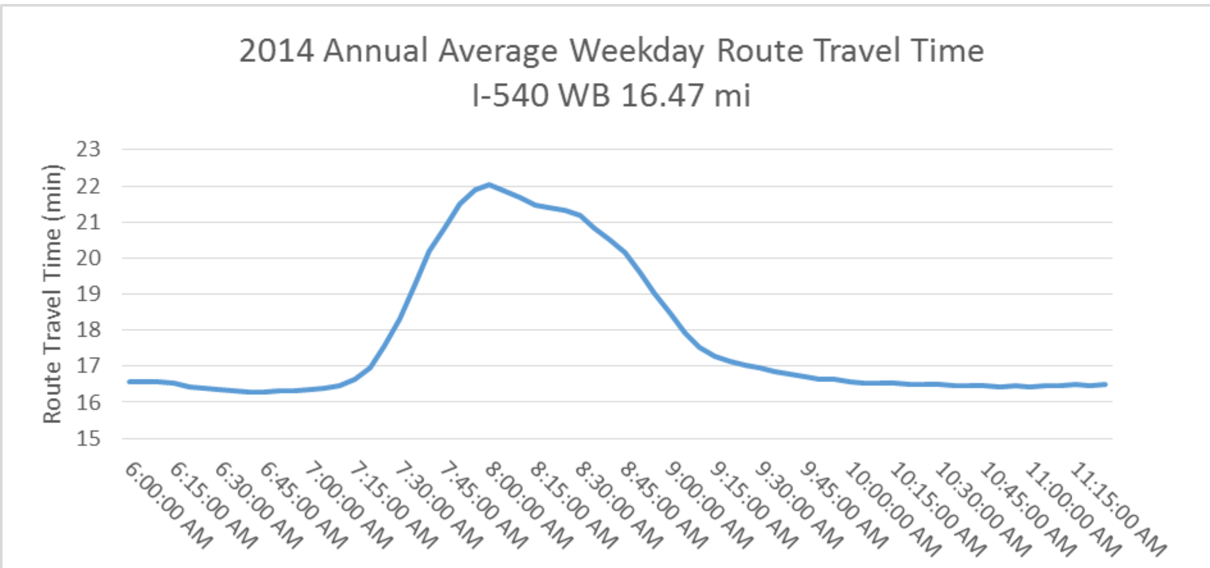
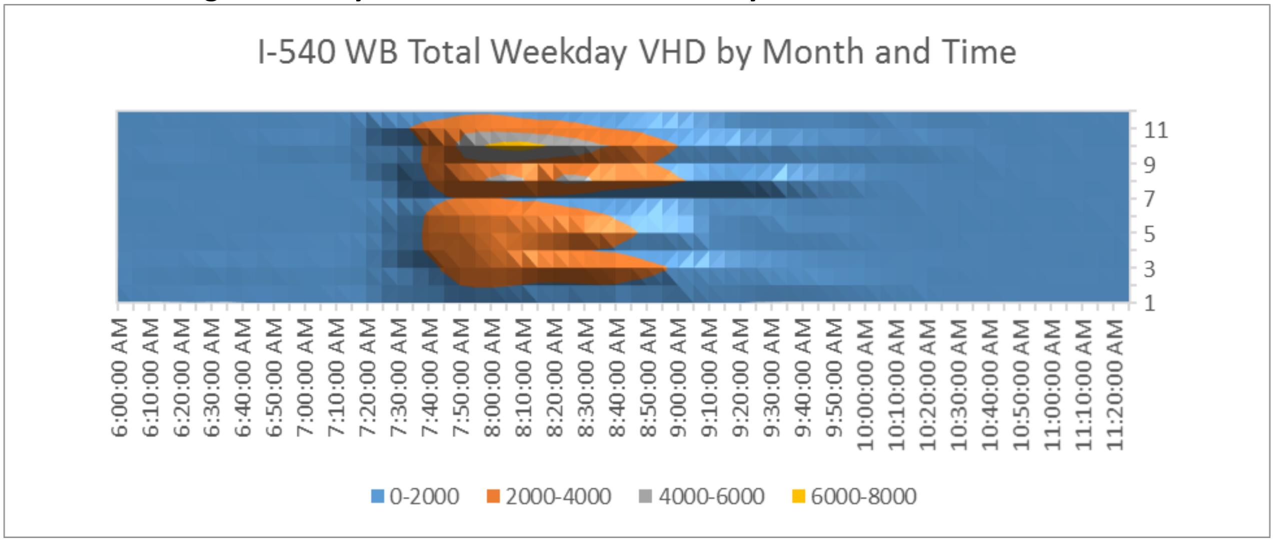


Exhibit 5 Monthly Volume Multipliers for I-540 WB

Month	1	2	3	4	5	6	7	8	9	10	11	12
Seasonal Multiplier	0.903	0.928	0.976	1.024	1.025	1.049	1.006	1.005	1.026	1.0654	1.0233	0.969

Exhibit 6 Average Weekday Route Vehicle Hours of Delay in 2014



3.2. Planning-Level Analysis

The before-and-after analysis methodology developed through this project utilizes methods from the Highway Capacity Manual (HCM) to estimate expected improvements on the operational performance of facilities either 1) *prior to* or 2) *after* ramp meter installation. Estimating the expected operational improvements can feed into benefit costs analysis to help the NCDOT make better-informed decisions regarding ramp meter installations. This section outlines the framework developed by the research team by summarizing the HCM analysis of the four westbound I-540 ramp metering facilities.

It should be noted that procedures employed in this section are from Chapters 10, 11, and 25 of the 6th edition of the HCM (2016). All required input parameters can be collected through different means, including the real world observations outlined in the above planning-level data collection method described in the previous section, which are used to develop and verify a calibrated model of pre-ramp metering conditions. This data is then used to construct the base case, which is referred to as the "before case" throughout this document. The "after case" is developed by applying ramp meters to the appropriate on-ramp facilities using the before case as a baseline. The resulting differences in performance measure outcomes are recorded and compared to identify the impacts of the ramp meters on travel time and system delay.

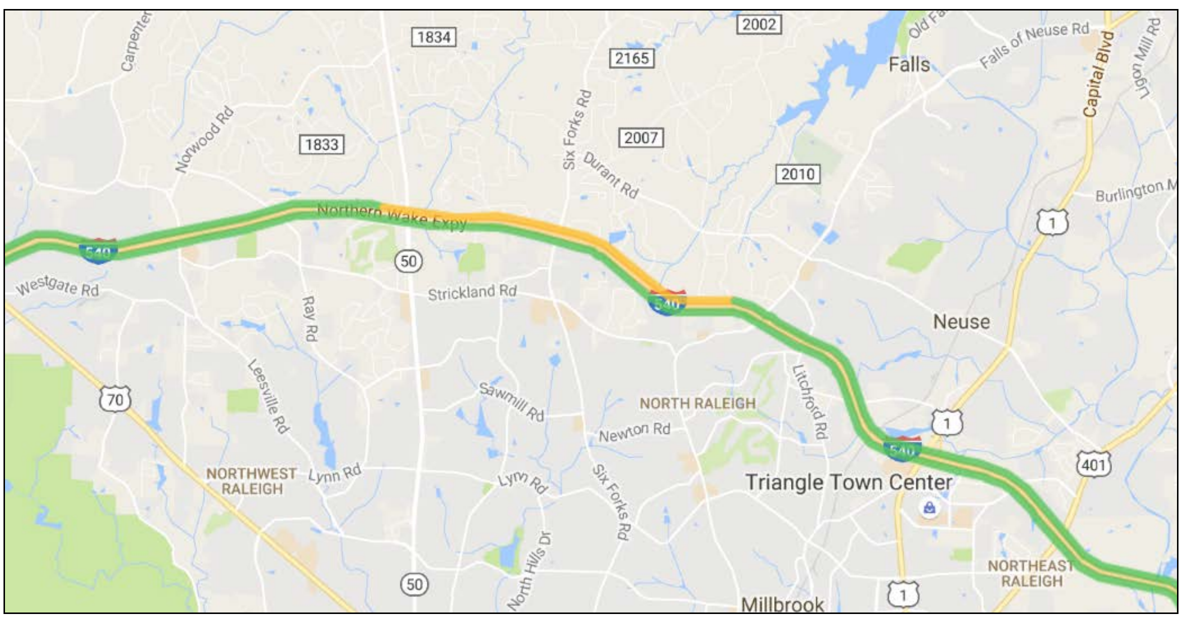
The detailed guidance for this method is in Appendix 2. It should be noted that this section explains the planning-level analysis method by simulating pre- and post-ramp metering performance measure outcomes using FREEVAL, the official computational engine of freeway analysis in Volume IV of the of the HCM, 6th edition. For the purposes of this report, FREEVAL was used to model the I-540 facility because it is capable of performing a wide range of analyses ranging from segment level to facility and reliability analyses (HCM, 2016). However, this method can be executed using any simulation tool that enables a researcher to effectively model and compare the before and after delay results of a ramp metering treatment. The step-by-step instructions for applying this methodology are provided in the following sections.

3.2.1. Selecting Temporal and Spatial Boundaries of the Analysis

The temporal and spatial boundaries used for the planning-level analysis should be carefully considered because they can influence the outputs of the model. For example, the westbound direction of I-540 facility undergoes morning peak travel demand that frequently leads to reoccurring congestion during morning hours. As a result, the research team investigated historic travel times for the area from mile marker 18 (Louisburg Rd) to 2 (Aviation Parkway) to identify typical recurring congestion boundaries for this facility. The research team utilized of INRIX traffic data, INTRIX to collect historic travel times due to the accessibility of the traffic intelligence provider, which the NCDOT provided. The historic travel times for Traffic Message Channels (TMCs), gathered through the planning-level data collection method, were investigated for all weekdays and weekends.

The recurring congestion during the AM peak period during weekdays was observed as being located between mile marker 14 (Falls of Neuse Rd) to 9 (Creedmoor Rd). It should be noted that the congestion boundaries differed for each weekday during the week. Exhibit 7 shows a schematic of the historic congestion boundaries for Wednesdays for the hour that the maximum is achieved. The freeway sections highlighted yellow represent the congested area, which was derived using INRIX definitions.

Exhibit 7 Boundary Congestion on I-540 WB on Wednesdays During the Peak Hour

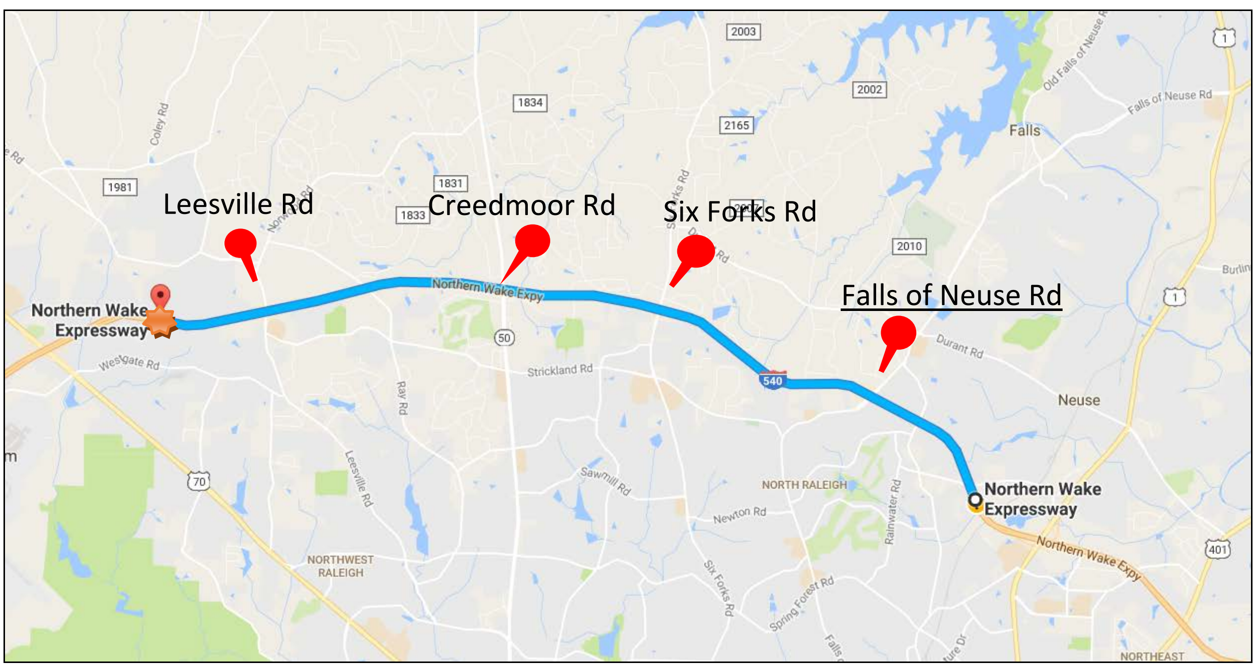


Per recommendations from Chapter 10 of the HCM, 6th edition, the temporal and spatial boundaries of any freeway facilities analysis should be determined based on the entire confines where congestion is most likely to occur (HCM, 2016). Based on this guidance, the starting point of an analysis should not contain any recurring congestion and none of the queues on the analyzed segments should pass the spatial boundaries in the analysis area.

In order to prepare for the travel time reliability analysis described in Chapter 11 of the HCM (2016), the research team selected a larger spatial and temporal domain to ensure that the queuing caused by fluctuations in demand, severe weather events, and incidents remains within the boundary of the recommended analysis area. Accordingly, the research team selected 6 AM to 11AM as the temporal boundary of the analysis. Based on historic traffic data from INRIX, this is the timeframe during which it is anticipated that the ramp meters will be activated due to congestion. Also, mile marker 14 (Falls of Neuse Rd) and 7 (Leesville Rd) were selected as the start and end points of the facility impact area because the traffic data showed this is the area most likely to be influenced by the ramp meters.

System-wide ramp meters read occupancies from sensors within certain vicinities of the ramps to meter traffic. The ramp meters are within this selected area. Exhibit 8 shows the spatial boundary of the westbound I-540 impact area used for the reliability analysis, along with the proposed location for the ramp meters. In the exhibit, red balloons indicated the location of the ramp meters.

Exhibit 8 Selected Spatial Boundary for HCM Analysis on the I-540 WB Facility



3.2.2. Inputting Data and Identifying HCM Parameters

The planning-level method developed through this study applies the core freeway facility analysis method in Chapter 10 of the HCM (2016). This method requires a number of input parameters be used to estimate resulting performance measures, such as travel times and speeds. These inputs consist of geometric data as well as demand flow rates for the mainline and ramps (HCM, 2016).

For the I-540 facility, the research team used Google maps to collect necessary geometric data, including the number of lanes, the length of acceleration and deceleration lanes, and the distance between each on- and off-ramp gore points. Following this process, the research team segmented the facility into 17 smaller segments, based on HCM recommendations. It should be noted that these segments are HCM "segments types" and do not necessarily match the TMC segments used by INRIX or here.com/traffic.com. Exhibit 9 summarizes the details of each segment.

Exhibit 9 HCM Segmentation and Geometric Data for I-540 WB Analysis

Segment #	Description	Segment Type	Segment Length (ft)	# of Lanes: Mainline
1		Basic	7815	3
2	Falls of Neuse Rd OFF-Ramp	Off-Ramp	1500	3
3		Basic	1531	3
4	Falls of Neuse ON-Ramp	On-Ramp	1500	3
5		Basic	7820	3
6	Six forks Rd OFF-Ramp	Off-Ramp	1500	3
7		Basic	2489	3
8	Six Forks Rd ON-Ramp	On-Ramp	2500	3
9		Basic	2534	3
10	Creedmoor Rd OFF-Ramp	Off-Ramp	1500	3
11		Basic	2940	3
12	Creedmoor Rd ON-Ramp	On-Ramp	2000	3
13		Basic	7438	3
14	Leesville Rd OFF-Ramp	Off-Ramp	1500	3
15		Basic	2923	3
16	Leesville Rd ON-Ramp	On-Ramp	2000	3
17		Basic	6340	3

The free flow speed for the facility was estimated to be 75 mph, based on historic traffic data. The on-ramp segments that were selected for ramp metering are 4, 8, 12, and 16, which represent the segments where the on-ramps are located. Appendix 3 shows more geometric details of the segments that have ramps.

The freeway facilities methodology outlined in Chapter 10 of the HCM (2016) requires 15 minute demand flow rates for the mainline and all ramps. Through here.com, NCDOT has access to sidefire radar specified points with in the selected I-540 facility boundary. The sensors used for these data sources report observed speed and volume for each lane. However, this data alone does not provide the sufficient inputs needed for the analysis because the HCM requires a more extensive set of demand data. In other words, sensors can only provide required data for some, but not all, segments within the facility. Other available demand data sources include AADTs for several points on the mainline and ramp segments, and INRIX, which provides the NCDOT with travel times reported for all TMC segments. However, the AADT data is not comprehensive for the facility, and INRIX uses probe-based data sources through which observed volumes are not reported.

As a result of these limitations, the research team carried out a “demand estimation” process to estimate demand flow rates for the mainline and each ramp. For the I-540 facility, the research team started the process by using AADTs along with the default daily distribution of flow rates during the day for the area. The resulting 15 minutes flow rates can be used as model inputs, in this case, for FREEVAL. However, they should not be used before undergoing calibration because the assumption that the default daily demand profile is representative for all entry and exit ramps is not accurate. Thus, the research team used the calibration procedure in Chapter 25 of the HCM (2016) to fine-tune demand volumes for this analysis. Appendix 4 provides the resulting 15 minute demand information for the HCM analysis of the westbound I-540 facility. Similar to the other methods in this report, these demand estimation and calibration processes can be applied in planning-level analyses for future North Carolina ramp meter facilities.

3.2.3. Calibrating “Before Case” Model

After estimating demands and entering the data into FREEVAL or another modeling tool, the uncalibrated HCM model is constructed. FREEVAL, by default, uses nominal HCM segment capacities. As such, the queuing and speed predictions for segments can be inconsistent with field observations. Therefore, the research team used the calibration procedure in Chapter 25 of the HCM to match the performance measures of the uncalibrated FREEVAL model to the observed sensor data for the I-540 facility. By adjusting the demand and capacity for each segment, a calibrated FREEVAL model that shows predictions that are more consistent with the real world can be constructed. Appendix 5 and Appendix 6 show the origin and destination demand adjustment factors for calibrating demands for the westbound I-540 facility.

The demand values generated by the use of AADTs and the default daily demand profile need to be adjusted by the origin and destination demand adjustment factors. For this purpose the origin and destination demand adjustment factors are multiplied to entry and exit demand volumes (e.g. on-ramps and off-ramps) respectively. The resulting adjusted demand volumes for the I-540 facility are presented in Appendix 5 and Appendix 6.

3.2.4. Verifying "Before Case" Conditions

Because it is important to verify the predicted results generated using FREEVAL or another modeling tool in comparison to the observed field data prior to conducting any ramp metering analysis, the speed data from for the I-540 facility was collected from here.com traffic counts (sidefire radars) sensors as well as INRIX probe-based sensors. In absence of access to one of these data sources, the model can still be calibrated based on the other one. In this research, both data sources were used to help ensure that the FREEVAL results most consistently match real world outcomes. The readings from these data sources along with calibrated FREEVAL results are shown in Exhibit 10 and Exhibit 11. The research team observed similar speed predictions by calibrated facility in FREEVAL. Therefore, the before case is assumed to accurately represent real world conditions.

Exhibit 10 Comparison of Predicted FREEVAL Speeds with Sidefire Radar Sensors (from here.com)

		HCM Seg #1	HCM Seg #2	HCM Seg #3	HCM Seg #4	HCM Seg #5	HCM Seg #6	HCM Seg #7	HCM Seg #8	HCM Seg #9	HCM Seg #10	HCM Seg #11	HCM Seg #12	HCM Seg #13	HCM Seg #14	HCM Seg #15	HCM Seg #16	HCM Seg #17
General Purpose Segment Name		N/A	Falls of Neuse Rd OFR	N/A	Falls of Neuse ONR	N/A	Six forks Rd OFR	N/A	Six Forks Rd ONR	N/A	Creedmoor Rd OFR	N/A	Creedmoor Rd ONR	N/A	Leesville Rd OFR	N/A	Leesville Rd ONR	N/A
Analysis Period	#1	75.0	67.8	74.4	68.5	75.0	70.3	74.8	71.3	74.9	67.6	74.8	69.9	75.0	68.2	74.8	70.0	75.0
	#2	71.9	68.7	73.2	66.1	70.1	69.0	72.3	67.7	68.9	68.3	71.5	66.7	69.0	68.6	71.0	66.3	67.8
	#3	72.2	68.4	73.7	65.0	68.8	68.8	71.3	66.8	67.1	67.1	69.9	65.5	66.4	66.4	69.9	66.2	67.1
	#4	69.2	68.5	71.5	63.8	65.3	65.3	68.7	64.3	64.3	64.3	68.1	63.3	63.3	63.3	67.3	62.1	62.1
	#5	69.9	68.0	72.7	64.3	67.0	67.0	71.1	67.1	67.5	67.5	71.5	66.5	68.7	67.9	72.0	66.6	68.7
	#6	68.9	68.2	71.6	63.8	65.5	65.5	69.6	64.9	64.9	64.9	69.7	65.1	65.6	65.6	69.8	65.9	66.6
	#7	61.8	61.8	65.0	58.1	46.0	42.8	28.0	58.1	58.1	62.8	35.4	58.1	58.1	58.1	63.3	58.7	58.7
	#8	62.7	66.3	30.4	36.7	33.6	32.7	26.0	58.2	51.3	40.7	27.6	58.2	58.2	58.2	62.9	57.4	57.4
	#9	53.7	36.8	21.7	47.9	44.1	49.6	28.5	40.1	35.8	35.0	27.5	58.2	58.2	58.2	63.3	58.6	58.6
	#10	47.4	31.0	21.5	37.3	36.6	47.9	30.8	37.3	53.0	61.8	30.0	58.2	58.2	58.2	62.4	56.9	56.9
	#11	66.5	49.9	29.3	62.0	49.8	41.2	27.3	39.0	58.2	71.6	30.5	58.2	58.2	58.2	62.2	58.4	58.4
	#12	67.6	65.1	43.4	54.1	46.1	44.5	28.6	38.9	58.2	73.8	31.4	58.2	58.2	58.2	61.6	57.8	57.8
	#13	73.1	68.6	74.1	66.3	71.9	64.6	60.6	56.3	67.3	67.3	58.7	66.0	66.9	66.9	69.8	66.4	67.4
	#14	73.9	68.8	74.5	67.0	72.4	69.4	73.9	69.1	71.8	68.3	73.6	68.1	72.6	68.5	73.9	68.2	72.3
	#15	73.1	68.8	74.0	66.8	71.6	69.3	73.3	69.0	71.4	68.6	73.0	67.5	71.2	68.8	72.6	67.6	70.8
	#16	74.4	69.0	74.5	67.3	73.0	69.7	74.0	69.5	72.5	68.7	73.7	68.0	72.4	68.6	73.7	68.5	72.7
	#17	74.1	68.9	74.5	67.6	73.4	69.8	74.3	69.7	72.9	68.7	74.0	68.3	73.0	68.9	73.9	68.4	72.7
	#18	74.7	68.8	74.5	67.7	73.9	69.9	74.6	70.2	73.9	68.6	74.6	68.8	74.0	68.6	74.7	69.0	74.0
	#19	75.0	68.6	74.5	68.4	74.9	70.2	74.8	70.8	74.8	68.7	74.8	69.3	74.8	68.7	74.8	69.5	74.8
	#20	74.1	69.0	74.5	67.2	72.8	69.5	74.0	69.6	72.7	68.6	73.9	68.2	72.9	68.6	74.0	68.6	73.1
Here.com Count Sensor ID		23780	23781	No Sensor	No Sensor	23782	23783	No Sensor	No Sensor	23784	No Sensor	No Sensor	No Sensor	23785	23786	No Sensor	No Sensor	23787/23788
Analysis Period	#1	63.2	67.7			66.9	65.4			66.5				65.2	66.4			69.6
	#2	63.2	68.1			67.3	65.4			66.3				65.7	66.1			69.3
	#3	63.4	67.9			67.3	64.6			64.7				65.9	65.5			68.8
	#4	63.6	68.0			67.6	63.5			63.1				66.0	65.1			68.7
	#5	64.1	67.7			66.8	61.2			61.7				65.5	64.6			68.4
	#6	62.6	62.7			59.0	52.2			53.2				62.0	59.6			66.4
	#7	58.6	54.3			51.2	43.6			45.1				59.7	56.8			64.1
	#8	57.7	54.5			49.4	41.5			41.6				58.2	55.2			62.3
	#9	60.9	59.2			51.7	44.5			43.0				58.7	54.9			62.0
	#10	62.7	62.4			54.8	47.9			45.1				58.8	55.5			61.8
	#11	63.7	64.3			58.0	51.9			47.9				60.0	57.1			63.6
	#12	63.3	66.2			62.5	58.4			54.0				62.1	60.9			66.1
	#13	63.1	66.7			65.8	63.9			61.2				64.2	63.7			67.6
	#14	63.0	66.8			67.1	65.5			63.7				64.7	65.1			68.5
	#15	62.9	67.2			67.5	65.9			64.3				65.3	65.6			69.0
	#16	62.6	67.4			67.8	66.0			64.8				65.2	66.1			69.0
	#17	62.0	67.3			67.8	66.1			64.7				65.1	66.0			69.1
	#18	61.6	67.4			68.0	66.1			65.3				65.0	65.9			69.1
	#19	61.7	67.3			68.1	66.2			64.9				65.0	66.0			69.1
	#20	61.6	67.4			68.2	66.0			64.4				65.0	66.0			69.2

Exhibit 11 Comparison of Predicted FREEVAL Speeds with Probe-Based Sensors (from INRIX)

		HCM Seg #1	HCM Seg #2	HCM Seg #3	HCM Seg #4	HCM Seg #5	HCM Seg #6	HCM Seg #7	HCM Seg #8	HCM Seg #9	HCM Seg #10	HCM Seg #11	HCM Seg #12	HCM Seg #13	HCM Seg #14	HCM Seg #15	HCM Seg #16	HCM Seg #17
General Purpose Segment Name		N/A	Falls of Neuse Rd OFR	N/A	Falls of Neuse ONR	N/A	Six forks Rd OFR	N/A	Six Forks Rd ONR	N/A	Creedmoor Rd OFR	N/A	Creedmoor Rd ONR	N/A	Leesville Rd OFR	N/A	Leesville Rd ONR	N/A
Analysis Period	#1	75.0	67.8	74.4	68.5	75.0	70.3	74.8	71.3	74.9	67.6	74.8	69.9	75.0	68.2	74.8	70.0	75.0
	#2	71.9	68.7	73.2	66.1	70.1	69.0	72.3	67.7	68.9	68.3	71.5	66.7	69.0	68.6	71.0	66.3	67.8
	#3	72.2	68.4	73.7	65.0	68.8	68.8	71.3	66.8	67.1	67.1	69.9	65.5	66.4	66.4	69.9	66.2	67.1
	#4	69.2	68.5	71.5	63.8	65.3	65.3	68.7	64.3	64.3	64.3	68.1	63.3	63.3	63.3	67.3	62.1	62.1
	#5	69.9	68.0	72.7	64.3	67.0	67.0	71.1	67.1	67.5	67.5	71.5	66.5	68.7	67.9	72.0	66.6	68.7
	#6	68.9	68.2	71.6	63.8	65.5	65.5	69.6	64.9	64.9	64.9	69.7	65.1	65.6	65.6	69.8	65.9	66.6
	#7	61.8	61.8	65.0	58.1	46.0	42.8	28.0	58.1	58.1	62.8	35.4	58.1	58.1	58.1	63.3	58.7	58.7
	#8	62.7	66.3	30.4	36.7	33.6	32.7	26.0	58.2	51.3	40.7	27.6	58.2	58.2	58.2	62.9	57.4	57.4
	#9	53.7	36.8	21.7	47.9	44.1	49.6	28.5	40.1	35.8	35.0	27.5	58.2	58.2	58.2	63.3	58.6	58.6
	#10	47.4	31.0	21.5	37.3	36.6	47.9	30.8	37.3	53.0	61.8	30.0	58.2	58.2	58.2	62.4	56.9	56.9
	#11	66.5	49.9	29.3	62.0	49.8	41.2	27.3	39.0	58.2	71.6	30.5	58.2	58.2	58.2	62.2	58.4	58.4
	#12	67.6	65.1	43.4	54.1	46.1	44.5	28.6	38.9	58.2	73.8	31.4	58.2	58.2	58.2	61.6	57.8	57.8
	#13	73.1	68.6	74.1	66.3	71.9	64.6	60.6	56.3	67.3	67.3	58.7	66.0	66.9	66.9	69.8	66.4	67.4
	#14	73.9	68.8	74.5	67.0	72.4	69.4	73.9	69.1	71.8	68.3	73.6	68.1	72.6	68.5	73.9	68.2	72.3
	#15	73.1	68.8	74.0	66.8	71.6	69.3	73.3	69.0	71.4	68.6	73.0	67.5	71.2	68.8	72.6	67.6	70.8
	#16	74.4	69.0	74.5	67.3	73.0	69.7	74.0	69.5	72.5	68.7	73.7	68.0	72.4	68.6	73.7	68.5	72.7
	#17	74.1	68.9	74.5	67.6	73.4	69.8	74.3	69.7	72.9	68.7	74.0	68.3	73.0	68.9	73.9	68.4	72.7
	#18	74.7	68.8	74.5	67.7	73.9	69.9	74.6	70.2	73.9	68.6	74.6	68.8	74.0	68.6	74.7	69.0	74.0
	#19	75.0	68.6	74.5	68.4	74.9	70.2	74.8	70.8	74.8	68.7	74.8	69.3	74.8	68.7	74.8	69.5	74.8
	#20	74.1	69.0	74.5	67.2	72.8	69.5	74.0	69.6	72.7	68.6	73.9	68.2	72.9	68.6	74.0	68.6	73.1

INRIX Probe Sensor ID		125-05082	125N05082	125-05081	125N05081	125-05080	125N05080	125-05079	125N05079	125-04899
Analysis Period	#1	69.8	70.1	70.7	70.7	71.5	71.2	70.6	70.9	70.9
	#2	70.4	70.9	71.2	71.2	71.7	71.4	70.8	71.2	71.1
	#3	70.7	71.4	71.5	71.5	72.0	71.7	70.8	71.1	71.5
	#4	70.4	71.1	71.2	71.0	71.4	71.0	70.6	71.4	71.9
	#5	69.9	70.2	70.7	70.3	70.8	70.3	70.0	70.8	71.5
	#6	67.4	64.6	65.7	65.8	66.7	66.3	66.9	68.6	70.1
	#7	60.9	49.9	53.1	53.0	54.4	54.4	60.4	65.4	68.4
	#8	55.1	43.2	45.9	43.7	45.6	45.9	56.0	62.0	67.3
	#9	58.3	47.1	47.0	43.0	43.4	43.9	54.5	60.1	66.7
	#10	62.4	53.4	51.1	46.5	46.6	46.5	55.0	59.7	66.6
	#11	64.8	58.1	55.3	50.4	49.7	48.4	55.7	60.1	66.7
	#12	66.6	62.6	60.0	54.9	54.3	53.4	59.2	64.1	68.3
	#13	68.1	66.5	65.8	62.6	62.5	62.0	64.8	68.0	69.7
	#14	68.6	68.9	69.0	67.5	68.0	68.0	68.1	69.9	70.5
	#15	68.4	69.1	69.8	68.7	69.5	69.5	69.2	70.6	71.0
	#16	68.8	69.1	70.0	69.2	70.0	70.3	69.9	71.1	71.1
	#17	69.0	69.4	70.3	69.4	70.3	70.6	70.2	71.3	71.1
	#18	69.1	69.4	70.3	69.4	70.5	70.6	70.3	71.3	71.2
	#19	69.0	69.5	70.7	69.8	70.8	71.0	70.3	71.2	71.2
	#20	68.9	69.3	70.5	69.8	70.9	70.8	70.5	71.3	71.4

3.2.5. Modeling Conditions with Ramp Metering

One of the most vital aspects of ramp metering implementation is algorithm selection (Bhargava, 2006). The algorithm applied to a ramp meter determines signal operation periods, acceptable ramp queue storage lengths, ramp coordination in in a system of meters, and more (Zhang, 2007; Bhargava, 2006). Because it is still unclear which algorithm will be used for the I-540 facility, and for the state as a whole, the research team did not have access to algorithm parameters calibrated specifically for North Carolina. Therefore, the algorithm used in this framework was assumed. When available, the actual algorithm selected for a facility should be used for future planning-level analyses, as doing so will significantly increase the accuracy of projected outcomes. It should be noted that the 2014 Atkins study approached the facility as a local system, and the algorithm used for that study is not known (Badgett, 2014).

The research team used findings from previous ITRE research projects involving the implementation of traffic responsive ramp meters in the HCM context to inform this portion of the developed method, including a project funded by STRIDE entitled as "Dynamic Traffic Control Interventions for Enhanced Mobility," which focused on modeling ALINEA and Fuzzy Logic ramp metering algorithms. Ultimately, the research team applied a system-wide Fuzzy Logic algorithm that is calibrated for I-95 northbound corridor in Miami, FL. This was the only available calibrated system-wide ramp metering algorithm in FREEVAL, and is used at multiple ramp meter locations across the country.

This system-wide choice of Fuzzy Logic assumes that the four I-540 ramp meters will operate in coordination instead of as isolated units. It is important to note that because the Fuzzy Logic ramp metering algorithm is calibrated for the Miami facility, the parameters used in the model applied to the I-540 analysis are not tuned for the specific conditions of that facility. Consequently, actual delay outcomes for the I-540 facility may be different than the outcomes estimated for I-540, and therefore the actual benefits may be lower or higher than those reported through this study.

Once the Fuzzy Logic ramp metering algorithm was incorporated, the after case model was complete. It should be noted that both the before and after cases represent a typical day of westbound I-540 facility operations. As such, no incidents or severe weather events are modeled in this step of the method. In the next section, the findings of HCM analysis with non-recurring sources of congestion such as incidents and severe weather conditions are modeled.

In the case of the I-540 facility, the research team found that the travel time on the mainline decreases from 10.66 minutes to 10.44 minutes, *on average,* on non-incident days. This 13.2 second decrease is due to the implementation of ramp meters, and is accompanied by a slight decrease in vehicle hours of delay (VHD) for the mainline and on-ramps. The VHD decreased from 968 hours to 966 hours. Although this change may seem small, it does not directly account for the safety impacts incurred through the use of ramp meters. The reliability analysis, discussed in the next section, accounts for increased reliability of the facility by including considerations for safety and incidents.

Exhibit 12 shows the speed contours of the FREEVAL results for both the before and the after cases. The slight improvement resulting due to the ramp meters is seen in the slight shift in congestion towards the downstream region. In other words, congestion migrates downstream due to the metering effect at each of the ramps.

Exhibit 12 Speed Contours of HCM Analysis on I-540 WB Facility for Before and After Cases

Before Case

Analysis Period	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	Seg. 12	Seg. 13	Seg. 14	Seg. 15	Seg. 16	Seg. 17
6:00 - 6:15	75.0	67.8	74.4	68.5	75.0	70.3	74.8	71.3	74.9	67.6	74.8	69.9	75.0	68.2	74.8	70.0	75.0
6:15 - 6:30	71.9	68.7	73.2	66.1	70.1	69.0	72.3	67.7	68.9	68.3	71.5	66.7	69.0	68.6	71.0	66.3	67.8
6:30 - 6:45	72.2	68.4	73.7	65.0	68.8	68.8	71.3	66.8	67.1	67.1	69.9	65.5	66.4	66.4	69.9	66.2	67.1
6:45 - 7:00	69.2	68.5	71.5	63.8	65.3	65.3	68.7	64.3	64.3	64.3	68.1	63.3	63.3	63.3	67.3	62.1	62.1
7:00 - 7:15	69.9	68.0	72.7	64.3	67.0	67.0	71.1	67.1	67.5	67.5	71.5	66.5	68.7	67.9	72.0	66.6	68.7
7:15 - 7:30	68.9	68.2	71.6	63.8	65.5	65.5	69.6	64.9	64.9	64.9	69.7	65.1	65.6	65.6	69.8	65.9	66.6
7:30 - 7:45	61.8	61.8	65.0	58.1	46.0	42.8	28.0	58.1	58.1	62.8	35.4	58.1	58.1	58.1	63.3	58.7	58.7
7:45 - 8:00	62.7	66.3	30.4	36.7	33.6	32.7	26.0	58.2	51.3	40.7	27.6	58.2	58.2	58.2	62.9	57.4	57.4
8:00 - 8:15	53.7	36.8	21.7	47.9	44.1	49.6	28.5	40.1	35.8	35.0	27.5	58.2	58.2	58.2	63.3	58.6	58.6
8:15 - 8:30	47.4	31.0	21.5	37.3	36.6	47.9	30.8	37.3	53.0	61.8	30.0	58.2	58.2	58.2	62.4	56.9	56.9
8:30 - 8:45	66.5	49.9	29.3	62.0	49.8	41.2	27.3	39.0	58.2	71.6	30.5	58.2	58.2	58.2	62.2	58.4	58.4
8:45 - 9:00	67.6	65.1	43.4	54.1	46.1	44.5	28.6	38.9	58.2	73.8	31.4	58.2	58.2	58.2	61.6	57.8	57.8
9:00 - 9:15	73.1	68.6	74.1	66.3	71.9	64.6	60.6	56.3	67.3	67.3	58.7	66.0	66.9	66.9	69.8	66.4	67.4
9:15 - 9:30	73.9	68.8	74.5	67.0	72.4	69.4	73.9	69.1	71.8	68.3	73.6	68.1	72.6	68.5	73.9	68.2	72.3
9:30 - 9:45	73.1	68.8	74.0	66.8	71.6	69.3	73.3	69.0	71.4	68.6	73.0	67.5	71.2	68.8	72.6	67.6	70.8
9:45 - 10:00	74.4	69.0	74.5	67.3	73.0	69.7	74.0	69.5	72.5	68.7	73.7	68.0	72.4	68.6	73.7	68.5	72.7
10:00 - 10:15	74.1	68.9	74.5	67.6	73.4	69.8	74.3	69.7	72.9	68.7	74.0	68.3	73.0	68.9	73.9	68.4	72.7
10:15 - 10:30	74.7	68.8	74.5	67.7	73.9	69.9	74.6	70.2	73.9	68.6	74.6	68.8	74.0	68.6	74.7	69.0	74.0
10:30 - 10:45	75.0	68.6	74.5	68.4	74.9	70.2	74.8	70.8	74.8	68.7	74.8	69.3	74.8	68.7	74.8	69.5	74.8
10:45 - 11:00	74.1	69.0	74.5	67.2	72.8	69.5	74.0	69.6	72.7	68.6	73.9	68.2	72.9	68.6	74.0	68.6	73.1

After Case

Analysis Period	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	Seg. 12	Seg. 13	Seg. 14	Seg. 15	Seg. 16	Seg. 17
6:00 - 6:15	75.0	67.8	74.4	68.5	75.0	70.3	74.8	71.3	74.9	67.6	74.8	69.9	75.0	68.2	74.8	70.0	75.0
6:15 - 6:30	71.9	68.7	73.2	66.1	70.1	69.0	72.3	67.7	68.9	68.3	71.5	66.7	69.0	68.6	71.0	66.3	67.8
6:30 - 6:45	72.2	68.4	73.7	65.0	68.8	68.8	71.3	66.8	67.1	67.1	69.9	65.5	66.4	66.4	69.9	66.2	67.1
6:45 - 7:00	69.2	68.5	71.5	63.8	65.3	65.3	68.7	65.5	64.3	64.3	68.1	63.9	63.3	63.3	67.3	63.5	62.1
7:00 - 7:15	69.9	68.0	72.7	64.3	67.0	67.0	71.1	67.1	67.5	67.5	71.5	66.5	68.7	67.9	72.0	66.6	68.7
7:15 - 7:30	68.9	68.2	71.6	63.8	65.5	65.5	69.6	65.7	64.9	64.9	69.7	65.1	65.6	65.6	69.8	65.9	66.6
7:30 - 7:45	61.8	61.8	61.6	48.8	58.1	58.1	49.1	39.1	58.1	58.1	43.8	38.2	58.1	58.1	63.3	61.6	58.7
7:45 - 8:00	62.7	62.7	33.6	35.8	52.6	60.0	30.4	36.5	58.2	56.1	29.8	36.5	58.2	58.2	62.9	60.5	57.4
8:00 - 8:15	66.0	60.5	36.0	42.5	39.1	52.6	39.6	39.1	46.1	39.2	27.6	36.3	58.2	58.2	63.3	61.5	58.6
8:15 - 8:30	45.5	38.4	22.5	38.2	36.8	49.2	33.1	33.8	48.8	56.5	45.6	36.4	58.2	58.2	62.4	60.0	56.9
8:30 - 8:45	65.0	53.6	30.3	57.8	47.8	45.1	27.5	36.4	58.2	58.2	51.4	36.4	58.2	58.2	62.2	61.3	58.4
8:45 - 9:00	67.6	67.6	69.8	60.0	49.3	46.1	28.2	36.4	58.2	58.2	55.5	36.4	58.2	58.2	61.6	60.9	57.8
9:00 - 9:15	73.1	68.6	74.1	65.5	69.9	69.0	72.0	61.8	67.2	67.2	74.8	59.8	67.2	67.2	70.1	66.5	67.7
9:15 - 9:30	73.9	68.8	74.5	66.9	72.3	69.3	73.8	69.1	71.7	68.3	73.5	68.1	72.4	68.5	73.8	68.2	72.2
9:30 - 9:45	73.1	68.8	74.0	66.8	71.6	69.3	73.3	69.0	71.4	68.6	73.0	67.5	71.2	68.8	72.6	67.6	70.8
9:45 -10:00	74.4	69.0	74.5	67.3	73.0	69.7	74.0	69.5	72.5	68.7	73.7	68.0	72.4	68.6	73.7	68.5	72.7
10:00 - 10:15	74.1	68.9	74.5	67.6	73.4	69.8	74.3	69.7	72.9	68.7	74.0	68.3	73.0	68.9	73.9	68.4	72.7
10:15 - 10:30	74.7	68.8	74.5	67.7	73.9	69.9	74.6	70.2	73.9	68.6	74.6	68.8	74.0	68.6	74.7	69.0	74.0
10:30 - 10:45	75.0	68.6	74.5	68.4	74.9	70.2	74.8	70.8	74.8	68.7	74.8	69.3	74.8	68.7	74.8	69.5	74.8
10:45 - 11:00	74.1	69.0	74.5	67.2	72.8	69.5	74.0	69.6	72.7	68.6	73.9	68.2	72.9	68.6	74.0	68.6	73.1

Along with the speed contours, Exhibit 13 shows the queuing and congestion contours of the I-540 HCM analysis for both before and after cases.

Exhibit 13 Congestion (Queuing) Contour of I-540 WB Facility for Before and After Cases

Before Case

Analysis Period	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	Seg. 12	Seg. 13	Seg. 14	Seg. 15	Seg. 16	Seg. 17
6:00 - 6:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6:15 - 6:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6:30 - 6:45	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6:45 - 7:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7:00 - 7:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7:15 - 7:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7:30 - 7:45	0%	0%	0%	9%	100%	100%	100%	0%	0%	6%	100%	0%	0%	0%	0%	0%	0%
7:45 - 8:00	0%	23%	100%	100%	100%	100%	100%	0%	79%	100%	100%	0%	0%	0%	0%	0%	0%
8:00 - 8:15	0%	0%	66%	80%	50%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%
8:15 - 8:30	21%	100%	100%	0%	80%	0%	94%	100%	0%	0%	90%	0%	0%	0%	0%	0%	0%
8:30 - 8:45	0%	0%	0%	0%	58%	100%	100%	100%	0%	13%	100%	0%	0%	0%	0%	0%	0%
8:45 - 9:00	0%	0%	0%	0%	20%	100%	100%	100%	0%	0%	82%	0%	0%	0%	0%	0%	0%
9:00 - 9:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9:15 - 9:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9:30 - 9:45	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9:45 -10:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:00 - 10:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:15 - 10:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:30 - 10:45	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:45 - 11:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

After Case

Analysis Period	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	Seg. 12	Seg. 13	Seg. 14	Seg. 15	Seg. 16	Seg. 17
6:00 - 6:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6:15 - 6:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6:30 - 6:45	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6:45 - 7:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7:00 - 7:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7:15 - 7:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7:30 - 7:45	0%	0%	31%	100%	0%	0%	49%	100%	0%	0%	68%	100%	0%	0%	0%	0%	0%
7:45 - 8:00	0%	0%	35%	100%	22%	40%	100%	100%	0%	97%	100%	100%	0%	0%	0%	0%	0%
8:00 - 8:15	0%	0%	5%	100%	100%	0%	36%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%
8:15 - 8:30	11%	0%	91%	94%	100%	0%	76%	100%	0%	0%	21%	100%	0%	0%	0%	0%	0%
8:30 - 8:45	0%	0%	0%	0%	75%	100%	100%	100%	0%	0%	36%	100%	0%	0%	0%	0%	0%
8:45 - 9:00	0%	0%	0%	0%	0%	0%	99%	100%	0%	0%	12%	100%	0%	0%	0%	0%	0%
9:00 - 9:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9:15 - 9:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9:30 - 9:45	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9:45 -10:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:00 - 10:15	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:15 - 10:30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:30 - 10:45	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10:45 - 11:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

The operation of the facility during the 15 minute analysis periods was also investigated. Exhibit 14 and Exhibit 15 show the vehicle hours of delay (VHD) and average travel time for each 15 minute analysis period for the I-540 facility. During the peak period, from 7:30am to 8:30am, there are improvements in travel time (shown as VHD) with ramp metering, but this improvement has a slight negative impact on delays on the on-ramps. This is because the VHD is slightly lower in both the before and after cases. As a result of ramp metering, during the 9am analysis period higher delay can be seen due to vehicles that are stored on the on-ramps.

Exhibit 14 Vehicles Hours of Delay for 15 Minute Analysis Periods With & Without Ramp Metering

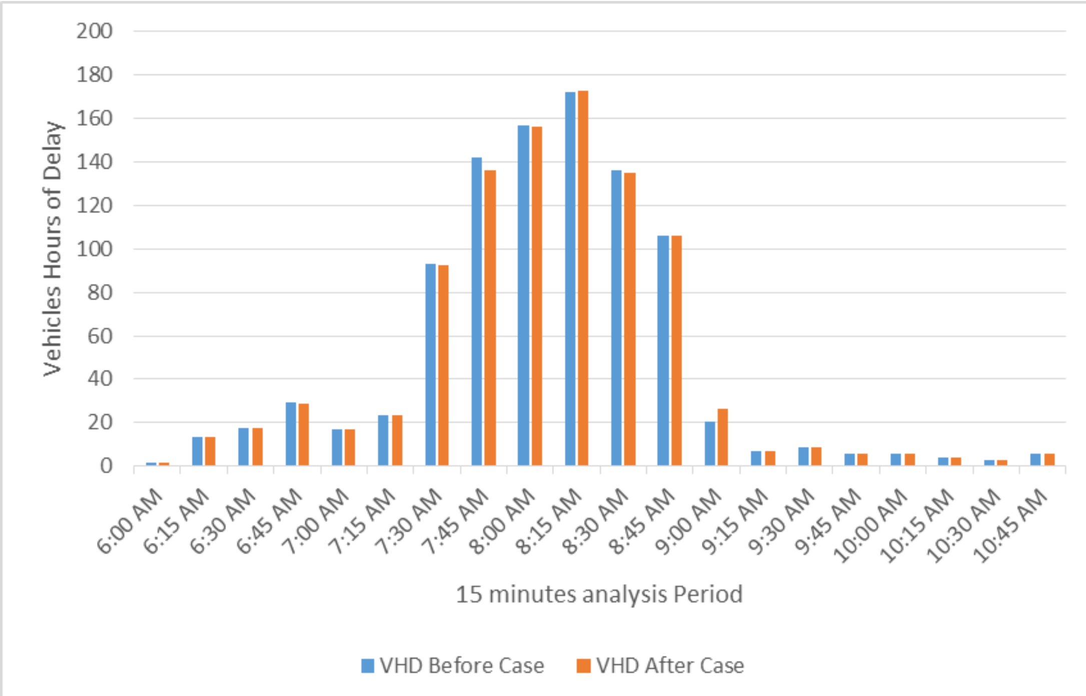
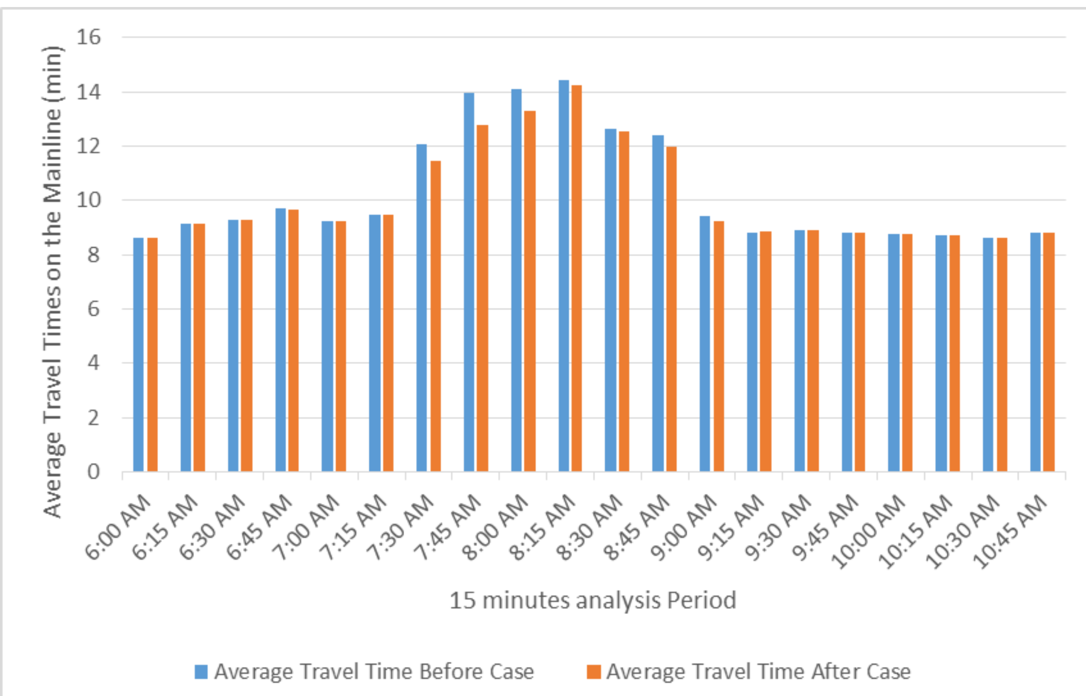


Exhibit 15 Average Travel Time on the Mainline With & Without Ramp Metering



3.2.6. Analyzing the Impacts of Ramp Metering (Reliability)

For the I-540 facility, an analysis of a typical day after ramp meter installation based on Chapter 10 of the HCM (2016) showed a slight improvement to operational performance measures. This process was conducted by turning the traffic responsive ramp meters on for the entire study period for all on-ramps in the analysis. Additionally, ramp meters in general can have considerable impact on safety, which can result in less incidents and congestion. The occurrence of incidents on a freeway, such as weather-related disruptions and vehicle crashes, are random both in terms of location and time. Therefore, to more accurately model the impact of incidents the research team employed a reliability scenario generation procedure, as documented in Chapter 25 of the HCM (2016).

The reliability scenarios include incidents that have been distributed on the facility consistent with vehicle miles traveled (VMT). One of the inputs of the reliability analysis is the crash rate, because studies have shown that this variable can improve after ramp meter installation. For the I-540 analysis, a crash rate of 165 crashes per 100 million VMT, the rate for I-40 in 2010, was assumed. The default values recommended by HCM were used for all of the other inputs required for the reliability scenario generation.

Ramp metering can result in a decrease in crashes stemming from congested conditions, which can in turn result in further congestion alleviation (Liu and Wang, 2013). Therefore, a percent reduction in crashes was built into the model as well. Because the impact of the ramp meters on crashes along the I-540 facility area is highly uncertain, the research team evaluated the outcomes of several different crash reduction scenarios to look at the sensitivity of the findings over a range of different potential improvements in safety. These improvements are expressed in terms of Crash Reduction Factors (CRFs), which are similar to Crash Modification Factors (CMFs). CRFs express the percent reduction that would be anticipated given a specific treatment, in this case ramp metering (FHWA, 2014; FHWA, 2016). The scenarios tested by the research team included reductions of 5% to 15%, explained further in the Life Cycle Cost Analysis section of this report.

The underlying data used to estimate demand outcomes is from 2014. However, this research project was developed to estimate the impact of ramp metering for a longer time horizon, 10 years into the future. Therefore, based on historic traffic growth trends within the facility area, the research team applied an annual traffic growth factor of 3% to realistically increase demands for the next 10 years. Appendix 8 shows the expected vehicle hours of delay (VHD) for years 2017 to 2026 for different CRFs.

The scenario generation procedure in the HCM incorporates a hybrid approach to model recurring and non-recurring sources of congestion. For modeling incidents, the HCM method uses a stochastic approach where incidents location and start time is determined randomly (HCM, 2016). This same approach should be applied to planning-level analyses for future ramp metering projects. The variations observed in Appendix 8 are due to this randomness.

It is important to note that the parameters of the ramp metering algorithm used in this analysis are *not* calibrated for this facility. More importantly, the logic of the algorithm is assumed to be Fuzzy, which may produce outcomes different than that of the actual ramp meters because the true algorithm for the facility is currently unknown. As a result, inaccurate predictions are inherently present. Consequently, the research team has developed a series of confidence intervals for predicted vehicles hours of delay. These are explained further in the next section.

3.3. Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCCA), also called Cost Benefit Analysis (CBA), is a method used to evaluate projects by monetizing estimated outcomes using a common monetary unit like the dollar (NCHRP Report 483, 2003; United States Office of Management and Budget, 1992). Monetizing is the process of applying a monetary value to non-monetary variables like decreases in driver travel times. The LCCA method is widely used in many fields, including transportation, because it enables agencies to compare the long-term costs and benefits of project and policy options. Such information helps decisionmakers identify the option that will provide the greatest return on investment for residents (United States Office of Management and Budget, 1992; Swiss, 2002).

The LCCA methodology accounts for the assumption that money today will be worth less in the future because of the potential for investment (Jawad, and Ozbay, 2005). As a result, LCCAs incorporate a "discount" rate, which operates similar to inflation. The rate, typically between 3% and 10%, is applied to monetized costs and benefits to adjust for the changing value of money over time (Litman and Doherty, 2009). Each cost and benefit is multiplied by an anticipated rate of change, selected based on the literature, which compounds annually over the timeframe of analysis (United States Office of Management and Budget, 2015), as shown in Equation 1.

Equation 1 Discounting

$$PV = \frac{AB_{y_f}}{(1+r)^{y_f - y_i}}$$

where:

PV = present value
AB (or AC) = annual benefit (or annual cost)
r = the discount rate
y_f = the final year in which the benefit or cost occurs
y_i = the initial year of analysis

In accordance with the standards released in 2016 by the United States Office of Management and Budget, this study uses a 3% discount rate for LCCA calculations. (United States Office of

Management and Budget, 2016). This value is also within the 3-5% standard recommended by the FHWA (FHWA, 2004).

The LCCA method developed through this study monetizes three categories of variables associated with ramp metering treatments: 1) facility installation, maintenance and operations, and replacement; 2) safety; and 3) user delay. Monetizing each of these involves unique inputs, standard values, and adjustments for changes in these values overtime. All of the monetary values in this study were converted to 2015 dollars for consistency. The guidance for the LCCA method outlined is in Appendix 7.

The research team conducted extensive research to identify the most appropriate values for monetizing the costs and benefits calculated. The LCCA method established through this report was specifically developed to evaluate North Carolina ramp metering projects. This method incorporates federal and state standards, as well as findings from peer-reviewed research, practitioner studies, and other reputable sources.

3.3.1. Installation, Maintenance and Operations, and Replacement

For the purposes of this study, installation costs are the capital funds needed to install a ramp meter infrastructure for the first time. Installation costs are typically considered to be a one-time expenditure that occurs only at the time period prior to the project completion. Most LCCA literature refers to the installation period of a project as "Year 0." This is because the additional costs and benefits associated with the project do not typically begin to accumulate until a facility is completed (Swiss, 2002). Therefore, a discount rate is not applied to initial construction costs and only costs and benefits that begin after "Year 0" will be discounted (MDOT, 2015; Swiss, 2002).

For example, because it is anticipated that each of the first four I-540 ramp meters will be installed by early 2017, 2016 will be used as "Year 0" in the LCCA outlined in this report. Additionally, because it is assumed that the facility will be operational by mid-2017, the analysis period for the LCCA for this facility begins in July 2017. Therefore, throughout this report, 2017 is the year that discounting will begin in the calculations. **Note that due to the timing of the installations, the "year" for each analysis period will run from July 1 of the given year through June 30 of the next**. For example, year 2017 in the analysis will actually be for the period July 1, 2017 to June 30, 2018.

Alternatively, maintenance costs are typically discounted and are considered to accumulate annually (MDOT, 2015). Maintenance costs include the annual and incremental operations and upkeep costs needed to keep a facility operational, as well as the cost of revising an intersection at the end of its anticipated service life.

Due to a lack of sound national data for the average annual costs for maintaining and operating ramp meters the research team opted to apply cost estimates for the I-540 facility developed through the Atkins report (Badgett, 2014). Atkins estimated that each ramp meter would require an annual investment of $7,491, which includes maintenance, operations, and annual software support (Badgett, 2014). For all four ramp meters, this is a total of $29,964, as shown in Exhibit 16. Future applications of the LCCA analysis developed through this report should instead use values based on NC-specific maintenance and operating costs, once available.

Exhibit 16 Maintenance and Operations Costs Estimated by Atkins

Location	Ramp Meter Configuration	Annual Costs O&M
Leesville Road	Two-lane	$ 7,491
Creedmoor Road	Two-lane	$ 7,491
Six Forks Road	Two-lane	$ 7,491
Falls of the Neuse Road	Two-lane	$ 7,491
Total		**$ 29,964**

Source: Badgett, 2014

Similarly, with capital investment costs for existing ramp meters across the nation ranging from $10,000 to nearly $170,000 (USDOT, 2016), the research team lacked the sound data needed to estimate installation costs. Therefore data from the 2014 Atkins study was again applied, with the total capital cost of installing all four westbound I-540 ramp meters estimated to be $830,170. The breakdown of this cost shown in Exhibit 17. Once available, more accurate NC-specific estimates should be used for future LCCAs.

Exhibit 17 Individual Ramp Meter Capital Costs Determined by Atkins

Location	Ramp Meter Configuration	Roadway Improvement	Capital Cost
Leesville Road	Two-lane	Extend two-lane ramp 130' with 720' merge taper	$ 238,240
Creedmoor Road	Two-lane	Extend two-lane ramp 125' with 720' merge taper	$ 214,364
Six Forks Road	Two-lane	None	$ 135,632
Falls of the Neuse Road	Two-lane	Extend two-lane ramp 315' with 720' merge taper	$ 241,934
Total			**$ 830,170**

Source: Badgett, 2014

It should be noted that in the absence of reliable data, the research team reached out to other transportation professionals in the country to obtain estimates for each of these variables. However, these efforts did not provide additional data.

In addition, a one-time programming cost will also be required in "Year 0" of the project. For a given region such as the Triangle, this cost will only be incurred once. Atkins estimates this cost to be $405,000, as shown in Exhibit 18.

Exhibit 18 One-Time Programming Cost Estimated by Atkins

Description	Cost
Central Software	
Software and Installation	$135,000
Driver and Installation	$95,000
Integration	$110,000
Training	$20,000
Servers (2)	$20,000
Misc. Central Communications Hardware	$25,000
Total	**$405,000**

Source: Badgett, 2014

Another consideration in LCCAs for capital investments like ramp meters is the service life, or the period during which a given facility will perform effectively before requiring significant repairs or replacement. The research team applied a service life of 10 years in the LCCA methodology because this is the standard service life used by the NCDOT for traditional signals, which involve infrastructure and hardware similar to that of ramp meters. Similar to installation costs, the research team lacked replacement cost estimations. As a result, the suggested timeframe of analysis for ramp metering pre-planning evaluations is 10 years. The total expected costs for installation, programming, maintenance and operations, and facility replacement of the I-540 facility ramp meters, is shown in Exhibit 19. The total anticipated cost is $1,490,749.

Exhibit 19 Total Installation, Programming, Operations, Maintenance, and Facility Replacement Cost for 2016-2026

Cost	Year 0 (2016)	Total Value Projected for Years 2017-26*
Installation (total for 4 ramp meters)	$830,170	
Programming (one-time investment)	$405,000	
Operations and Maintenance ($7,491 annually for each ramp meter)		$255,579
Facility Replacement**		$0
Total Cost for Years 2016-26		***$1,490,749***

*These projections are discounted into the future

**It is not expected that the facility will need to be replaced until after 10 years

3.3.2. Safety

One valuable benefit of ramp metering is improved safety outcomes. Transportation researchers often use as method called Crash Reduction Factors (CRFs) to estimate how a given treatment will reduce roadway collisions. CRFs express the percentage of crashes that are expected to decrease with the implementation of a given countermeasure (FHWA, 2014). CRFs are the inverse of Crash Modification Factors, which are multiplicative factors that are used to calculate the number of crashes that are projected to occur after a specific countermeasure is implemented (FHWA, 2016). Both CRFs and CMFs can be applied to existing crash frequency data as a ratio of change expected to occur with the installation of a countermeasure (HSM, 2010). Because outcomes stemming from this LCCA method will likely be shared with the public, the research team opted to use CRFs instead of CMFs because this former method is more readily understood.

Due to the limited literature on the safety impacts of ramp metering, there are minimal sound CRFs available. Consequently, the FHWA's CMF Clearinghouse (FHWA, 2016), the most reputable repository of CRFs and CMFs in the country, only includes one CRF for ramp metering treatments: a value of 36% from a study conducted by Liu and Wang (2013) which was conducted solely on freeways in northern California. Although empirically sound, this value was deemed as too high for inclusion in this methodology because other studies conducted across the country show that crash reduction benefits most often range from 5% to 37% (Lee, Hellinga, and Ozbayc, 2006). In addition, the Liu and Wang (2013) study examines only periods of ramp meter activation for actual ramp meter outcomes, while this method is designed to estimate crash reduction outcomes for the entire potential ramp metering period because the actual times of activation will be unknown until after installation.

Consequently, for the westbound I-540 the outcomes associated with two different CMFs were investigated: 5%, an extremely conservative estimate, and 15%, which aligns with the most common outcomes seen across studies conducted in other parts of the nation, as shown in Exhibit 3. As a result, the actual crash reduction outcomes on the westbound I-540 facility may be lower or higher than the projections developed using the CMF from this study.

This method uses crash data for the temporal and spatial parameters selected as part of the planning-level analysis to monetize ramp metering benefits. Benefits associated with crash reductions are then monetized by multiplying the proportional reduction in crashes by the crash costs that would be anticipated to occur on average each year in the absence of the given ramp meters. NCDOT annual KABCO costs, which break down costs based on injury by severity, are used to estimate the benefits of increased safety expected to result from the ramp meters.

Exhibit 20 includes descriptions of KABCO severity categories.

Exhibit 20 NCDOT Crash Severity Type Categories

Crash Severity Types	
Category	**Description**
K (fatal)	Death occurred within twelve months of the crash
A (disabling)	Injuries serious enough to prevent normal activity for at least one day such as massive loss of blood, broken bones, etc.
B (evident)	Non-fatal or A injuries are evident at the scene such as bruises, swelling, limping, etc.
C (possible)	No visible injury but there are complaints of pain or momentary unconsciousness
O (property damage only)	Pain or momentary unconsciousness

Source: NCDOT, 2013

In alignment with the practices NCDOT uses, the crash costs are monetized using the combined crash categories and associated tiers of costs: 1) K + A injuries, 2) B + C injuries, and 3) PDO injuries, as shown in Exhibit 21.

Exhibit 21 Crash Costs by Severity Type

NCDOT Safety Costs (one per crash)	
K & A Injury Types:	$ 4,544,000
B & C Injury Types:	$ 134,000
Property Damage Only:	$ 6,700

Source: NCDOT, 2014

For the analysis of the I-540 facility, five years (April 2011 to March 2016) of crash data was collected for the areas within the temporal and spatial parameters selected. Only data for crashes occurring on the mainline, entrance ramp, and the ramp terminal areas was selected for monetization. Crashes involving animals and other anomalies were removed. This data was organized by crash type. No crashes involving fatalities were present and the majority of the crashes in the dataset were at the C and PDO level. Each crash was then multiplied by the appropriate KABCO cost value, the appropriate CRFs were applied, and the value of the resulting value for each 12-month period were summed to identify the annual corresponding benefits for each year-long period. These annual benefits were then averaged and this value was discounted 10 years into the future and summed to produce the expected benefits of safety outcomes associated with the I-540 ramp metering facility.

The result of this analysis for CRFs of 5% and 15% are shown in Exhibit 22 and Exhibit 23, respectively. After 10 years, it is expected that a crash reduction of 5% due to ramp metering will produce benefits of $1,389,956, which a reduction of 15% is estimated to produce $4,169,867 in benefits.

Exhibit 22 Crash Reduction Benefits Expected Due to Ramp Metering on I-540 WB (5% CRF Applied)

Year	Actual Cost	Cost After 5% CRF Applied	Projected Crash Reduction Benefits
2011	$2,030,100	$1,928,595	$101,505
2012	$1,467,300	$1,393,935	$73,365
2013	$6,922,500	$6,576,375	$346,125
2014	$2,077,000	$1,973,150	$103,850
2015	$3,798,900	$3,608,955	$189,945
Average Value of Crashes Per Year	*$3,259,160*	*$3,096,202*	*$162,958*
Total Value Projected for Years 2017-26*	***$27,799,113***	***$21,655,509***	***$1,389,956***

*These projections are discounted into the future

Exhibit 23 Crash Reduction Benefits Expected Due to Ramp Metering on I-540 WB (15% CRF Applied)

Year	Actual Cost	Cost After 15% CRF Applied	Projected Crash Reduction Benefits
2011	$2,030,100	$1,725,585	$304,515
2012	$1,467,300	$1,247,205	$220,095
2013	$6,922,500	$5,884,125	$1,038,375
2014	$2,077,000	$1,765,450	$311,550
2015	$3,798,900	$3,229,065	$569,835
Average Value of Crashes Per Year	*$3,259,160*	*$2,770,286*	*$488,874*
Total Value Projected for Years 2017-26*	***$27,799,113***	***$19,375,982***	***$4,169,867***

*These projections are discounted into the future

Also, while these crashes were monetized using an average annual value with the assumption that the overall number of crashes will remain consistent, in reality, the number of crashes could naturally increase over time with increased volumes.

3.3.3. User Delay

One of the major benefits of ramp metering is an improvement in overall roadway user delay due to decreased congestion (USDOT, 2013; Zhang and Levison, 2010; WisDOT, 2006). It is therefore appropriate to monetize these outcomes because delays related to congestion can come at a high price for roadway users (VDOT, 2013). These costs can be attributed to time lost waiting in traffic, increased vehicle wear and tear, fuel lost due to idling, and other factors. The LCCA framework developed through this study specifically examines the costs associated with the value of the time of vehicle users.

This analysis is accomplished using the delay estimations produced by method described in the previous section. Delay costs are calculated by subtracting the estimated “after” ramp metering delay outcomes from the “before” outcomes, therefore monetizing reductions in delay as a benefit. It should be noted that delay calculations in this methodology are solely focused on vehicle demand and do not account for pedestrian or bike usage.

The benefit of decreased delay is monetized by applying the standard value of travel time released by the Texas A&M Transportation Institute, which estimates the value of an hour of time for passenger and heavy vehicles (Schrank, Eisele, Lomax, and Bak, 2015). These figures are shown in Exhibit 24.

Exhibit 24. Defaults for Value of User Travel Time

Value of User Travel Time Per Hour Per Person	
Passenger Vehicle	$ 17.67
Heavy Vehicle	$ 94.04

NCDOT ArcGIS volume data can be used to identify the percent of heavy vehicles expected for a facility. Within the LCCA method, this value is used to weight the value of user travel time proportionally. For example, based on volume data for the westbound I-540 facility, the research team decided to apply a heavy vehicle percentage of 5%. As a result, 5% vehicle hour delays are valued at $94.04 and the remaining 95% are valued at $17.67, for an average of $21.49 per user.

Because it cannot be assumed that only one person is occupying each vehicle at an intersection, this cost is multiplied by 1.25, the standard number of persons per vehicle developed by the Texas A&M Transportation Institute (Schrank, Eisele, Lomax, and Bak, 2015). This value is widely used by other researchers across the country to develop the cost per hour per vehicle, which this report refers to as vehicle hours of delay (VHD).

Typically, an LCCA model of this kind would incorporate an annual traffic volume growth factor (VGF) to adjust projections for future delay times. These percentage increases in delay stemming from the increases in volume compounding over time would be used in LCCA calculations as shown in the equation in

Equation 2 below.

Equation 2 **Volume Growth**

$$Volume\ Growth = (T_2/T_1)^{1/(Y2-Y1)}$$

where:

T1 = traffic flow in year Y1
T2 = traffic demand in year Y2
With the annual traffic growth compounding

Source: FHWA

However, for analysis outlined in this report, a VGF is not applied as part of the LCCA methodology because VGF is an input in FREEVAL, which is used as part of the planning-level analysis method. The same is true for most simulation tools that may be used in place of FREEVAL in future ramp metering evaluations. Calculating VGF as part of both methods would result in double-counting because delay projections developed in the planning-level analysis method are monetized in the LCCA method. It should be noted that several years of NCDOT ArcGIS volume data showed and average annual VGF of 3% for the westbound I-540 facility.

Per the pre-planning method, ranges were established for the delay outcomes and benefits associated with the I-540 facility, as shown in the below section. This is the result of two factors: 1) the actual outcomes of ramp metering may vary widely from the projections in this report because the reliability model employed accounted for the randomness of incidents on the facility by simulating multiple scenarios to produce annual VHD outcomes which will be monetized; and 2) because the actual reduction in crashes, and therefore reduction in congestion stemming from crashes due to ramp metering along the I-540 facility area is highly uncertain, the outcomes of crash reduction scenarios for CRFs of 5% and 15% were investigated.

To assess the impacts of different crash reductions on congestion, the VHD for each scenario was captured and an average incorporating the probability of each scenario was calculated using the new HCM (2016) reliability methodology, in which the probability of reliability scenarios are equal. The resulting average day VHD was then used to compute annual VHD by multiplication of weekdays in a year.

The annual breakdown of these expected benefits or costs of delays resulting from ramp meters on the I-540 facility are shown in Exhibit 25. The 10 year (2017-2026) monetized values of these delays are shown in Exhibit 26. Over the ten year period, benefits range from $28,335,293 to $70,731,406. Negative VHDs and monetized values indicate and increase in delays due to ramp metering, while positive numbers indicate a reduction. This variance overtime is due to the reliability method described earlier, which modeled multiple incident scenarios that can lead to congestion levels higher than that of a typical, non-incident day.

Exhibit 25 Expected Average VHD Per Day Considering Different Reductions in Crashes

		Crash Reduction Factors (CRFs)	
	Year	**5%**	**15%**
Net Vehicle Hours of Delay Benefits*	**2017**	749.65	1073.51
	2018	680.38	1167.81
	2019	-12.79	1360.15
	2020	1249.62	1885.60
	2021	-265.41	620.18
	2022	1042.98	1658.56
	2023	610.04	942.25
	2024	-410.52	1223.31
	2025	529.77	1301.94
	2026	493.40	552.24

* Note: positive values indicate a benefit, negative values indicate a cost

Exhibit 26 Value of Net Delay Reduction Benefits for Years 2017-26

		Expected Congestion Reduction Due to Reduced Crashes	
	Year	**5%**	**15%**
Net Delay Reduction Benefits*	**2017**	$5,083,238	$7,279,268
	2018	$4,479,196	$7,688,088
	2019	-$81,722	$8,693,525
	2020	$7,754,416	$11,700,904
	2021	-$1,599,018	$3,736,374
	2022	$6,100,610	$9,701,267
	2023	$3,464,320	$5,350,869
	2024	-$2,263,386	$6,744,653
	2025	$2,835,762	$6,969,075
	2026	$2,561,877	$2,867,383
	Total value of reduction in delay due to RM for 2017-2026**	***$28,335,293***	***$70,731,406***

*Positive values indicate a benefit, negative values indicate a cost

**These projections are discounted into the future

Exhibit 27 shows the standard deviation and confidence intervals for daily delay resulting due to the two CRF values, including the monetized value of the benefit for each outcome.

Exhibit 27 Average of Net Delay Benefits by CRF Value Per Weekday for 2017-26

Crash Reduction Factor (CRF) Value Applied		5%		15%	
Average Net VHD Reduction Benefits*		466.7		1178.6	
Standard Deviation of Net VHD Reduction Benefits*		540.7		415.2	
Variation*		Min	Max	Min	Max
80% Confidence Interval	VHD	-225.41	1,158.84	647.09	1,710.02
	Value**	($6,055)	$31,129	$17,382	$45,935
90% Confidence Interval	VHD	-420.07	1,353.50	497.62	1,859.49
	Value**	($11,284)	$36,358	$13,367	$49,951
95% Confidence Interval	VHD	-593.11	1,526.53	364.75	1,992.36
	Value**	($15,932)	$41,006	$9,798	$53,520

*Positive values indicate a benefit, negative values indicate a cost
**These values are not discounted into the future

Due to the reliability method, the standard deviation is quite large, ranging from 415.2 (CRF= 15%) to 540.7 (CRF = 5%). For this reason, the research team advises that the range in the value of delay benefits over ten years be reported, as shown in Exhibit 26: $28,335,293 to $70,731,406.

3.3.4. *Total Benefits*

Ultimately, as shown in Exhibit 28, the total benefits expected to accumulate over ten years for the westbound I-540 ramp meters is estimated to be between $28,234,500 and $73,410,500. It should be noted that 2016 is reported in the below table as well because it is considered the installation year, "Year 0," with benefits accumulating from 2017 to 2026.

Exhibit 28 Total Benefits Ramp Metering Benefits for I-540 WB Over 10 Years (2016-26)

	Expected Percent of Reduced Crashes (CRF)	
Benefit/Cost Type	**5%**	**15%**
Installation Cost	$830,170	$830,170
Programming Cost	$405,000	$405,000
Operations and Maintenance Costs	$255,579	$255,579
Facility Replacement Cost*	$0	$0
Crash Reduction Benefits*	$1,389,956	$4,169,867
User Delay Benefits*	$28,335,293	$70,731,406
Benefits of Ramp Meters Over 10 Years*	***$28,234,500***	***$73,410,524***

*These projections are discounted into the future

3.4. Before-and-After Evaluation

After the ramp meters are installed, each of the planning-level methods outlined in the earlier sections: 1) planning-level data collection, 2) planning-level analysis, and 3) life cycle cost analysis, can be applied to evaluate actual ramp metering outcomes. The guidance for applying these methods as part of a before-and-after evaluation is in Appendix 9.

For the first method, after data can be collected in the same manner as that outlined for before data. If desired, a physical data collection method such as the collection of count data can be incorporated. The same tenants of the second method can be applied to gain insight into the true outcomes of the ramp meters, and to adjust projections accordingly for future analyses. In this case, actual post-installation delay data can be compared to the before case developed through the method. In addition, the LCCA can be easily applied by using actual installation, maintenance and operations, and replacement; safety; and user delay costs to examine the monetized benefits of the true performance of the ramp meters.

4. Conclusion and Recommendations

This research outlined in this report was focused on estimating the outcomes of the first four ramp meters in North Carolina along westbound I-540:

- Falls of Neuse Road (Exit 14)
- Six Forks Road (Exit 11)
- Creedmoor Road (Exit 9)
- Leesville Road (Exit 7)

Additionally, this study was designed to develop four frameworks focused on the four phases of the ramp metering evaluation process that can be used to evaluate not only the I-540 ramp meters, but also future projects. These include:

1) Planning-level data collection method
2) Planning-level analysis method
3) Life cycle cost analysis method
4) Before-and-after evaluation guidance

In the absence of clear national methods for incorporating ramp metering strategies into agency planning processes, these customized frameworks of evaluation were developed to appropriately and accurately assess the outcomes of North Carolina ramp meters. Each of these frameworks incorporated national and state best practices, including those outlined in the Highway Capacity Manual and by the Federal Highway Administration. Throughout this report, the westbound I-540 facility serving a case study for the applications of methods.

Data collected for the I-540 ramp meter facility was used to conduct planning-level modeling of the outcomes of the ramp meters, the finding of which were then incorporated into a life cycle cost analysis. The analysis showed that the estimated costs and benefits of the four westbound I-540 ramp meters over ten years are as follows:

- Costs of $1,490,749 related to installation, maintenance and operations, replacement, and programing
- Benefits of between $1,389,956 and $4,169,867 stemming from increased safety (crash reduction)
- Benefits of between $28,335,293 and $70,731,406 associated with decreased user delay

In total, it is estimated that the westbound I-540 ramp meters will provide estimated benefits of between $28,234,500 and $73,410,500 over the next ten years. While these results are empirically sound, the research team utilized ranges for the benefits associated with increased safety and decreases in user delay because of the limited information available on the parameters and algorithms that will be used for the ramp meters, as well as a lack of existing data on the actual outcomes of NC-specific ramp meters. A discussion on these limitations and related recommendations are outlined in the final sections of this report.

4.1. Sensitivity Analysis

The research team committed a great deal of time to running multiple analyses and tests to examine how different variables and input values influence findings related to ramp metering outcomes. This process, called sensitivity analysis, is a standard practice for life cycle cost analyses (Swiss, 2012). The research team conducted the sensitivity analyses by applying extreme values on the high and low end, similar to the process described above for examining the impact of applying vastly different Crash Modification Factor values.

As a result of these sensitivity analyses, the research team developed a list of several factors that should be considered by the NCDOT when utilizing the methods and findings of this report:

- **Algorithm Choice**: As previously referenced, ramp metering outcomes can depend heavily on the metering algorithm selected. Because the algorithm that will be used for sites in the Triangle has not yet been selected, the research team used a system-wide Fuzzy Logic algorithm in the before-and-after model used to estimate treatment outcomes. Consequently, true outcomes of the I-540 ramp meters may vary, perhaps significantly, from these projections. Additionally, it is recommended that the true algorithm selection be applied in all future analyses using the before-and-after analysis methodology for more accurate findings. The algorithm used for the 2014 Atkins study of the facility to estimate outcomes is unknown (Badgett, 2014).
- **System Coordination:** Similar to algorithm selection, the research team assumed that the first four I-540 sites will operate as a coordinated system of ramp meters instead of as isolated, standalone local units. If the NCDOT instead opts to use a local system of ramp metering management, the benefits outlined in this report will likely be lower than projected and will not accurately reflect actual outcomes of the treatments. The 2014 Atkins study approached the facility as a local system (Badgett, 2014), although the plan to operate the I-540 ramp meters in succession indicates that coordination is highly likely.

- **Facilities Examined:** This study examined the impact of the first I-540 ramp meters on freeway mainline and ramp segments. Accounting for the additional impact on arterial and local roadways could result in different outcome projections, due to the impact of traffic diversions. However, some national studies have shown this impact is minimal.
- **Reliability Scenarios**: To more accurately model the impact of incidents on the I-540 facility, the research team employed the reliability scenario generation procedure documented in the HCM. This process involved the randomized generation of possible incidents on the freeway facility, such as weather-related disruptions and vehicle crashes. While this method offers a more realistic view of the long-term impacts of ramp metering, the random scenario generation also creates a high margin of error for delay outcomes, and therefore the projections of monetized values for related variables may not reflect actual outcomes for the facility.
- **Crash Reduction Impacts**: Similar to the reliability scenarios, it is difficult to predict the impact that a possible reduction in crashes due to ramp metering will have on the facility. This is because of the inherent random nature of the incidents that can influence overall congestion. As a result, the research team evaluated the outcomes of two different crash reduction scenarios of 5% to 15%. However, these resulting delays and monetized values are varied and have large margins of errors due to the reliability scenario generation, and therefore may not accurately predict true ramp metering outcomes.

4.2. Future Research

4.2.1. Additional Variables

This report, although limited in scope, includes the first frameworks developed to analyze ramp meters in North Carolina. Future ramp metering studies could add additional variables to the methodology presented here to more thoroughly investigate the array of performance measures associated with ramp metering. Based on other national studies, these additional variables could include outcomes related to fuel use or idling, improvements in quality of life due to reduced stress related to highway congestion, enhanced travel time reliability, operating and ownership costs (MDOT, 2015; WisDOT, 2006).

4.2.2. Calibrated Analysis

As part of a post-installation study, the methods and models developed through this project should be calibrated using the actual algorithms and parameters used for the four sites. In addition, “after” data for the facility impact area should be utilized for the calibration, including information on actual ramp meter activation periods, area of impacts, etc. Adjusting the models and methods with these improved inputs will increase their accuracy, which can also be applied to the analysis of future North Carolina ramp meters at other locations.

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6. Appendices

Appendix 1: Planning-Level Data Collection Guide

Segmentation and Traffic Message Channel (TMC) Codes

1. Segment the roadway of interest according to segmentation principles in Chapter 10 in the 6th edition of the Highway Capacity Manual.
2. Identify HERE sensor locations using this website: https://trafficsensors.ext.here.com/#/data-warehouse/reports. Data from HERE will be used to gain volume data.
   a. User name and password will be needed.
   b. Write down the sensor ID (6 digit log number) next to the segment in which it directly lies in (as opposed to the area it is in).
   c. In cases where a sensor is in an area with multiple types of geometric properties (for example, where a 3 lane highway turns into a 4 lane highway), use the data for the sensor in that area for the segments that have similar properties (number of lanes, location, etc.).
   d. Download data from Data Warehouse->Reports->five_min which will be a zip file with each day's data for the full network. Alternatively, manually navigate to each sensor of interest and download daily files separately.
3. Apply Traffic Message Channel (TMC) codes to applicable segments.
   a. TMC technology provides traffic data for areas in which they are located. TMC codes run from ramp-ramp and will almost always contain multiple HCM segments.
   b. Record the applicable TMC code for each segment in a spreadsheet so volume data can be determined even if there is no applicable HERE sensor. Sometimes a segment will not have a HERE sensor located on it and a nearby one will need to be assigned.
   c. Use INRIX or RITIS website data to determine TMC codes of desired route.
      i. Link to INRIX data: http://i95.inrix.com/I95/Login.aspx?ReturnUrl=%2fi95
      ii. User name and password will be needed.
      iii. Click on segment and pop-up window should appear that lists TMC code, among other things.
   d. Use HERE segments for any TMC travel times after April 2016 (when the NCDOT's contract began with HERE). Use RITIS (which has both HERE and INRIX data) to identify TMC codes based on start/end exits using the massive data download tool.
      i. Link to RITIS data: https://vpp.ritis.org/suite/download/.
      ii. User name and password will be needed.
      iii. Download both INRIX and HERE travel times from the RITIS site.
      iv. TMC code definitions are included in the download from INRIX and HERE.

AADT Estimation and Application

4. Apply and estimate the AADT for each segment by either using 1) ArcGIS or 2) NCDOT PDF maps
   1) Use an ArcGIS .shp file from NCDOT, determine the majority of AADTs for the segments.
   a. Link to file: https://connect.ncdot.gov/resources/gis/Pages/default.aspx OR http://ncdot.maps.arcgis.com/home/webmap/viewer.html?webmap=a16c594d660e43428cde01de5736532e .

b. Open ArcGIS and load the .shp file. Using the Identify tool in ArcGIS, click on the desired link. Scroll down in the Identify pop-up window, and view the AADT data for the segment, which should be listed near the bottom.

c. HOWEVER, between an off ramp and an on ramp within an interchange, the AADT value given in the .shp file is not accurate or reliable. Therefore, instead of using this value directly, estimate the AADT for the segments within an interchange using the following method:

  i. Take the AADT value for the basic segment up-stream of interchange and subtract the AADT given for the off ramp of the said interchange.

  ii. Take the AADT value for the basic segment down-stream of interchange and subtract the AADT given for the on ramp of the said interchange.

  iii. Take the average the previous two values. This average AADT is used as an estimate for AADT of the segment.

2) Use AADT (traffic volume) map PDFs provided by the NCDOT to manually record AADT data.

a. This method can be used instead of the ArcGIS maps to identify AADTs, however, it is not as accurate and is more time consuming.

b. Link to PDF maps: https://www.ncdot.gov/travel/statemapping/trafficvolumemaps/.

Determining Travel Time

5. Determine Travel Time per TMC segments.

a. Download RITIS speed data and travel time data for the desired time period along the entire facility of interest.

  i. Make sure the data is in 5 minute time slots.

  ii. Speed data will be used for VHD calculations.

b. Open the data in Excel and create a new column that be used to add the 5 minute time slots.

  i. Assuming that the time stamp from the downloaded RITIS data is in column B of the file, the following command can be used to populated the new column for 5 minute data: =HOUR(B2)&":"&MINUTE(B2).
  If the timestamps are in a column other than column B then this formula will need to be adjusted so that the calculations for the 5 minute data is accurate.

  ii. Note that times like 6:05 and 7:05 will be displayed as 6:5 and 7:5. Make sure not to confuse these with 6:50 and 7:50.

c. Create a Pivot table of selected data in Excel.

  i. First highlight all the cells in the downloaded data, including the recently created Time-only variable.

  ii. Then, go to “Insert” and chose to create a pivot table; selected data should already be in the “Select table or range” section and chose to add the table in the existing workbook under a new tab.

  iii. In the Pivot table fields menu, select and drag the recently created Time-only variable under the Rows section.

  iv. Then, drag the travel time minutes variable under Values section and left click the variable name and select the Value Field Settings option and chose to summarize the field by Sum, at which time your Pivot table is set up.

  v. In column beside Pivot table, create a new Average Travel Time column.

  vi. In your new Average Travel Time column and in it divide the sum of the travel time minutes column by the total amount of days in desired time period, which will depend on the time period of analysis. For example, for one year that includes weekends, this would be 365 days. This column will then show the average Travel Time for the facility per 5 minute time slot for the desired time period.

Determining VHD

6. VHD can be split into two parts: 1) a Time component and 2) a Volume component.
   1) The Time component is free flow travel time minus actual travel time. The Time component of VHD must always be greater than or equal to 0. If it is less than or equal to zero then the time component is assumed to be 0. We can calculate the travel time component from the RITIS data downloaded in Step 5.
   2) The volume component is the total amount of vehicles that passed through a segment during a selected time period. The volume components are calculated using HERE sensor data.

   a. Determine time component of VHD per TMC and per Segment.
      i. To create a new Pivot table for VHD data, highlight all the cells in the downloaded data, including the recently created Time-only variable.
      ii. Then, go to “Insert” and chose to create a pivot table; selected data should already be in the “Select table or range” section and chose to add the table in the existing workbook under a new tab.
      iii. In the Pivot table fields menu, select and drag the measurement time stamp variable (will include time and data) under the Rows section.
      iv. Then, drag the sum of travel time minutes variable under Values section and left click the variable name and select the Value Field Settings option and chose to summarize the field by Sum, at which time your Pivot table is set up.
      v. Then, use this Pivot table to determine the travel time component by applying “If” and VLOOKUP functions. An example of the function is below, with N5 through P23 storing free flow travel time and corresponding data and column G containing the Travel time data from RITIS.
         VLOOKUP Example Function:
         =IF(G2>VLOOKUP(A2,$N$5:$P$23,3,FALSE), G2-VLOOKUP(A2,$N$5:$P$23,3,FALSE),0).
      vi. Create a Pivot table in which the rows are time stamps, the columns are TMC codes, and the values are sums of VHD time components calculated using a formula like the one above.
      vii. Because there may be multiple facility segments within a TMC code, split up the calculated time components per TMC into time components per segment. For example: TMC 125-05083 has a travel time component of 1 minute for a certain time slot. Within TMC 125-05083 there are 3 segments of varying length. These 3 segments have weighted ratios to total TMC length of .45, .25, and .30. In the Excel table, take that one minute time component and multiply it by these weighted length ratios to get the time component for each segment during this certain time period.
      viii. The time component should now be calculated for each SEGMENT per 5 minute time slot.

   b. Determine Volume component of VHD.
      i. AADTs per segment were determined in Step 4 of this methodology
      ii. Now, 5 minute volumes must be estimated for each HCM segment to determine VHD

1. Using HERE sensor volume data, record the yearly weekday average volume for all HERE stations for a certain time slot and divide it by the facility's YEARLY weekday average volume for all stations for the full 24 hours. This ratio operates like a K-Factor for the facility.
2. If data is only available in 15 minute time slots, divide the value by 3 and apply to the three 5 minute time slots. Time periods greater than 15 minutes should not be used in this method.
3. These factors are used for the average weekday in the year. In order to incorporate seasonality, divide each month or season average daily volume by the yearly average daily volume to calculate the monthly/seasonal multiplier.
4. Estimated 5 minute volume for a segment is the AADT multiplied by 5 minute factor and monthly/seasonal multiplier

iii. Multiply the estimated volume and the time component calculated in step 6a. This is the final VHD for each 5 minute period, which should be summed across the study period.

Appendix 2: Planning-Level Analysis Guide

This methodology is intended to be applied for analysis procedures including macro or microscopic simulation. Other modeling techniques such as HCS can also be applied, as long as the selected analysis tool can appropriately model ramp metering conditions. For the I-540 ramp meter study outlined in this report, the research team utilized FREEVAL (user guide available at http://hcmvolume4.org/) to analyze ramp metering performance. However, the below high-level methods can be applied using any analysis tool that is appropriate for modeling ramp meter conditions, although FREEVAL tips are included in this guide.

1. Scope Analysis
    a. Identify the temporal and spatial boundaries of the analysis.
    b. Note: Always include all congested time periods and queued segments with consideration that non-recurring congestion may occur, extending the parameters of the analysis.
2. Develop Base Model
    a. Create HCM Segments from the facility, based on the spatial boundaries determined in Step 1. Additional guidance on segmentation can be found in HCM 6 Chapter 10.
    b. Input geometric details of the segments (e.g. # of lanes, segments lengths and etc.).
    c. Input demands, or alternatively, AADTs and hourly demand distribution. NC-specific profiles are available through the NCDOT 2015-009 project.
    d. Run the initial model.
3. Calibrate Base Model
    a. Collect observational data for the facility. Data from INRIX, HERE.com and side-fire microwave radar sensors can be used.
    b. Compare initial FREEVAL results with observational data. If they are not consistent, then proceed to step c and calibrate the facility.
    c. Apply FREEVAL Calibration using the Calibration Guidance in HCM6 Chapter 25.
4. Perform Whole Year Analysis
    a. Perform a whole-year reliability analysis on the calibrated file, based on HCM Chapter 11.
    b. Record vehicles hours of delay (VHD) for all reliability scenarios.
5. Model Ramp Metering Impacts
    a. For single day analysis
        i. Use a FREEVAL version that can model adaptive ramp metering, such as FREEVAL-DSS.
        ii. Model adaptive ramp metering for desired on-ramps. The ramp metering algorithm and its parameters should be determined in advance.
    b. For whole year analysis
        i. Use single day analysis file and perform a whole year reliability analysis with non-recurring sources of congestion such as incidents and severe weather conditions.
        ii. CRFs of 5% or 15% must be expanded to the impact on overall incidents frequencies.
        iii. Record vehicle hours of delay (VHD) for all scenarios.
6. Develop MOEs for Base and Future Year Models
    a. Compare vehicle hours of delay (VHD) for the before and after cases. The VHD savings in the after case will be used in benefit costs analysis.

Appendix 3: Geometric Details of the Ramp Segments

Segment Number	Segment Name	Acc/Dec Lane Length (ft)	Number of Lanes: On-ramp	On-ramp Queue Capacity (veh)	On-ramp Free Flow Speed (mph)	Number of Lanes: Off-ramp	Off-ramp Free Flow Speed (mph)
Seg. 2	Falls of Neuse Rd OFF-Ramp	989	N/A	N/A	N/A	1	45
Seg. 4	Falls of Neuse ON-Ramp	1113	1	100	45	N/A	N/A
Seg. 6	Six forks Rd OFF-Ramp	1750	N/A	N/A	N/A	2	45
Seg. 8	Six Forks Rd ON-Ramp	2270	1	100	45	N/A	N/A
Seg. 10	Creedmoor Rd OFF-Ramp	300	N/A	N/A	N/A	1	45
Seg. 12	Creedmoor Rd ON-Ramp	1488	1	100	45	N/A	N/A
Seg. 14	Leesville Rd OFF-Ramp	200	N/A	N/A	N/A	1	45
Seg. 16	Leesville Rd ON-Ramp	1634	1	100	45	N/A	N/A

Appendix 4: 15 Minute Demand Flow Rates for Mainline Entry (4% Trucks), On-Ramps and Off-Ramps

15 Minutes Analysis Period	15 Minutes Demand Flow Rates (vph)								
	Mainline Entry Demand	ONR Seg#4	ONR Seg#8	ONR Seg#12	ONR Seg#16	OFR Seg#2	OFR Seg#6	OFR Seg#10	OFR Seg#16
1	2132	780	540	540	540	352	432	432	396
2	4400	884	612	612	612	400	488	488	448
3	4341	988	684	684	684	444	548	548	500
4	4969	1092	756	756	756	492	604	604	552
5	4838	1192	828	828	828	536	660	660	608
6	5026	1164	804	804	804	524	644	644	592
7	6040	1132	784	784	784	508	628	628	576
8	5924	1104	764	764	764	496	612	612	560
9	5357	1072	744	744	744	484	592	592	544
10	5537	1000	692	692	692	452	556	556	508
11	5144	932	644	644	644	420	516	516	472
12	5242	860	596	596	596	388	476	476	436
13	4087	792	548	548	548	356	440	440	400
14	3793	760	528	528	528	344	420	420	388
15	4085	732	508	508	508	328	404	404	372
16	3573	700	484	484	484	316	388	388	356
17	3689	672	464	464	464	304	372	372	340
18	3384	672	464	464	464	304	372	372	340
19	2947	672	468	468	468	304	372	372	344
20	3711	676	468	468	468	304	372	372	344

Appendix 5: Origin Demand Adjustment Factors for Demand Calibration

15 Minutes Analysis Period	Origin Demand Adjustment Factors																
	Seg #1	Seg #2	Seg #2	Seg #3	Seg #3	Seg #4	Seg #4	Seg #5	Seg #5	Seg #6	Seg #6	Seg #7	Seg #7	Seg #8	Seg #8	Seg #9	Seg #9
1	1.00	1.00	1.00	1.14	1.00	1.00	1.00	0.84	1.00	1.00	1.00	0.81	1.00	1.00	1.00	1.17	1.00
2	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.19	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.19	1.00
3	1.00	1.00	1.00	1.19	1.00	1.00	1.00	1.12	1.00	1.00	1.00	1.09	1.00	1.00	1.00	0.86	1.00
4	1.00	1.00	1.00	0.98	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.18	1.00	1.00	1.00	1.14	1.00
5	1.00	1.00	1.00	0.96	1.00	1.00	1.00	0.81	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.00	1.00
6	1.00	1.00	1.00	0.93	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.04	1.00	1.00	1.00	0.82	1.00
7	1.00	1.00	1.00	1.07	1.00	1.00	1.00	1.11	1.00	1.00	1.00	1.18	1.00	1.00	1.00	0.83	1.00
8	1.00	1.00	1.00	1.19	1.00	1.00	1.00	1.06	1.00	1.00	1.00	1.15	1.00	1.00	1.00	0.98	1.00
9	1.00	1.00	1.00	1.17	1.00	1.00	1.00	1.06	1.00	1.00	1.00	1.19	1.00	1.00	1.00	0.89	1.00
10	1.00	1.00	1.00	1.12	1.00	1.00	1.00	1.09	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.08	1.00
11	1.00	1.00	1.00	1.13	1.00	1.00	1.00	1.17	1.00	1.00	1.00	1.10	1.00	1.00	1.00	0.81	1.00
12	1.00	1.00	1.00	0.94	1.00	1.00	1.00	1.16	1.00	1.00	1.00	1.11	1.00	1.00	1.00	0.87	1.00
13	1.00	1.00	1.00	1.19	1.00	1.00	1.00	1.03	1.00	1.00	1.00	0.90	1.00	1.00	1.00	0.93	1.00
14	1.00	1.00	1.00	1.09	1.00	1.00	1.00	1.17	1.00	1.00	1.00	0.82	1.00	1.00	1.00	1.17	1.00
15	1.00	1.00	1.00	1.02	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.20	1.00	1.00	1.00	1.05	1.00
16	1.00	1.00	1.00	1.15	1.00	1.00	1.00	1.07	1.00	1.00	1.00	1.06	1.00	1.00	1.00	0.81	1.00
17	1.00	1.00	1.00	0.89	1.00	1.00	1.00	1.14	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.11	1.00
18	1.00	1.00	1.00	1.09	1.00	1.00	1.00	0.81	1.00	1.00	1.00	0.94	1.00	1.00	1.00	1.05	1.00
19	1.00	1.00	1.00	0.84	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	0.99	1.00
20	1.00	1.00	1.00	1.08	1.00	1.00	1.00	1.01	1.00	1.00	1.00	0.97	1.00	1.00	1.00	0.88	1.00

Appendix 6: Destination Demand Adjustment Factors for Demand Calibration

15 Minutes Analysis Period	Destination Demand Adjustment Factors																
	Seg #1	Seg #2	Seg #2	Seg #3	Seg #3	Seg #4	Seg #4	Seg #5	Seg #5	Seg #6	Seg #6	Seg #7	Seg #7	Seg #8	Seg #8	Seg #9	Seg #9
1	1.00	1.15	1.00	1.00	1.00	1.13	1.00	1.00	1.00	1.18	1.00	1.00	1.00	0.88	1.00	1.00	1.00
2	1.00	0.91	1.00	1.00	1.00	1.04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	1.00	1.00	1.00
3	1.00	1.08	1.00	1.00	1.00	0.89	1.00	1.00	1.00	0.83	1.00	1.00	1.00	1.17	1.00	1.00	1.00
4	1.00	0.92	1.00	1.00	1.00	0.85	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.02	1.00	1.00	1.00
5	1.00	1.19	1.00	1.00	1.00	1.14	1.00	1.00	1.00	1.10	1.00	1.00	1.00	1.11	1.00	1.00	1.00
6	1.00	1.03	1.00	1.00	1.00	1.04	1.00	1.00	1.00	1.13	1.00	1.00	1.00	1.14	1.00	1.00	1.00
7	1.00	0.81	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	1.00	1.00	1.00	1.16	1.00	1.00	1.00
8	1.00	1.18	1.00	1.00	1.00	0.83	1.00	1.00	1.00	0.80	1.00	1.00	1.00	1.03	1.00	1.00	1.00
9	1.00	1.07	1.00	1.00	1.00	0.83	1.00	1.00	1.00	0.81	1.00	1.00	1.00	1.11	1.00	1.00	1.00
10	1.00	0.98	1.00	1.00	1.00	0.94	1.00	1.00	1.00	1.03	1.00	1.00	1.00	0.93	1.00	1.00	1.00
11	1.00	1.02	1.00	1.00	1.00	0.93	1.00	1.00	1.00	0.88	1.00	1.00	1.00	0.90	1.00	1.00	1.00
12	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.08	1.00	1.00	1.00	0.81	1.00	1.00	1.00
13	1.00	1.13	1.00	1.00	1.00	1.12	1.00	1.00	1.00	1.07	1.00	1.00	1.00	1.06	1.00	1.00	1.00
14	1.00	0.99	1.00	1.00	1.00	1.14	1.00	1.00	1.00	1.19	1.00	1.00	1.00	1.14	1.00	1.00	1.00
15	1.00	1.08	1.00	1.00	1.00	1.15	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.93	1.00	1.00	1.00
16	1.00	0.83	1.00	1.00	1.00	0.97	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.16	1.00	1.00	1.00
17	1.00	1.03	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.03	1.00	1.00	1.00	0.92	1.00	1.00	1.00
18	1.00	1.02	1.00	1.00	1.00	1.02	1.00	1.00	1.00	1.05	1.00	1.00	1.00	1.15	1.00	1.00	1.00
19	1.00	1.06	1.00	1.00	1.00	1.08	1.00	1.00	1.00	0.89	1.00	1.00	1.00	0.97	1.00	1.00	1.00
20	1.00	0.86	1.00	1.00	1.00	1.20	1.00	1.00	1.00	1.04	1.00	1.00	1.00	1.19	1.00	1.00	1.00

Appendix 7: Planning-Level Life Cycle Cost Analysis Guide

This methodology is designed to monetize the outcomes of ramp metering identified during through the pre-planning data collection and analysis processes. These below steps can be applied to data from sources other than those outlined in this report, such as FREEVAL, as long the type and format of the data is similar.

1. Identify Discount Rate and Years of Analysis
   a. Select the discount rate that will be used to adjust for the changing value of money over time. Based on best practices, it is suggested that an annual rate of 3% be applied.
   b. Decide how many years of data will be monetized.
      i. For example, ten years would include monetized estimations for 2017 to 2026.
      ii. Make sure that only costs and not benefits are counted during the construction period, as benefits cannot start until the meters are operational.
2. Calculate Installation, Maintenance and Operations, and Replacement Costs
   a. Gather data on the following, using vendor estimates or expert estimations for the specific sites to be metered:
      i. Annual maintenance and operations costs
         a) Develop estimates for EACH INDIVIDUAL ramp meter location in the system.
         b) Note: Maintenance costs include the annual and incremental operations and upkeep costs needed to keep a facility operational, as well as the cost of revising an intersection at the end of its anticipated service life.
      ii. Capital costs for construction
         a) Develop estimates for EACH INDIVIDUAL ramp meter location in the system.
         b) These are one-time costs that will be applied only in the first period ("Year 0") of analysis, with benefits not beginning until "Year 1."
      iii. One-time programming costs
         a) These will vary depending on whether the ramp meters are being installed in an area that has existing ramp metering infrastructure nearby that will be utilized.
         b) This is a one-time costs that will be applied only in the first period ("Year 0") of analysis, with benefits not beginning until "Year 1."
         c) The 2014 Atkins study estimated this cost to be $405,000.
      iv. Facility replacement/revision cost
         a) Develop estimates for EACH INDIVIDUAL ramp meter location in the system.
         b) Only include this cost in the life cycle cost analysis (LCCA) if the timeframe of analysis is for more than 10 years.
   b. Project the total for all installation, maintenance and operations, and replacement costs.
      i. Apply the compounding discount rate to each year of the selected timeframe to estimate the life cycle costs.
      ii. Note: Any one-time costs accrued in "Year 0" should not be discounted. Discounting should begin in "Year 1."
      iii. Add all costs for the full timeframe of analysis to calculate the total cost of installation, maintenance and operations, and replacement costs for the ramp meters of interest.

3. Calculate Safety Benefits
   a. Identify the Crash Reduction Factors (CRFs) that will be used to develop a range for potential safety benefits.
      i. CRFs of 5% (low estimation) and 15% (high estimate) are recommended based on other studies.
      ii. These CRFs represent the reduction in crashes that are expected at each ramp metering site due to the treatment.
   b. Obtain and analyze five years or more of crash data for the areas within the selected temporal and spatial parameters.
      i. Include crashes occurring on the mainline, entrance ramp, and the ramp terminal areas.
      ii. Remove crashes involving animals and other anomalies from the analysis.
      iii. Organize data by KABCO crash type, which is clearly labeled within the data from the NCDOT; see Exhibit 20 for more details.
      iv. Aggregate the crash data by type annually and then develop averages for the number of crashes per year by KABCO type.
         a) Note: In alignment with NCDOT methods, some types will need to be added together before monetization, forming three categories: 1) K and A, 2) B and C, and 3) PDO.
         b) The resulting annual averages will be used for monetization.
      v. Multiply these averages for these three KABCO categories by the low and high CRFs selected, respectively.
         a) The resulting values are reduction in crashes that are expected to be seen with the ramp meters.
         b) These will also be used for monetization.
   c. Monetize data using the most recent standard NCDOT crash costs; see Exhibit 21 for more information.
      i. Estimate the current cost of crashes for the area to be metered.
         a) Multiply the average annual number of crashes per KABCO type category for the years of data from the site by the estimated cost for the appropriate type category.
         b) These values will not be used further, but are useful for showing establishing a “before” care for crash costs.
      ii. Estimate the value of the safety benefits of the ramp meters.
         a) Multiply the average annual number of crashes per KABCO type category for the expected crash reduction numbers by the estimated cost for the appropriate type category.
         b) Conduct for each of the CRF crash reduction estimates.
         c) These numbers will be used to generate the total safety benefits expected over time
   d. Project the total for all safety benefits.
      i. Apply the compounding discount rate to each year of the selected timeframe to estimate the life cycle benefits.
      ii. Add all benefits for the full timeframe of analysis to calculate the total safety benefits for the ramp meters of interest.
      iii. Conduct for each of the monetized CRF crash reduction estimates to show the low and high values for the expected range of benefits.

4. Calculate User Delay Benefits/Costs
    a. Identify values to be used to monetize user delay.
    b. Analyze NCDOT geocoded data in ArcGIS to identify the average percent of heavy vehicles for the selected temporal and spatial parameters.
    c. Select the standard value of user travel time.
        i. Different values should be used for passenger and heavy vehicles.
        ii. It is recommended that the most recent values from the Texas A&M Transportation Institute's annual Urban Mobility Report be used, as seen in Exhibit 24.
    d. Select the number of people that will be expected to occupy each vehicle, on average.
        i. It is anticipated that the more than one person will occupy each vehicle on the facility.
        ii. It is recommended that 1.25 occupants per vehicle be used, based on the most recent values from the Texas A&M Transportation Institute's annual Urban Mobility Report.
    e. Establish an annual traffic volume growth factor (VGF) for the facility area.
        i. Use the NCDOT's projected annual traffic volume growth estimations for the full ramp metering impact area when selecting the VFG to be applied.
        ii. Do not re-calculate future delay estimations if such calculations have already been applied as part of the planning-level operational analysis. If the VGF has not yet been applied, use

Equation 2 to estimate future volumes for the selected timeframe of analysis.

f. Utilize delay data from planning-level operational analysis, making sure that it incorporates:
    i. Future volume estimations developed by applying an annual traffic volume growth factor (VGF) for the facility area based on the NCDOT's annual traffic volume growth estimations and the formula in

Equation 2

ii. Vehicle hours of delay (VHD) projections
  a) Make sure that the congestion impacts of reduced crashes at the level of the low and high CMFs used in the safety benefits analysis have been incorporated into the VHD estimations to create a range of overall delay benefits.
  b) Ensure that VHD calculations are annualized for each year of the time of analysis.

e. Project the total for all delay benefits
  i. Apply the compounding discount rate to each year of the selected timeframe to estimate the life cycle benefits.
  ii. Add all benefits for the full timeframe of analysis to calculate the total safety benefits for the ramp meters of interest.
  iii. Conduct for each of the monetized CRF crash reduction estimates to show the low and high values for the expected range of benefits.

5. Estimate Total Benefits
   a. Add the total monetized values for all costs and benefits as calculated above.
   b. Conduct separate analysis for both the low and high CRFs to create a range of benefits .
   c. For safety and user delay, compare the estimated monetized "before" conditions of the ramp metering facility area to the "after" conditions.

Appendix 8: Average Vehicle Hours of Delay Projection for Next 10 Years Considering Different Crash Reduction Factors (CRFs)

Year	Before Case	After Case (CRF=5%)	After Case (CRF=15%)
2017	27,901	27,151	26,828
2018	34,565	33,884	33,397
2019	40,971	40,984	39,611
2020	49,917	48,667	48,031
2021	57,464	57,729	56,844
2022	68,837	67,794	67,178
2023	78,824	78,214	77,881
2024	91,013	91,424	89,790
2025	104,034	103,505	102,732
2026	116,687	116,194	116,135

Appendix 9: Before and After Analysis Guide

This methodology is intended to serve as a framework for before and after evaluation of ramp meters. This evaluation involves operational, safety, and capital/maintenance costs of the facility, although the analysis period may differ for each level. These three impacts can be combined into a Life Cycle Cost Analysis, as shown in the following methodology.

1. Operational Analysis
    a. Scope: Ensure that the facility is evaluated for an appropriate duration (i.e. don't use a single day analysis to make annual comparisons) and that if samples are taken they are from the same time of year to account for seasonality.
    b. Method: Select the method that is most appropriate for the facility. An example of choosing a model over observational data may be where the model can accurately measure delays on ramps that are not available from sensor/probe data.
        i. Observational: Use Appendix 1 for each time period, report changes in volume.
        ii. Modeled: Use Appendix 2 for each time period (with actual rather than projected model inputs for after period), report changes in demand and other model inputs (crash rate, etc.).
    c. Output: Outputs include change in VHD (can be monetized) and travel time as well as contextual information on volume/demand changes that may contribute to change apart from the ramp meter implementation. Additionally, updated model calibration may allow for new default values to better recreate North Carolina-specific ramp meter impacts.

2. Safety Analysis
    a. Scope: Ensure a long enough duration to perform an accurate safety analysis. This duration may be adjusted due to data availability or analysis method.
    d. Method: Use the method from Appendix 7 to collect a crash history for the facility. Select an appropriate method to perform the analysis. For instance, if crash data is available for similar facilities (by type and volume), the empirical Bayes method can account for regression to the mean.
    e. Output: Outputs vary by method, the empirical Bayes method can output the reduction in expected number of crashes as well as an index of effectiveness that can correspond to a crash reduction factor.

3. Capital/Maintenance Costs Analysis
    a. Scope: This analysis can be repeated as additional costs come to light, but a fully scoped analysis should ensure that enough time has passed to have performed regular maintenance on the facility.
    b. Method: Review the costs as planned and designed to actual as built costs. Where costs are location specific (i.e. certain ramps need additional tree removal or added lanes) be sure to record the cause for any unplanned costs. Maintenance and operation costs should be considered with respect to future builds, since one-time software costs may not be incurred on additional facilities until the software license expires.

c. Output: Difference in planned and actual costs as well as better informed standard cost estimates for future systems.

4. Life Cycle Cost Analysis (LCCA)
   b. Scope: The scope for this analysis may vary, as certain costs may still need to be estimated if the LCCA scope is more restrictive than appropriate one of the three previous analyses (i.e. an LCCA may be done after 1 year of operations, so safety analysis cannot be performed and must be estimated instead).
   c. Method: Perform analysis or estimate each of the previous three costs as appropriate with regards to scope and use the method shown in Appendix 7.
   d. Output: The LCCA will estimate the overall savings due to ramp meters.