RESEARCH & DEVELOPMENT

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

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NCDOT Project 2018-19

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NCDOT 2018-19 Project Report

North Carolina
Department of Transportation
Research Project No. 2018-19

Post-Installation Evaluation of the Effects of Ramp Metering in North Carolina

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Since September 2017, the first four on-ramp signals in North Carolina, positioned on the westbound lanes of I-540 in Wake County, have been regularly activated Monday to Friday from 6:30 - 9am. This report focused on the impact of these on-ramp signals. The results identified are the product of data collected in the I-540 WB area over multiple years from numerous sources, both before and after on-ramp signals. When feasible, the costs and benefits of the on-ramp signals were monetized using benefit cost analysis methods. The results of this study show that the on-ramp signals resulted in benefits including a forecasted net savings of $7,949,541 over the ten years after the installation of the on-ramp signals. In addition, the analytical methods updated and developed through this study will provide NCDOT with planning and evaluation frameworks that can be readily applied to future on-ramp signal projects. In the future, NCDOT can use the planning-level tools to evaluate the potential of implementing on-ramp signals in other locations in the state and can apply the evaluation tools to assess the impacts of the on-ramp signals after installation. Ultimately, the methods, processes, and lessons learned delivered with this study can help North Carolina save make faster and more accurate decisions about future on-ramp signal projects.</td></tr>
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Executive Summary: The First Year of the I-540 On-Ramp Signals

This analysis examines the first-year operational impacts of the first four on-ramp signals in Wake County, North Carolina, positioned on the westbound lanes of I-540. The analysis is part of a study conducted by the Institute for Transportation Research and Education (ITRE) at North Carolina State University on behalf of the North Carolina Department of Transportation (NCDOT). The results identified are the product of data collected in the I-540 WB area over multiple years from numerous sources, both before and after on-ramp signals. Since September 2017, the on-ramp signals, have been regularly activated Monday to Friday from 6:30 - 9am.

A comparison of before and after traffic conditions during morning weekday peak hours shows the following results, on average, after the installation of on-ramp signals.

Decreased Delay Benefits

- $9.6 million in driver delay savings over 10 years
- 13 hours of delay savings over 10 years for the average daily commuter vehicle
- 8.5% annual decrease in vehicle hours of delay
- $38 a year in delay savings for the average daily commuter vehicle

Travel Time Reductions

- 84% of commuters experienced shorter drive times
- Up to 2 minutes (7.3%) decrease in drive time per day for a commuter

Congestion and Volume Improvements

- 9% decrease in reoccurring congestion
- 12-minute decrease in congested period per day
- Overall increase in driver volumes

The total net benefits forecasted to accumulate over the ten years after the installation of the on-ramp signals is $7,949,541 over 10 years.

These traffic improvements accrued during the morning weekday peak period despite an annual average 3-4% growth in traffic volumes. According to a 2018 U.S. Census report, 63 people move to Wake County each day, around 23,000 new residents each year. Many of these individuals use the I-540 corridor, and traffic congestion in the area continues to grow with the additional traffic. Yet, in the first year of the on-ramp signal, traffic flow in the area of the on-ramp signals was smoother and congestion and breakdowns were reduced. Given these results, it is anticipated that drivers will continue to experience benefits of on-ramp signals into the future as the technology mitigates the impacts of growing traffic in the area.

The findings in this report exclude estimations of the cost savings associated with safety benefits, which cannot be determined without additional years of before-and-after data. Given the results of ramp meters in other parts of the United States, it is likely that the I-540 WB on-ramp signals will result in long-term safety benefits. As part of the 2016 pre-installation study, the on-ramp signals were forecasted to result in an additional $1.4 to $4.1 million in benefits over 10 years due to a reduction in traffic crashes.

The post-installation evaluation of the I-540 WB on-ramp signals, further detailed in the full project report, provides conclusions based on the available data and specific conditions of the I-540 on-ramp signal area. Therefore, the results of on-ramp signals at other locations may vary and the before-and-after results of this study are not transferable to similar North Carolina projects. However, this project and the 2016 pre-implementation study of the corridor, *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways,* provide tools NCDOT can use to forecast and evaluate on-ramp signal outcomes into the future.

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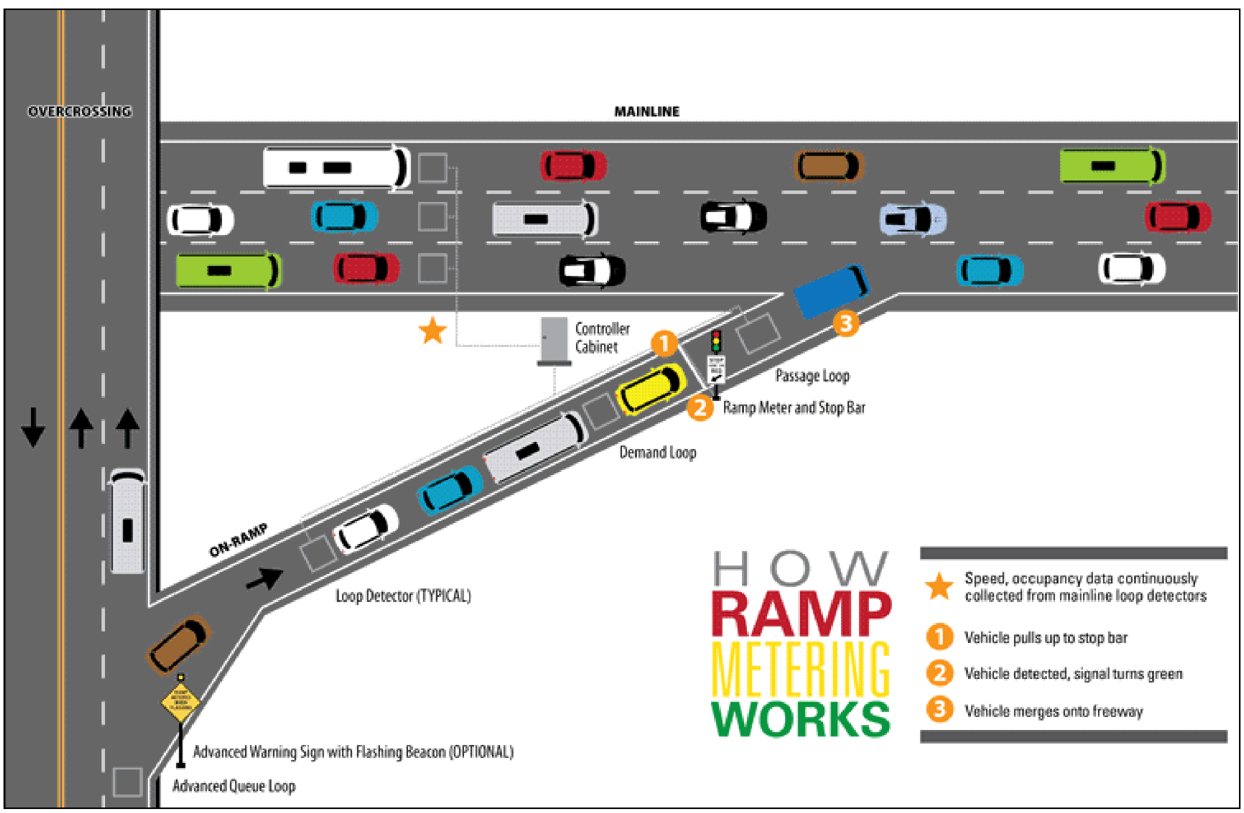
1. Introduction

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. This trend is of more urgent concern in urban regions of the state such as the Charlotte Metro and Triangle (Raleigh, Durham, and Chapel Hill) areas. To mitigate the growing highway congestion, the North Carolina Department of Transportation (NCDOT) is introducing new traffic management strategies including on-ramp signals.

The Federal Highway Administration (FHWA) refers to "on-ramp signals" as "ramp meters," defined as "the application of control devices to regulate the number of vehicles entering or leaving the freeway in order to achieve operational objectives (FHWA, 2006)." An Active Transportation Management (ATM) and Active Traffic and Demand Management (ATDM) strategy, ramp meters (on-ramp signals) have been increasingly used to mitigate congestion by throttling incoming freeway traffic using an on-ramp signal. A lower cost alternative to congestion management strategies that involve large capital projects like freeway expansion, ramp metering has been deployed in more than 20 municipalities and states across the United States since its introduction in the early 1960s (USDOT, 2016; Zhang and Levison, 2010, WisDOT, 2006, Zhang, 2007). Exhibit 1 shows how ramp metering works.

Exhibit 1: Ramp Meter Operations Example



Source: NCDOT, 2016

The strategy involves controlling the number of vehicles that are allowed to enter the freeway, disrupting platoons of vehicles released from an upstream traffic signal for smoother merging at freeway on-ramps, therefore increasing the capacity of the freeway merge segments (Fontaine and Miller, 2010). This approach can help transportation agencies maximize freeway throughput, reduce driver travel time, and improve safety by reducing the number and severity of traffic incidents (Zhang, 2007; Fontaine and Miller, 2010).

On September 26, 2017, NCDOT activated the state's first four ramp meters, or on-ramp signals, along the I-540 westbound corridor in the City of Raleigh in Wake County. According to a 2018 U.S. Census report, 63 people move to Wake County each day, around 23,000 new residents each year. Many of these individuals use the I-540 corridor, resulting in an annual average growth of 3-4% growth in traffic volumes and increasing traffic congestion in the area.

This report details the results of a study conducted by the Institute for Transportation Research and Education (ITRE) at North Carolina State University on behalf of the North Carolina Department of Transportation (NCDOT). The results identified are the product of data collected in the I-540 WB area over multiple years from numerous sources, both before and after the on-ramp signal installations.

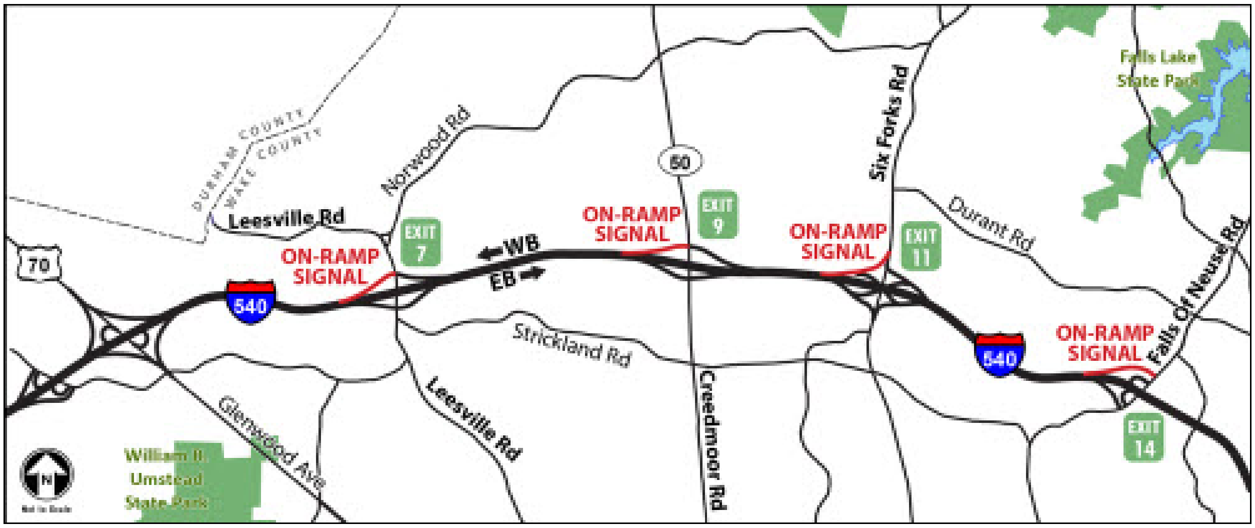
1.1. Background

This study was conducted to evaluate the post-installation effects of on-ramp signals in North Carolina. Specifically, this study evaluated the first year of operations of the four sites in the Raleigh-Durham area along I-540 westbound. These on-ramp signals are located at the ramps of:

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

The four on-ramp signal sites are shown in Exhibit 2, and work together as a system to reduce congestion within the corridor. Since September 2017, these on-ramp signals have been regularly activated Monday to Friday from 6:30 - 9am in the locations shown.

Exhibit 2: First Four I-540 Westbound On-Ramp Signal Locations



Source: NCDOT, 2016

To prepare for the implementation of the first North Carolina on-ramp signals, NCDOT commissioned multiple planning-level studies, including the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* study. Through this effort, a customized evaluation framework was developed to appropriately and accurately *estimate* the outcomes of on-ramp signals in North Carolina before they are installed. Through this study, NCDOT developed a state-specific method that can be incorporated into planning processes to evaluate future on-ramp signal projects.

The planning-level evaluation focused on four major steps in the on-ramp signal 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 the report, which used I-540 as a case study. The post-installation study of the I-540 on-ramp signals outlined in this 2018 report used the frameworks developed through the 2016 study to analyze the impacts of the on-ramp signals using before-and-after traffic data. The analyses detailed in this report examined the impacts of the first four on-ramp signals during the first year after installation. Analyses comparing the first-year results following the post-installation were conducted using available data from September 2017 (pre-on-ramp signals) and October 1, 2017 – September 30, 2018 (post-on-ramp signals).

In addition, methods developed through the 2016 study were updated through the 2018 study to provide NCDOT with planning and evaluation frameworks that can be readily applied to future on-ramp signal projects. NCDOT can use these updated tools to evaluate the potential of implementing on-ramp signals in other North Carolina locations as well as to evaluate the impacts of the on-ramp signals after installation. The methods, processes, and lessons learned produced through this study can help North Carolina plan and assess on-ramp signal projects more quickly and accurately in the future.

1.2. Objectives and Scope

The primary objective of this research project is to provide a post-installation analysis of the four I-540 sites and to establish best practices for future evaluations to NCDOT.

As such, the goals of this project include:

1) Collect post-installation data for the four initial I-540 sites for each of the performance measures of interest, including local and system-wide delay and safety.
2) Compare previously collected before data to after data and outcome projections developed prior to installation for the four sites, including cost-benefit analyses.
3) Use these before-and-after analyses to calibrate North Carolina's on-ramp signal evaluation framework and planning models to ensure more accurate projections for future on-ramp signal projects.
4) Develop a white paper incorporating lessons learned and presenting recommendations to NCDOT for future implementation of on-ramp signals.

1.3. Considerations

This report provides tools NCDOT can use to forecast and evaluate on-ramp signal outcomes into the future, with several important considerations. The outcomes of the first four North Carolina on-ramp signals detailed in this report reflect the conclusions based on the available data and specific conditions of the I-540 on-ramp signal area. Because there is not a one-size-fits-all framework for evaluating the outcomes associated with on-ramp signals, the results of this study should not be transferred in full to future on-ramp signal projects. The before-and-after outcomes as well as performance measures for on-ramp signals at other locations in the state may vary because each site will include unique traffic considerations and facility specifications.

Additionally, while on-ramp signals can provide numerous benefits to some roadway users, such as travel time reliability, the strategy can simultaneously include costs to other roadway users, such as slight increases in travel times, particularly on arterial roadways (Zhang, 2007). These types of tradeoffs are common in traffic management strategies and are incorporated into the evaluation methods revised and developed through this study. The before-and-after outcomes in this report reflect the net benefits and costs considering all roadway users in the I-540 WB on-ramp signal area.

2. Methodology and Guidance Development

As explained previously, the 2016 study, *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways*, established methods for evaluating the impact of on-ramp signals before and after the installation of the strategy. The methodology developed through this previous study was applied to accomplish the goals of the 2018 post-installation study. These goals and the location of the associated updated methods and documentation are provided in the following sections.

2.1. Collect Post-Installation Data

This post-installation evaluation of on-ramp signals replicated many of the data collection methods developed as part of the pre-installation study, *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways*. In addition to the pre-installation data collected as part of the 2016 study, new data was collected during the period immediately before and following the installation of the on-ramp signals to measure the actual impact of the on-ramp signals. For example, actual post-installation travel time data was compared to pre-installation travel time data captured as part of the 2016 study. This data was used to evaluate how travel times for drivers changed after the on-ramp signals were installed.

Key data types include travel time data, volume data, operational data, and safety data. Specific data sources are as follows:

- Probe Travel Times: NCDOT has a statewide contract with HERE which provides travel times on state roads at a resolution of five minutes. These travel times are available for all freeway and arterial sections of the nine routes of interest identified that traveled through the on-ramp signal corridor, as shown in Exhibit 16.

- On-Ramp Signal Data: The software provided by the on-ramp signal vendor records the measurement of counts and speeds as well as the logs of the traffic signal patterns for each day. ITRE reviewed these files to compare counts and speeds to other sources and for calibration of the FREEVAL model described in section 2.6 of this report.

- Radar-based Traffic Counts: NCDOT maintains microwave side-fire radar detectors to measure speed and traffic counts at approximately one dozen locations in the Triangle. One sensor was located on I-540 Westbound just downstream of the on-ramp signal system and another was located upstream. In addition, the research team installed two temporary side-fire radar sensors near the Falls of Neuse and Six Forks Rd on-ramps to calibrate and adjust the counts across the corridor.

- Annual Average Daily Traffic (AADT): NCDOT maintains a statewide database of AADT for all state routes that are updated annually on the I-540 corridor. These were used in comparing traffic trends over time and compared to the radar traffic counts.

- Bluetooth Travel Times: In addition to the probe travel times, the vendor for the on-ramp signals provided travel times for the I-540 corridor from Bluetooth sensors. The research team installed additional sensors on each on-ramp to measure on-ramp travel times that are not measured using the HERE dataset. These travel times are additionally useful as they show the distribution of individual driver travel times compared to the HERE dataset which reports average travel time.

- Traffic Monitoring Video: ITRE collected video from monitoring cameras showing each of the on-ramps in the on-ramp signal corridor. These video files were reviewed to confirm the traffic counts measured from each of the candidate sources.

The 2016 report details the overall data collection approach, while Appendix 1 and Appendix 2 outline the traffic data collection methods and procedures.

2.2. Analyze Collected Data

After all of the data was collected for each specific type of analysis, the research team worked to clean, process, and analyze the data. Occasionally, these analyses resulted in before-and-after comparisons like those shown in 3. Evaluation Results, other times the results of data analysis were used to support model or method verification efforts, such as those described in 2.6 Modeling Verification for North Carolina.

For several types of analyses, data were analyzed by applying updated versions of methods developed through the 2016 study *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways.* Many of these methods are outlined in the appendices, including:

- Appendix 1: Planning-Level Data Collection Guide
- Appendix 2: Planning-Level Analysis Guide
- Appendix 3: Life Cycle Cost Analysis Guide
- Appendix 4: Before and After Analysis Guide
- Appendix 5: Vehicle Hours of Delay Methodology

Data collected through the 2016 study was compared to new data collected after the on-ramp signal installation. To evaluate the long-term impact of the on-ramp signals, benefit cost analysis of the before-and-after impact of the on-ramp signals was also developed. The results of this analysis are detailed in the Benefit-Cost Analysis section of this report.

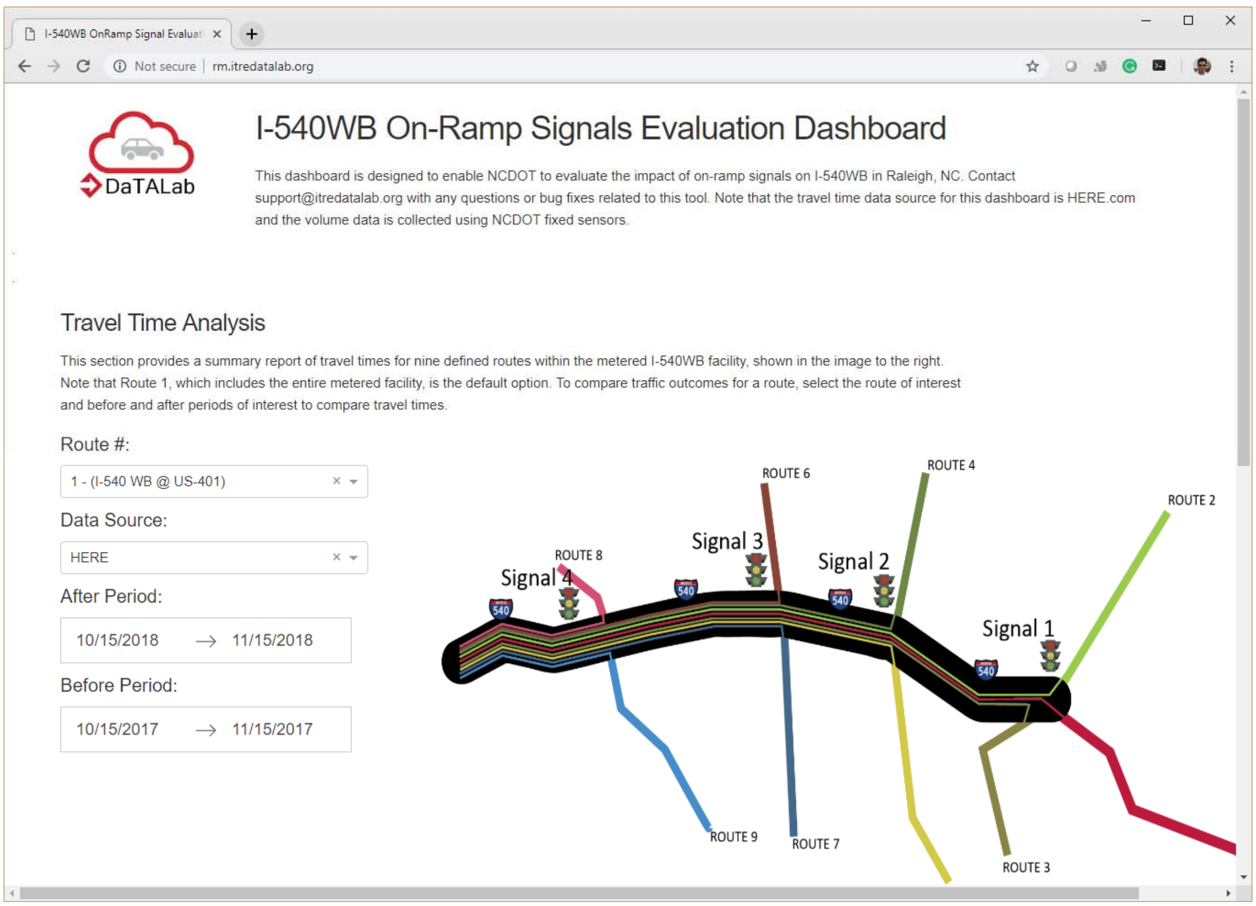
Throughout the first half of the project, the research team captured the incremental benefits to travel time and arterial impacts through weekly reports shared and discussed at in-person meetings with NCDOT. These reports included travel time, volumes, and other before-and-after comparisons that equipped NCDOT with traffic condition information to support decision-making about the on-ramp signals after installation. Additionally, the research team delivered an interim report that outlined the results of the first six months of on-ramp signals.

2.3. Develop and Compare Historical Traffic Profiles

To assess the before-and-after outcomes of the on-ramp signals, historical profiles of pre-installation traffic conditions for the I-540 WB on-ramp signal area were developed using the data analysis methods referenced in the previous section. This data included volume, travel time, speed, and other forms of data that allowed for the identification of patterns and differences in traffic over time. Data collected following the installation of the on-ramp signals was compared against historic data to examine the change in traffic conditions and verify analysis results.

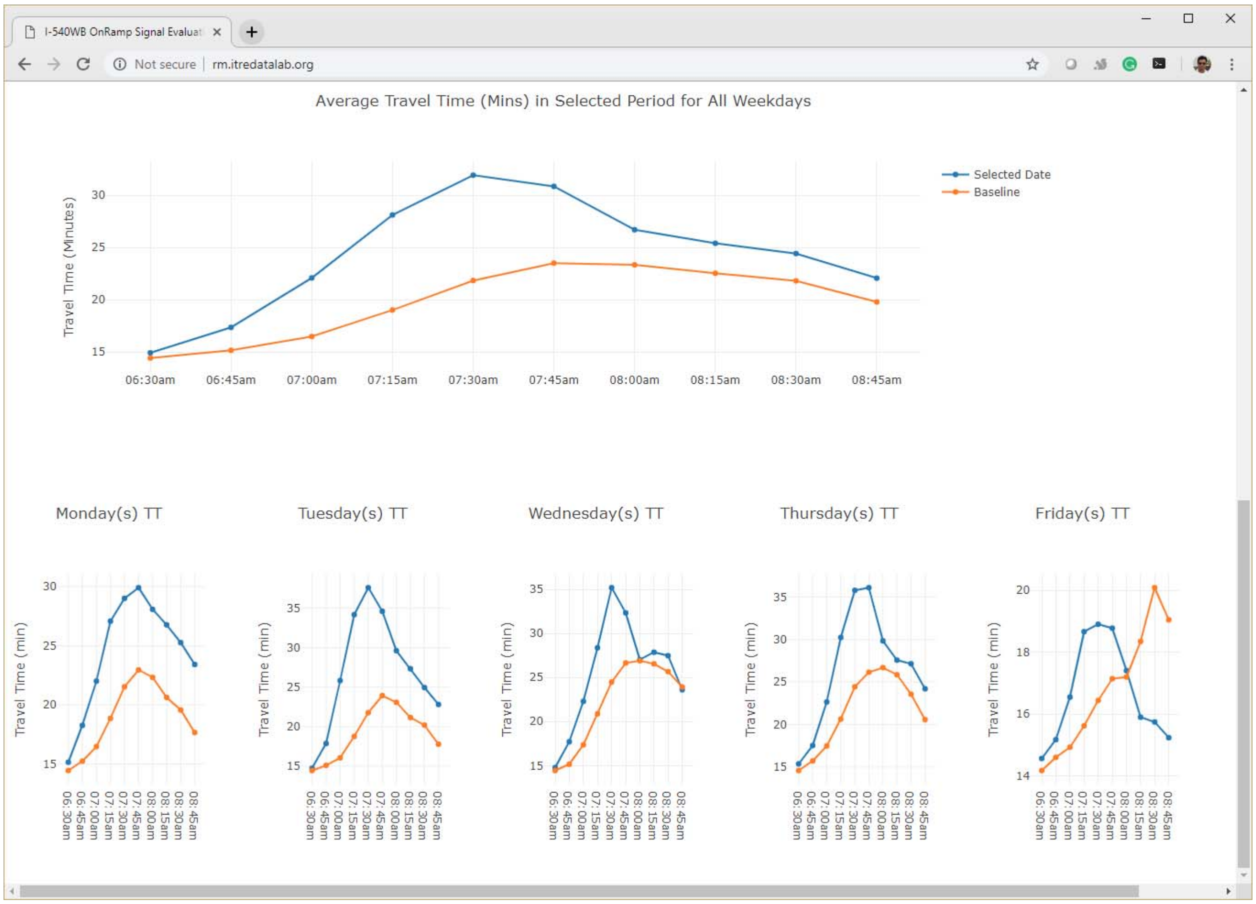
During this project, the research team obtained access to probe-based, real time, travel time data through RITIS APIs, and travel times are fed into this dashboard on a daily basis. As part of evaluating the performance of the on-ramp signals, an online dashboard was developed to summarize the travel times across nine defined routes. This tool can assist NCDOT in obtaining timely analysis of on-ramp signal sections on-demand. The dashboard is hosted on Driver and Transportation Analytics Laboratory's (DaTA Lab) RHEL servers that are accessible at rm.itredatalab.org. Exhibit 3 shows the screen shot of the dashboard landing page.

Exhibit 3: Landing Page of Online Dashboard for Evaluating On-Ramp Signal Impacts



As seen in Exhibit 3, the user can select one of the nine predefined routes that are impacted by the on-ramp signals on I-540 WB. A user can select two periods to enable a before-and after comparison of the travel times and observed volumes. Exhibit 4 shows the travel times for the two periods selected in Exhibit 3. As shown, the travel times are broken further by day of the week to further allow the user to assess the impact of on-ramp signals.

Exhibit 4: Travel Time Comparison In Online Dashboard



2.4. Assist with The Manual Metering Plan

In addition to collecting and analyzing data, the research team assisted NCDOT with identifying internal and external measures, including defining thresholds for interim success. The research team also aided NCDOT efforts to optimize a manual metering plan that best meets these measures. Additionally, the research team worked with NCDOT to review operations with metering rate changes. Lessons learned from this process and results from previous tasks to were used to help inform decisions related to refining time-of-day metering plans.

2.5. Assist with Migration To Traffic Responsive System

Following aiding NCDOT with analysis and decisions related to the manual metering plan, the research team helped NCDOT make informed decisions related to a traffic responsive on-ramp signal system. This task included assisting NCDOT with developing measures of success for the for the first months of 2018 and longer term, setting up an iterative process to evaluate and adjust traffic settings based on objectives identified by NCDOT, and reviewing patterns in the vendor's MaxView system, to better understand impacts of metering adjustments. The research team used data available through MaxView, when possible, to examine on-ramp signal operations and to examine capacity conditions and provided recommendations for optimizing traffic responsiveness.

2.6. Modeling Verification for North Carolina

To enhance NCDOT's ability to estimate the potential operational impacts of on-ramp signals, the research team updated the planning level HCM/FREEVAL model to account for North Carolina-specific characteristics of on-ramp signals. The previously developed on-ramp signal algorithms were updated to model MaxView metering logic that is used in the signal system vendor (Intelight)'s software. The project team developed necessary Java "modules," "classes," and a "graphical user interface (GUI)." The updated components were incorporated into the FREEVAL computational engine.

The North Carolina specific version of FREEVAL (FREEVAL-NC) was used to allow for the use of NC-specific segmentation databases. These updates enable NCDOT staff and consultants to more accurately model freeways in North Carolina for on-ramp signals that use MaxView. Moreover, NCDOT planners can apply this revised model, part of the FREEVAL NC software, during the project planning phase of on-ramp signals.

The MaxView on-ramp signal algorithm uses a lookup table with specified metering rates and selects an appropriate metering rate when certain conditions are met. Conditions are evaluated based on vehicles speed, occupancy, and flow rates. Exhibit 5 shows an example of the MaxView lookup table used for the I-540 WB on-ramp signals.

Exhibit 5: Example of Lookup Table in MaxView Used for I-540 WB On-Ramp Signals

Intersection: 101 - I-540 @ Leesville Rd¬6/12/2018 2:38 PM Metering Plans

Level	Metering Rate	Flow Rate Threshold	Occupancy Threshold	Speed Threshold (mph)
1	1000	1400	8	70
2	700	2800	12	60
3	600	3000	14	50
4	500	3200	16	40
5	400	3400	17	35
6	300	3600	18	30

The "Active Queue" property of the MaxView ramp metering algorithm is not modeled in this study. Enabling this property will increase the metering rate when the back-of-queue reaches to the end of on-ramp. This will try to avoid congestion on the arterial due to queue spillback.

HCM's framework (based on oversaturated freeway methodology) will disable traffic metering when the back of queue reaches to the end of on-ramp. This will increase the metering rate equal to ramp demand. Despite the fact that "Active Queue" property of the MaxView algorithm is not modeled, however, HCM's framework fulfills its absence by increasing the metering rate to be equal to demand.

The same algorithm was modeled in FREEVAL-NC to regulate traffic flow based on the traffic conditions present at a given time frame. Exhibit 6 show the lookup table configuration in FREEVAL-NC.

Exhibit 6: Lookup Table in FREEVAL-NC Developed for On-Ramp Signals Using MaxView

Edit Adaptive Ramp Metering Parameters

ALINEA | Fuzzy Logic | MaxView

Scheme: Default

Parameter	Value
Active Queue Length Trigger (Number of vehicles)	50.0
Metering Rate for L1	1000.0
Metering Rate for L2	700.0
Metering Rate for L3	600.0
Metering Rate for L4	500.0
Metering Rate for L5	400.0
Metering Rate for L6	300.0
Occupancy Threshold for L1	7.0
Occupancy Threshold for L2	9.0
Occupancy Threshold for L3	12.0
Occupancy Threshold for L4	15.0
Occupancy Threshold for L5	17.0
Occupancy Threshold for L6	19.0
Per Lane Volume Threshold for L1	1025.0
Per Lane Volume Threshold for L2	1950.0
Per Lane Volume Threshold for L3	2188.0
Per Lane Volume Threshold for L4	2425.0
Per Lane Volume Threshold for L5	2638.0
Per Lane Volume Threshold for L6	2850.0
Speed Threshold for L1	70.0
Speed Threshold for L2	60.0
Speed Threshold for L3	50.0
Speed Threshold for L4	40.0
Speed Threshold for L5	35.0
Speed Threshold for L6	30.0

Add | Remove | OK | Cancel

Per the methodology explained in the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* study, a longer strech of I-540 WB was modeled in FREEVAL-NC to account for past and future queue interactions near the interchanges of interest. The results of the application of the model are shown in Exhibit 7.

The baseline data selected for the example analysis is for an average weekday in April 2017. The exhibit shows, in order, , the resulting speed contours obtained using FREEVAL for 1) “No Ramp Metering,” 2) “Uncalibrated Ramp Metering”, and 3) “Calibrated Ramp Metering” cases. The “No Ramp Metering” contour shows FREEVAL results for the modeled facility while no ramp meters are present. The “Uncalibrated Ramp Metering” contours represent the analysis in FREEVAL conducted as part of the 2016 study, while the “Calibrated Ramp Metering” contours represent the updated model developed using the MaxView on-ramp signal parameters. The method used for the 2016 study is in Appendix 2.

Exhibit 7: Comparison of The Before-and-After Results Modeled Using FREEVAL-NC

			Falls of Nuese Interchange				Six Forks Interchange				Creedmoor Interchange				Leesville Interchange			
No Ramp Matering Case	6:00am	70.0	64.7	69.6	63.7	69.9	65.6	69.8	65.9	69.9	64.6	69.9	64.4	69.9	64.5	69.9	64.7	69.9
	6:15am	69.8	64.6	69.6	62.5	68.5	64.9	69.8	64.6	67.8	64.2	69.4	63.2	68.0	64.4	69.4	63.3	67.8
	6:30am	69.3	64.1	69.5	61.5	67.3	64.8	69.0	64.2	66.6	64.1	68.8	62.0	65.8	64.1	68.4	62.1	65.4
	6:45am	65.2	64.1	67.9	58.4	61.2	61.2	66.3	60.0	60.0	60.0	65.7	60.1	61.6	61.6	66.1	59.7	61.1
	7:00am	64.3	63.7	67.9	57.3	60.0	60.0	65.3	57.3	57.3	57.3	64.3	57.8	58.1	58.1	63.1	56.0	56.0
	7;15am	61.6	61.6	66.0	51.9	53.3	53.3	61.5	53.4	53.4	53.4	61.1	54.5	49.5	45.0	27.5	57.3	57.6
	7:30am	49.8	41.5	29.4	34.9	41.5	43.3	24.4	40.4	45.0	47.4	24.9	40.8	40.9	33.5	23.8	57.4	57.7
	7:45am	46.7	44.5	20.1	34.4	41.5	34.1	21.3	41.1	43.7	40.7	23.4	44.6	47.3	36.9	24.9	57.6	57.7
	8:00am	51.5	40.9	22.6	46.4	44.9	37.6	22.7	38.9	33.7	31.0	23.4	50.4	36.4	32.0	24.2	57.5	57.7
	8:15am	70.0	60.2	54.8	57.2	45.1	48.9	29.7	39.5	38.3	67.9	36.7	45.6	40.8	40.6	24.4	57.5	57.7
	8:30am	67.3	64.1	69.2	54.7	47.5	50.0	26.0	45.9	40.3	60.0	33.1	34.7	36.9	61.9	37.0	57.7	57.7
	8:45am	68.0	64.4	69.4	55.3	56.3	57.7	39.1	57.7	48.7	57.7	40.0	40.7	38.7	57.7	51.8	57.7	57.7
	9:00am	69.9	64.7	69.6	62.4	70.0	65.1	69.8	64.4	66.1	64.2	64.7	58.6	51.2	62.7	69.8	60.9	62.6
	9:15am	70.0	64.7	69.6	63.9	70.0	65.7	69.8	65.9	69.9	64.6	69.9	64.3	69.8	64.6	69.9	64.6	69.8
With UnCalibrated Fuzzy Logic Ramp Metering	6:00am	70.0	64.7	69.6	63.7	69.9	65.6	69.8	65.9	69.9	64.6	69.9	64.4	69.9	64.5	69.9	64.7	69.9
	6:15am	69.8	64.6	69.6	62.5	68.5	64.9	69.8	64.6	67.8	64.2	69.4	63.2	68.0	64.4	69.4	63.3	67.8
	6:30am	69.3	64.1	69.5	61.9	67.7	64.9	69.3	64.3	67.1	64.2	69.1	62.2	66.2	64.1	68.6	62.3	65.8
	6:45am	65.2	64.1	67.9	58.9	61.7	61.7	66.6	61.0	61.0	61.0	66.2	60.5	62.3	62.3	66.6	60.1	61.8
	7:00am	64.3	63.7	67.9	57.3	60.0	60.0	65.3	58.8	58.8	58.8	65.1	58.7	59.5	59.5	64.1	58.0	58.1
	7;15am	61.6	61.6	66.0	52.0	53.4	53.4	61.5	54.0	54.0	54.0	61.5	55.1	55.1	55.1	57.9	54.4	54.4
	7:30am	60.4	60.4	54.3	50.9	46.6	41.1	26.2	57.6	57.6	57.6	41.4	46.1	46.9	52.0	26.5	57.4	57.7
	7:45am	64.9	63.7	42.5	41.2	44.2	42.9	23.5	52.6	52.5	54.6	25.0	57.3	47.4	40.9	25.5	57.6	57.7
	8:00am	58.5	45.7	21.7	33.1	38.8	37.9	22.0	38.7	37.7	41.8	23.4	46.2	44.5	33.6	24.9	57.5	57.7
	8:15am	69.2	61.6	53.4	57.8	61.7	70.0	33.0	57.8	44.7	57.7	27.7	57.4	50.1	41.7	25.0	57.5	57.7
	8:30am	67.3	64.1	69.2	54.7	66.4	54.7	28.4	53.1	52.4	40.2	24.7	57.4	55.4	40.0	25.7	57.7	57.7
	8:45am	68.0	64.4	69.4	57.3	61.8	65.7	30.7	58.0	54.4	36.6	25.7	57.7	60.3	40.2	27.2	57.7	57.7
	9:00am	69.9	64.7	69.6	62.8	68.9	65.3	69.7	64.7	61.9	61.6	42.9	61.9	69.1	70.0	38.0	60.7	62.1
	9:15am	70.0	64.7	69.6	63.9	70.0	65.7	69.8	65.9	69.9	64.6	69.9	64.3	69.8	64.6	69.9	64.6	69.8
With MaxVew Ramp Metering	6:00am	70.0	64.7	69.6	63.7	69.9	65.6	69.8	65.9	69.9	64.6	69.9	64.4	69.9	64.5	69.9	64.7	69.9
	6:15am	69.8	64.6	69.6	62.7	68.7	64.9	69.8	64.7	68.0	64.2	69.5	63.3	68.2	64.4	69.5	63.4	68.0
	6:30am	69.3	64.1	69.5	62.0	67.8	64.9	69.3	64.4	67.1	64.2	69.1	62.2	66.3	64.1	68.6	62.3	65.8
	6:45am	65.2	64.1	67.9	58.5	61.2	61.2	66.3	60.9	60.9	60.9	66.2	60.4	62.3	62.3	66.5	60.1	61.7
	7:00am	64.3	63.7	67.9	57.4	60.0	60.0	65.3	59.6	59.6	59.6	65.5	59.9	61.3	61.3	58.9	59.7	60.6
	7;15am	61.6	61.6	64.3	47.7	45.1	57.6	35.3	57.6	57.6	57.6	63.8	58.1	58.2	59.3	37.0	57.3	57.6
	7:30am	52.6	53.3	30.9	37.8	42.4	48.1	24.9	57.7	54.7	57.0	45.4	46.9	41.0	51.6	28.7	57.4	57.7
	7:45am	58.3	38.6	19.4	32.1	35.2	30.4	21.5	37.1	42.5	44.2	24.8	47.3	45.3	55.7	29.2	57.7	57.7
	8:00am	36.5	33.2	20.6	34.1	39.2	37.0	22.5	40.3	40.4	40.7	24.0	44.2	43.8	53.4	28.6	57.5	57.7
	8:15am	66.4	63.9	41.3	57.7	49.2	61.2	24.4	68.4	45.4	69.5	29.5	57.3	54.5	69.1	29.3	57.5	57.7
	8:30am	67.3	64.1	69.2	54.7	52.5	68.2	33.8	58.8	49.5	66.3	30.0	57.7	43.5	57.7	35.7	57.7	57.7
	8:45am	68.0	64.4	69.4	55.3	70.0	58.9	50.1	69.3	52.5	65.6	30.2	57.7	46.1	57.7	48.1	57.7	57.7
	9:00am	69.9	64.7	69.6	60.3	66.4	64.7	68.4	62.9	59.9	69.8	33.4	59.4	55.9	57.9	40.6	57.7	57.7
	9:15am	70.0	64.7	69.6	63.9	70.0	65.7	69.8	65.9	69.9	64.6	69.9	64.3	69.8	64.6	69.9	64.4	69.6

On-ramp signals are designed to regulate the flow of vehicles into a facility by holding the vehicles on the on ramp. This will increase the average speed on the mainline and increase delay for the vehicles that are waiting on the ramp. Overall, a successful on-ramp signal implementation should strike a balance between adding benefits to drivers on the mainline and not severely worsening conditions for drivers on the on-ramp. On-ramp signals can specifically help improve traffic conditions on the “fringes” of traffic where freeways are nearing capacity. This impact can take advantage of availability capacity when roadways are not fully saturated, which can keep traffic moving more smoothly on the mainline.

Exhibit **7** shows these results in the case of the uncalibrated and calibrated models. By comparing “No Ramp Meter” and “Calibrated Ramp Metering” contours, it appears that the resulting speeds are relatively improved by operation of on-ramp signals.

To assess conditions related to these outcomes and how they are modeled differently with the updated model, an analysis of the I-540 WB corridor was conducted. Exhibit 8 shows the high-level comparison of the operational conditions of the corridor identified using the FREEVAL-NC model. Three cases were modeled: conditions with on-ramp signals managed through MaxView, with the application of the uncalibrated algorithm used for the 2016 study, and with no on-ramp signals.

Exhibit 8: Comparison of Model Results for Operational Conditions

Condition	No Ramp Metering Modeled	Uncalibrated "Fuzzy Logic" Ramp Metering	Calibrated MaxView Ramp Metering
Length (mi)	13.5	13.5	13.5
Average Travel Time (min)	13.0	12.8	12.9
VMTD (veh-miles / interval)	653,337.9	653,337.9	653,337.9
VMTV (veh-miles / interval)	653,333.9	653,350.8	653,351.6
PMTD (p-miles / interval)	653,337.9	653,337.9	653,337.9
PMTV (p-miles / interval)	653,333.9	653,350.8	653,351.6
VHT (travel / interval (hrs))	10,520.7	10,324.5	10,401.1
VHD (delay / interval (hrs))	1,689.5	1,739.4	2,234.6
Space Mean Speed (mph)	62.1	63.3	62.8
Reported Density (pc/mi/ln)	10.48	10.26	10.35
Max D/C	1.15	1.15	1.15
Max V/C	1.00	1.06	1.01

Overall, this updated model enables NCDOT to better evaluate the feasibility of implementing on-ramp signals at other locations in the state in future. Notably, this enhanced FREEVAL NC model was adapted using the lookup table and operational data for the specific I-540 WB on-ramp signals. As such, the model will require planners to provide several inputs and parameter changes specific to future on-ramp signal locations to help ensure the accuracy of results. The forthcoming revision to the FREEVAL NC guidance will provide details for applying the model at other locations.

2.7. Develop White Paper

Throughout the process, the research team worked with NCDOT to document "lessons learned" that NCDOT can incorporate into the planning processes for future on-ramp signal project to improve efficiency and effectiveness. This information was incorporated into a lessons learned white paper located in Appendix 6. The white paper summarizes the opportunities for improvement identified by the research team and NCDOT team members. This document can serve as a reference for NCDOT consideration in the future.

3. Evaluation Results

After the on-ramp signals were installed in September 2017, each of the planning-level methods outlined in the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* study were applied to the "after" on-ramp signal data to compare to the "before." In some cases, these methods were revised based on lessons learned through the current study. The guidance for applying these methods as part of a before-and-after evaluation is in the Appendices of this report.

In addition, innovative approaches, such as the Average Historical Congestion Index (AHCI), were applied to comprehensively evaluate the change in traffic conditions after on-ramp signals. The following sections outline the results of these analyses by type.

3.1. Incident Frequency and Duration

As the population of an area increases, the number of commuters using the local roadway infrastructure naturally increases as well. This additional usage often leads to added congestion and traffic incidents. Consequently, on-ramp signals can help reduce the frequency of incidents and the time it takes to clear an incident from the system.

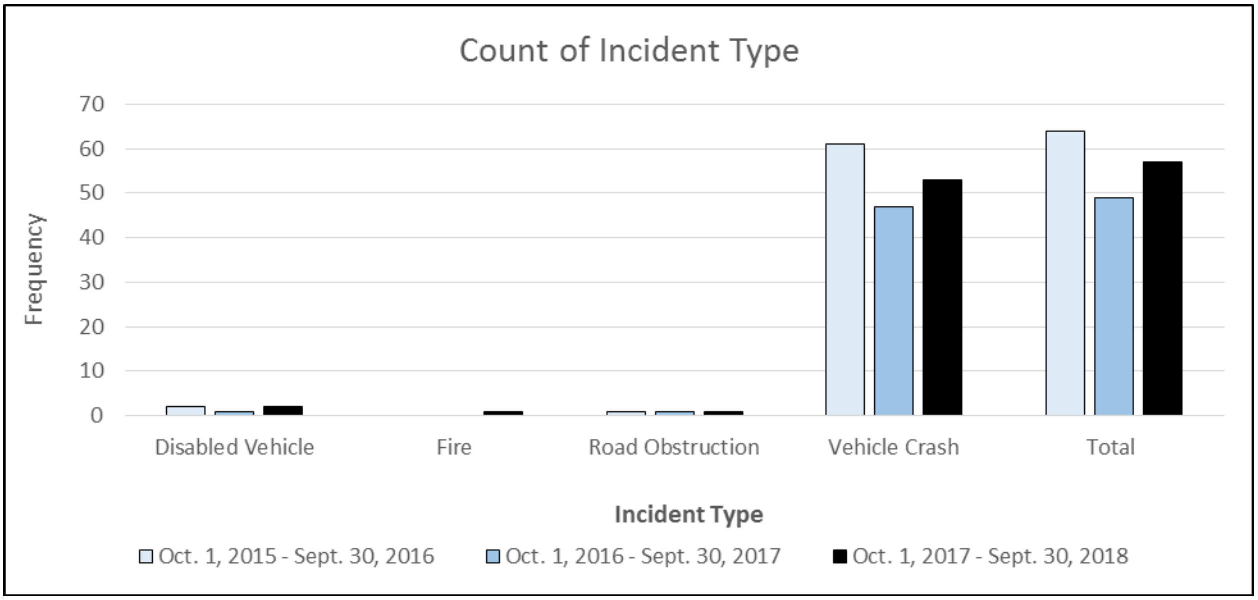
To analyze the changes in incident frequency and duration in the I-540 on-ramp signal area, incident data was compared over time. The occurrence of incidents recorded in the NCDOT Traffic Information Management System (TIMS) for the I-540 westbound on-ramp signal corridor was analyzed for three one-year periods from October 1 to September 30 in 2015-16, 2016-17, and 2017-18. TIMS data was used instead of crash data because this source enabled the research team to examine how incidents beyond crashes may be impacted by on-ramp signals. TIMS also provides granular details recorded by the NCDOT Statewide Operations Center that allowed for the analysis of incident duration and other variables.

In this case, 2015-16 and 2016-17 are the "before" on-ramp signal periods and 2017-18 is the "after" on-ramp signal period. The timeframe of analysis was 6:30am to 9:30am, with the consideration that traffic conditions during the peak period (6:30-9am) may impact incident occurrences past the peak period. These analyses include holiday and inclement weather days to account for all incidents that occur in a full year.

As shown in Exhibit 9, NCDOT records data on different types of incidents that may cause travel time delays and other traffic problems. "Maintenance" and "road obstruction" types are also included in TIMS, but were removed from this analysis because these incidents would not typically be impacted by the presence of on-ramp signals. Across all three periods the most frequent type of incident is traffic crashes.

The analysis presented in Exhibit 9 shows that vehicle crashes decreased for the period after on-ramp signal installation compared to 2015-16 and increased slightly compared to 2016-17, in spite of growing traffic volumes. The frequency of other types of incidents were relatively consistent across the three years. Note that this exhibit excludes incidents categorized as "reported incident" and "other."

Exhibit 9: Incident Frequency by Type Before and After On-Ramp Signals



On-ramp signals may also help reduce the duration of incidents. Exhibit 10 shows the incidents per period by duration in 30 minute increments: incidents that were cleared from interrupting traffic in less than 30 minutes, between 30 minutes and under an hour, etc. As shown in Exhibit 10, the frequency of incidents with a duration of 29 minutes or less and 59 minutes or less decreased for the period after on-ramp signal installation compared to 2015-16. Incidents lasting 1 hour to 1.5 hours and 2 or more hours decreased after on-ramp signals compared to the previous two years, in spite of growing traffic volumes.

Exhibit 10: Duration of Incidents Before and After On-Ramp Signals

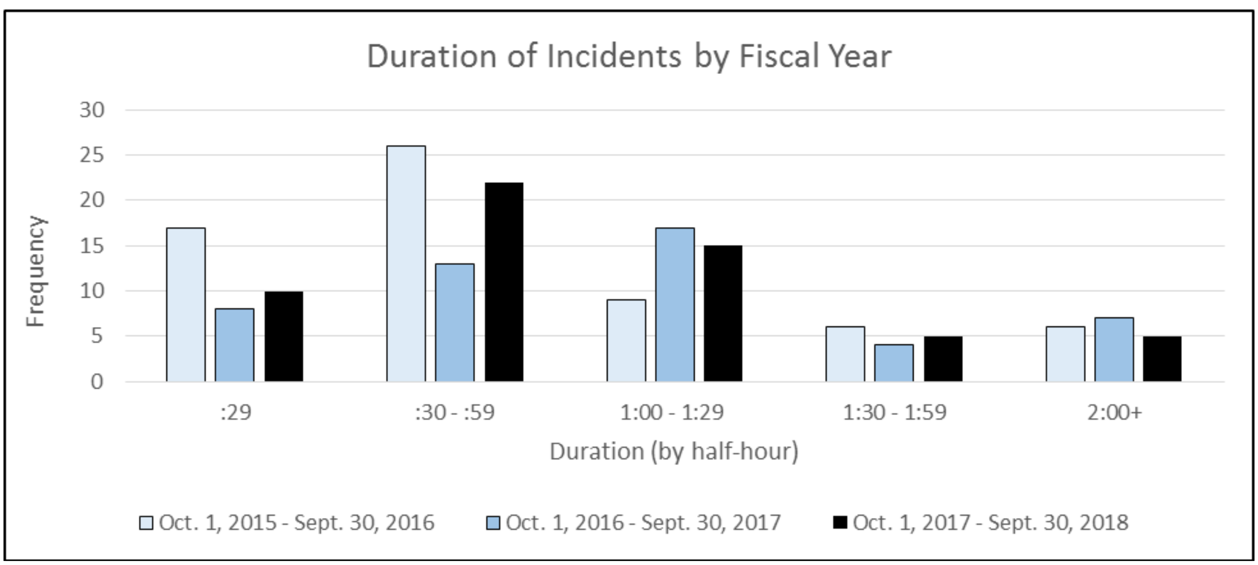


Exhibit 11 and the corresponding data table in Exhibit 12 present the duration patterns by percentage compared the total number of incidents in each period. The percentage of total incidents that lasted 29 minutes less was decreased by 9% after on-ramp signals compared to 2015-16. This trend is visible in Exhibit 11.

Additionally, the percentage of total incidents after on-ramp signals that lasted 1.5 hours or more remained relatively consistent over the three years, in spite of growing traffic volumes. These results indicate that the frequency and duration of incidents was relatively constant after the installation of on-ramp signals, and in several cases, conditions have improved during the period after on-ramp signals.

Exhibit 11: Percent of Total Incidents by Duration Before and After On-Ramp Signals Chart

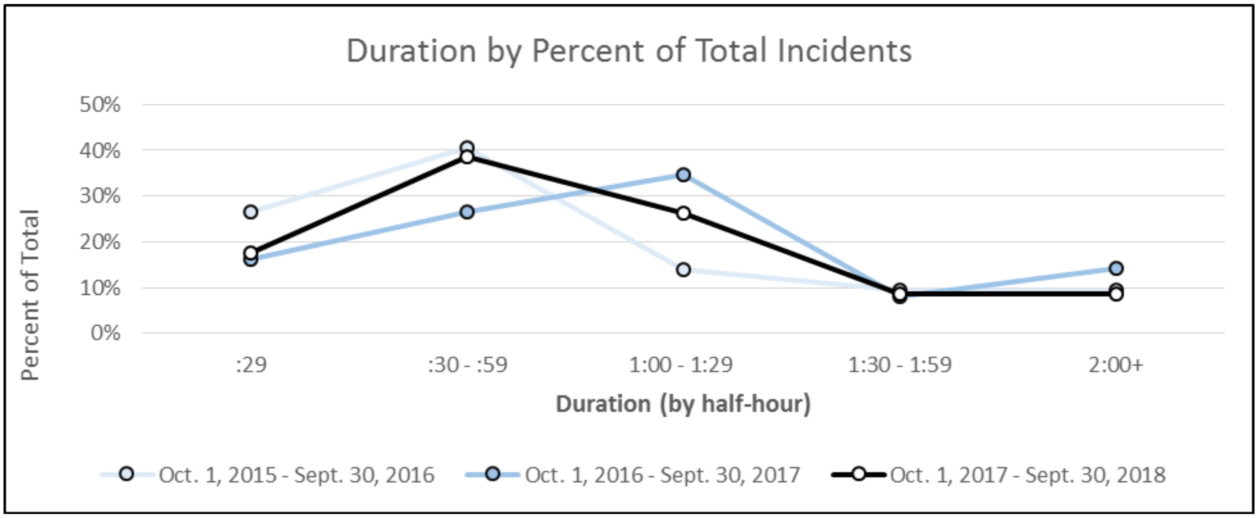


Exhibit 12: Percent of Total Incidents by Duration Before and After On-Ramp Signals Table

Thirty Minute Period	Oct. 1, 2015 - Sept. 30, 2016	Oct. 1, 2016 - Sept. 30, 2017	Oct. 1, 2017 - Sept. 30, 2018
:29	27%	16%	18%
:30 - :59	41%	27%	39%
1:00 - 1:29	14%	35%	26%
1:30 - 1:59	9%	8%	9%
2:00+	9%	14%	9%
Total	100%	100%	100%

Note: The incident impact analyses in this report are not equivalent to a full safety impact analysis, which requires 3-5 years of data to examine the long-term impact of a traffic management strategy. Consequently, crash reduction benefits are not monetized through this study and are not included in the benefit cost analysis portion of this report.

3.2. Freeway Reliability

One of the primary benefits of on-ramp signals is the potential to improve the reliability of traffic conditions for roadway users. The Average Historical Congestion Index (AHCI) is a travel time reliability measure that captures the location and duration of recurring congestion. As part of this measure, recurring congestion is defined as a segment of road with 30% or more weekdays with average speeds below 50 mph for a given time of day. Exhibit 13 shows a comparison of the recurring congestion before and after on-ramp signals for the metered corridor. The section of roadway used for this AHCI comparison included traffic data for the westbound lanes of I-540 in the area of the on-ramp signals from Exit 4 to Exit 18.

Exhibit 13: Recurring Congestion Before and After

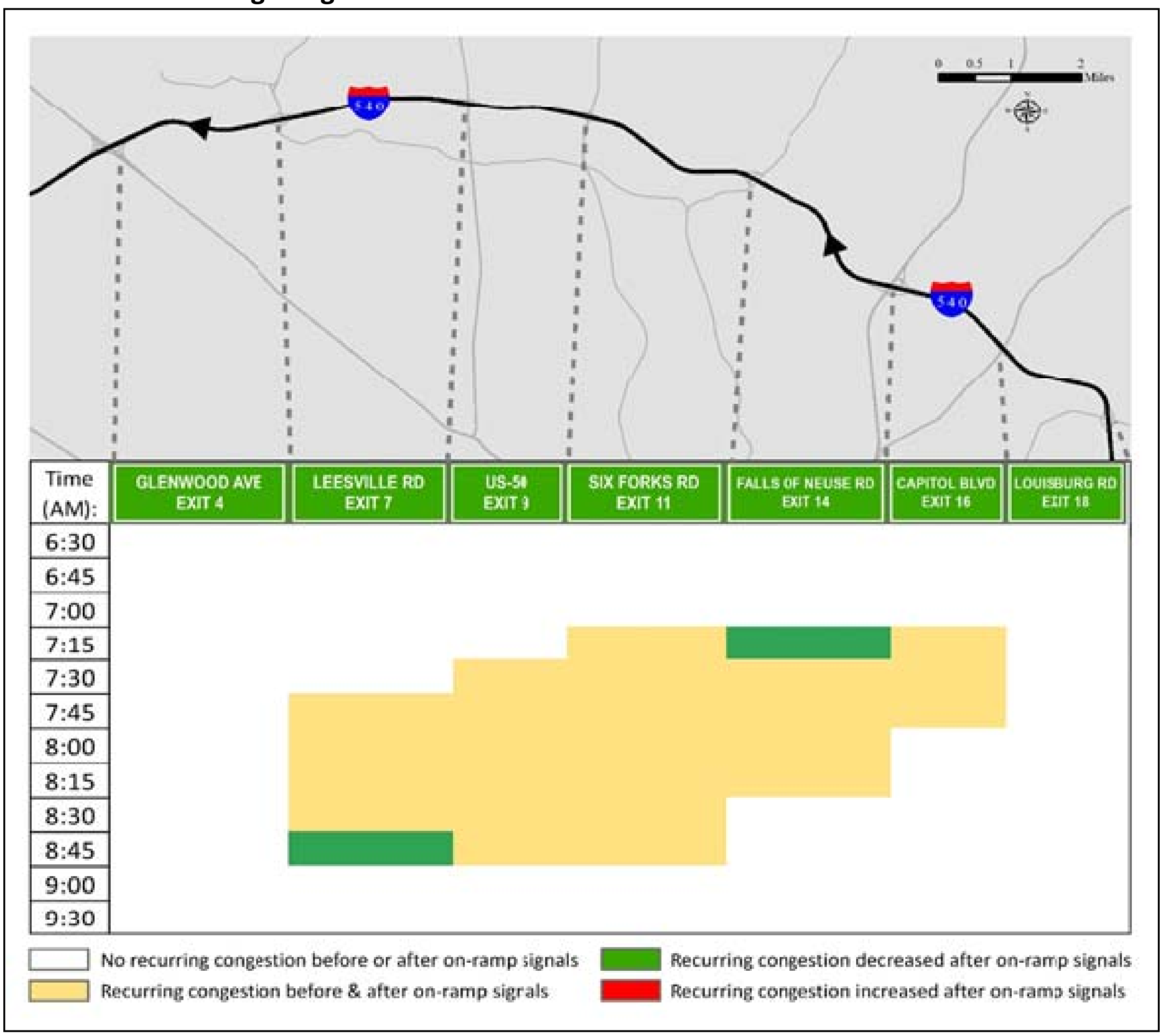


Exhibit 13 compares recurring annual congestion from October 1 to September 30 on non-incident weekdays for the "before" period of 2016-17, and the "after" period of 2017-18. Green sections indicate portions of traffic that experienced recurring congestion before, but not after, on-ramp signals.

On average, there was a 12-minute decrease in the congested period per day along the I-540 on-ramp signal corridor, excluding arterial roadways. This is a 9% overall decrease in reoccurring congestion compared to the period before on-ramp signals. The start of congestion each day was reduced by 6 minutes and congested ended 6 minutes earlier. Importantly, no time periods experienced new traffic congestion since the implementation of the on-ramp signals.

This exhibit also shows that recurring congestion, represented by red sections, did not increase after the installation of on-ramp signals. Overall, this analysis indicates that recurring congestion was reduced upstream and downstream of the on-ramp signal corridor without increasing congestion at any point on I-540 WB. These results reinforce that on-ramp signals can help reduce congestion on the “fringes” of congested periods along the freeway, as the improvements are seen at the beginning and end of the peak congestion period.

3.3. Arterial Reliability

The impact of on-ramp signals to arterials crossing I-540 WB were investigated from a travel time reliability perspective on a monthly basis. In order to reduce the impact of seasonality in the analysis, the monthly reliability travel time measures of effectiveness (MOEs) were compared to the same month in the year before. Through travel times on these corridors obtained from INRIX (probe-based data source) were used for this analysis, with the summation of travel times on the TMC links considered to be the through travel times which may be influenced by the queue spill back from freeway on-ramps.

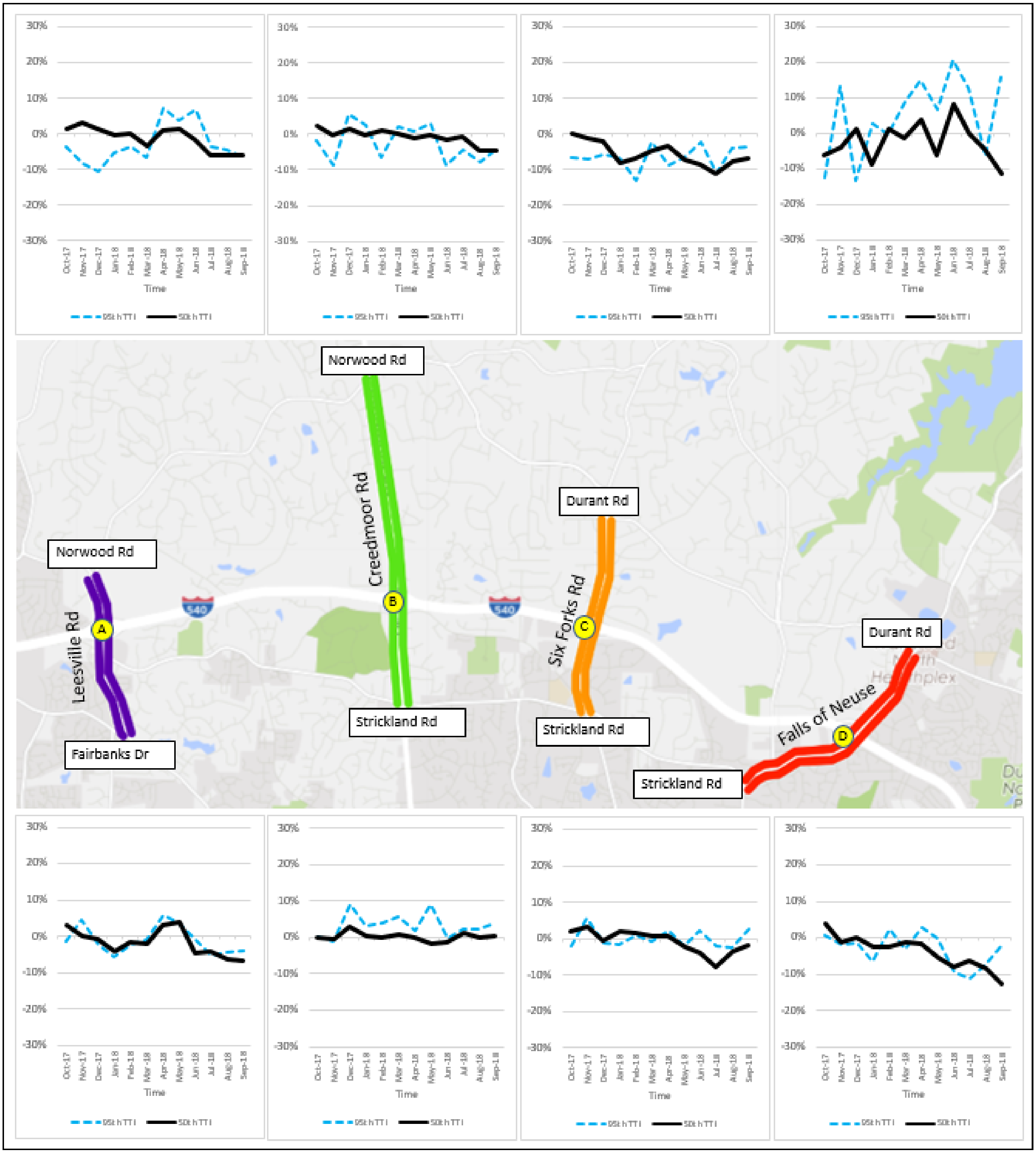
The operational conditions of the crossing arterials on I-540 WB are shown in Exhibit 14. The operational condition is represented by 50th (solid black line) and 95th percentile travel times (blue dashed line). The 95th percentile travel time indicates the reliability of the corridor and can be valuable even in the cases where average travel times do not show improvements. Values below zero indicate more positive outcomes.

This analysis shows that the operation of on-ramp signals on I-540WB impacted the traffic conditions at four of the eight crossing arterials analyzed. Specifically, the reliability of traffic conditions at Six Forks and Creedmoor roads were steadier after on-ramp signals. For these arterials, the amount of variation on the monthly observations are negligible and are likely caused by non-recurring sources of congestion such as severe weather conditions and incidents.

At Leesville Road, the results in Exhibit 14 indicate that the amount of improvement on the operation condition of the arterial is increasing by time. Compared to the other routes, Falls of the Neuse Road experienced a significant amount of fluctuation, which was much better in the Strickland Road area compared to the Durant Road area. This behavior is suspected to be caused by some of the differences in the on-ramp signal operational parameters at this location compared to the other four on-ramps.

The trends shown can also be impacted by the growth in traffic demand, however, improvements are seen for both 50th and 95th percentile travel times. Overall, improvements were observed for the operation of crossing arterials. Additional research related to the before-and-after reliability of these arterials can help further clarify the impact of the on-ramp signals, as a significant amount of variability in the results was observed which limited the ability to make more concrete conclusions.

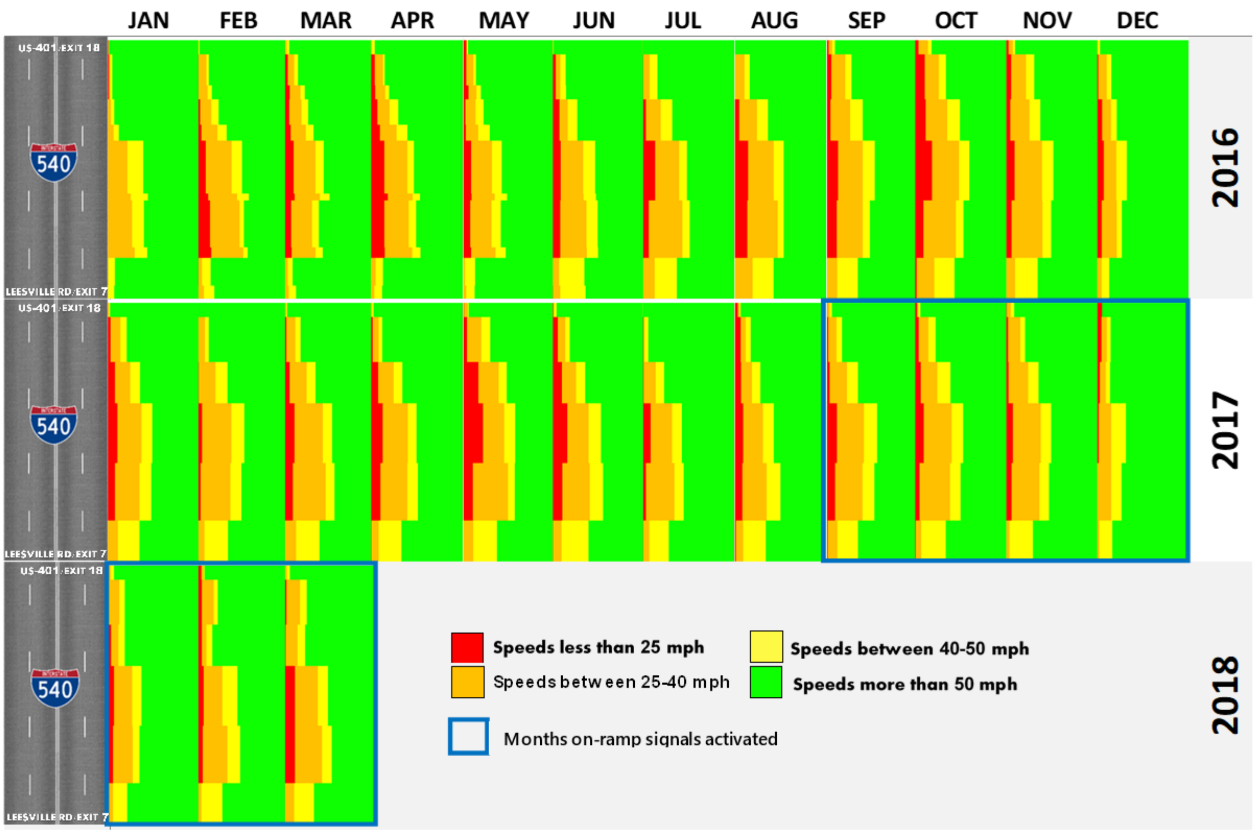
Exhibit 14: Operational Conditions of Four Crossing Arterials Crossing I-540 WB



3.4. Congestion Magnitude

Congestion stack graphs were also generated to evaluate the magnitude of, and change in, congestion over multiple years. For this study, speed observations for I-540 WB freeway lanes near the ramp signals were collected using INRIX and were grouped into monthly bins. This process was conducted for each INRIX TMC (Traffic Message Channel) segment. Exhibit 15 compares the percentage of each month that driver speeds were at given levels of service along segments of I-540 WB, with red indicating severe congestion and green indicating little to no congestion. A blue box is drawn around the time periods that on-ramp signals were activated.

Exhibit 15: Year-to-Year Monthly Morning Peak Congestion Levels by Speed

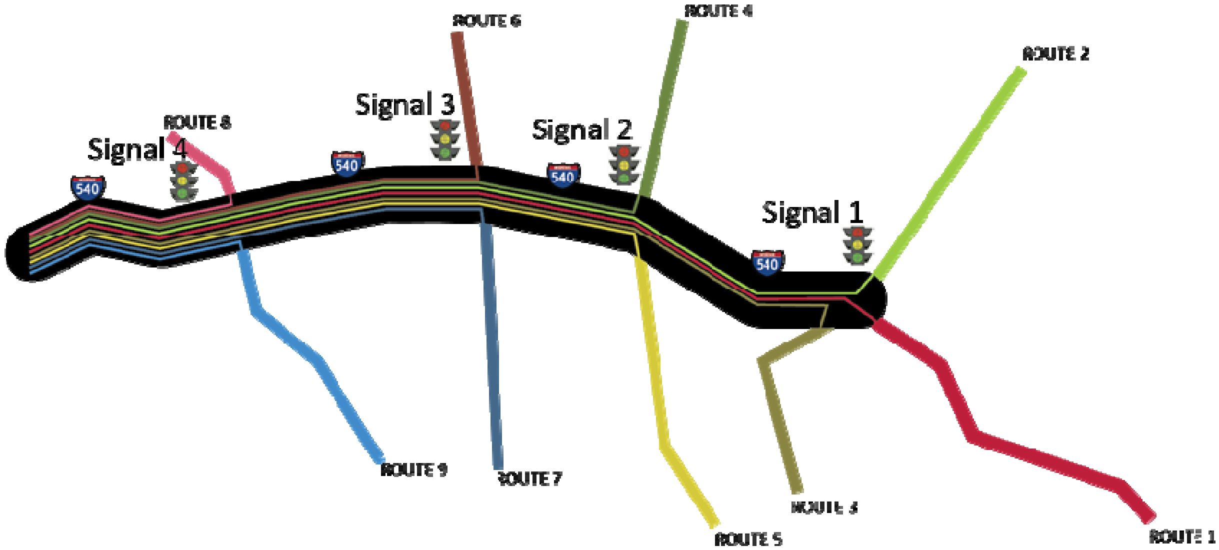


Overall, congestion has decreased and speeds above 50 mph have increased approximately 5% with on-ramp signals. Note that this analysis includes the first six months of the on-ramp signal period because data after this time was unavailable, as NCDOT discontinued use of INRIX after this time.

3.5. Travel Times

Travel (drive) times before and after on-ramp signals were examined for nine typical commuter routes that drivers would possibly drive during the weekday morning peak hours. All routes end at US-70 on I-540 WB and include arterial roads to capture the potential impacts of on-ramp signals on surrounding roads, as shown in Exhibit 16.

Exhibit 16: Nine Commuter Routes Used for Driver Travel Time Analysis



Using traffic data, travel times were analyzed for each day from 6:30am to 9:30am to evaluate the potential impacts of on-ramp signals. The following exhibits show the change in the time it takes a driver to travel from the start of a route to the end of the metered area on I-540 WB, including each of the arterial roadway movements. The route number shown above represents the starting point for each route, with the finish being the end of the on-ramp signal corridor to the west. The period of analysis is October 1 to September 30, with the "before" period in 2016-17 and the "after" period in 2017-18. This analysis excludes holidays and severe weather days.

The average percent reduction in travel times by route and day is presented in Exhibit 17. Averages for the "before" periods were compared to those of the "after" periods, including consideration for seasonality. The negative numbers in green cells indicate benefits due to reductions in travel times for drivers, while the positive numbers in the grey cells show increased travel times.

Exhibit 17: Percent Reduction in Driver Travel Times After On-Ramp Signals Compared to Previous Year

Morning Peak: 6:30-9:30 AM		Average Percent Reduction in Travel Times by Route by Day				
Route Number	Route Start Location	Monday	Tuesday	Wednesday	Thursday	Friday
1	I-540 WB @ US-401	-3.2%	-5.3%	7.5%	-5.1%	0.3%
2	Falls of Neuse @ New Falls	-4.6%	-7.3%	2.5%	-3.5%	-1.5%
3	Falls of Neuse @ Spring Forest	-3.7%	-6.5%	1.4%	-3.3%	-0.9%
4	Six Forks @ Norwood	-5.3%	-5.7%	-0.7%	-3.9%	-0.7%
5	Six Forks @ Spring Forest	-4.0%	-5.4%	0.4%	-3.0%	-0.5%
6	Creedmoor @ Norwood	-4.6%	-4.8%	0.1%	-2.5%	-0.8%
7	Creedmoor @ Lynn	-3.9%	-3.9%	0.6%	-2.0%	-0.6%
8	Leesville @ Hickory Grove Ch.	-4.9%	-4.9%	-1.8%	-3.7%	-1.9%
9	Leesville @ Lynn	-2.9%	-4.5%	-1.9%	-2.7%	-1.6%

As shown, times have consistently improved 84% of the time for drivers using the metered area during the morning on weekdays, with up to a nearly 2 minute (7.3%) decrease per person per day. These benefits accrued despite an annual increases in traffic volumes. The cause of increased travel times on Wednesday for some routes is unknown.

Exhibit 18 to Exhibit 22 present the same information as distributions, with blue lines showing travel times for the year prior to on-ramp signals and black lines showing travel times for the metered period. The travel time changes for Route 1, which includes the I-540 WB corridor from beginning to end, are shown in Exhibit 18. Black lines lower than blue lines indicate a reduction in travel time after on-ramp signals that resulted in time savings for many drivers using the metered area.

Overall, travel times on most routes were consistently lower for drivers after on-ramp signals, particularly after 7:30am when traffic congestion is at the highest level. These results indicate that the on-ramp signals are improving traffic conditions and reducing travel times for many I-540 WB drivers.

Exhibit 18: Travel Time Comparison for Route 1 (I-540 WB at US-401)

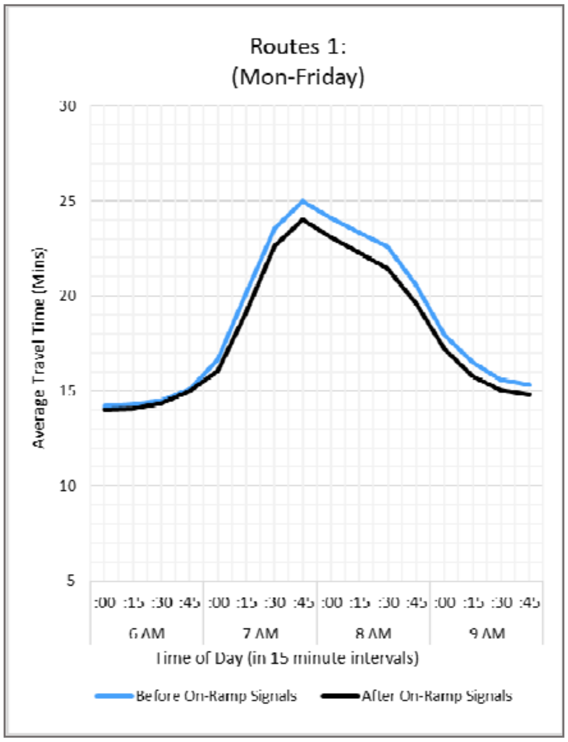
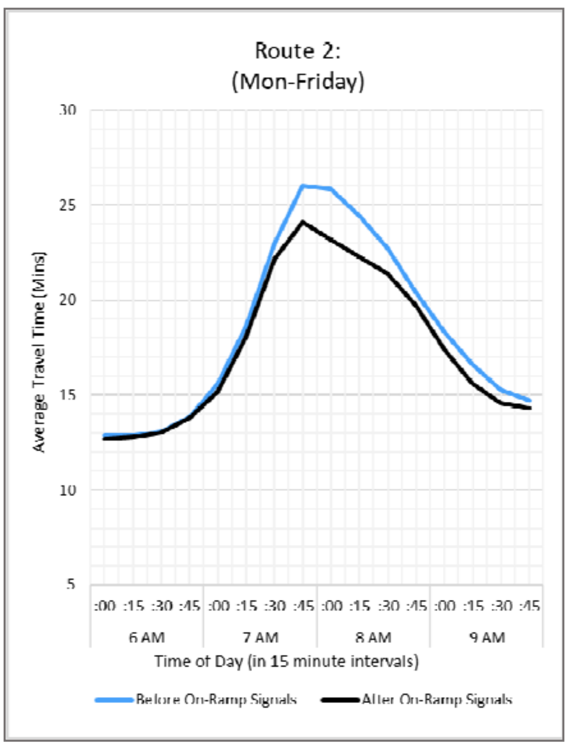


Exhibit 19: Travel Time Comparison for Route 2 (Falls of Neuse Rd. at New Falls) and Route 3 (Falls of Neuse Rd. at Spring Forest)



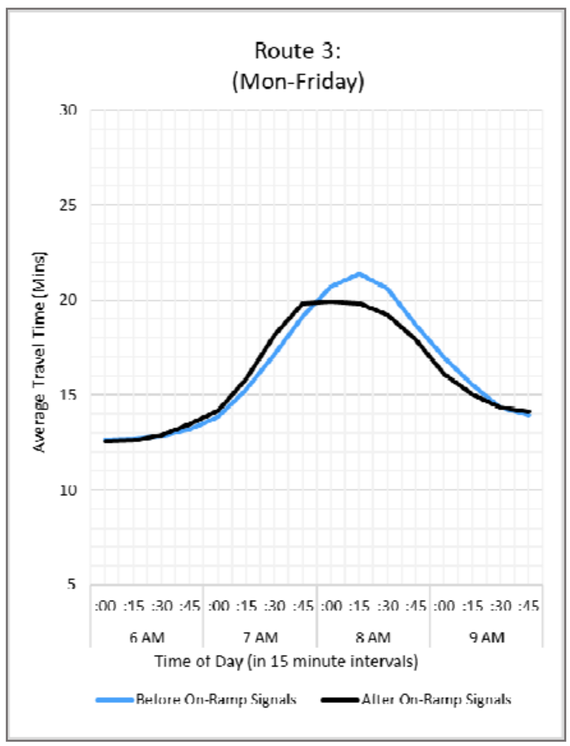
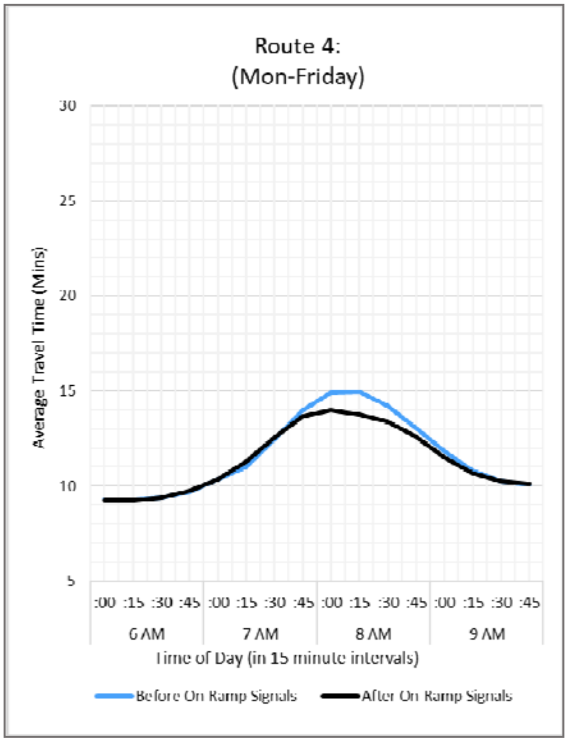


Exhibit 20: Travel Time Comparison for Route 4 (Six Forks Rd. at Norwood) and Route 5 (Six Forks Rd. at Spring Forest)



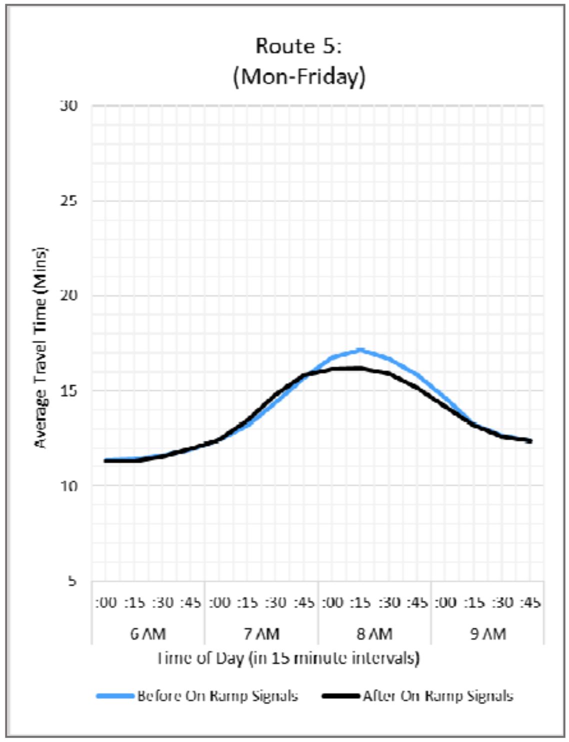
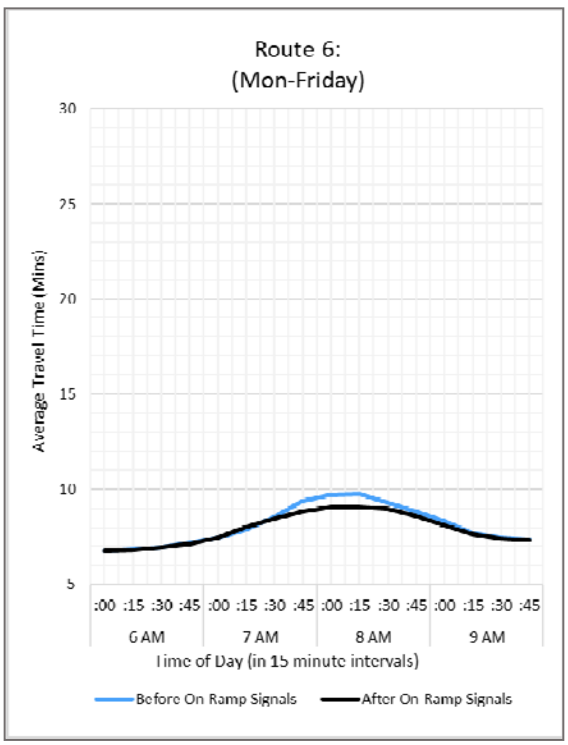


Exhibit 21: Travel Time Comparison for Route 6 (Creedmoor Rd. at Norwood) and Route 7 (Creedmoor Rd. at Lynn)



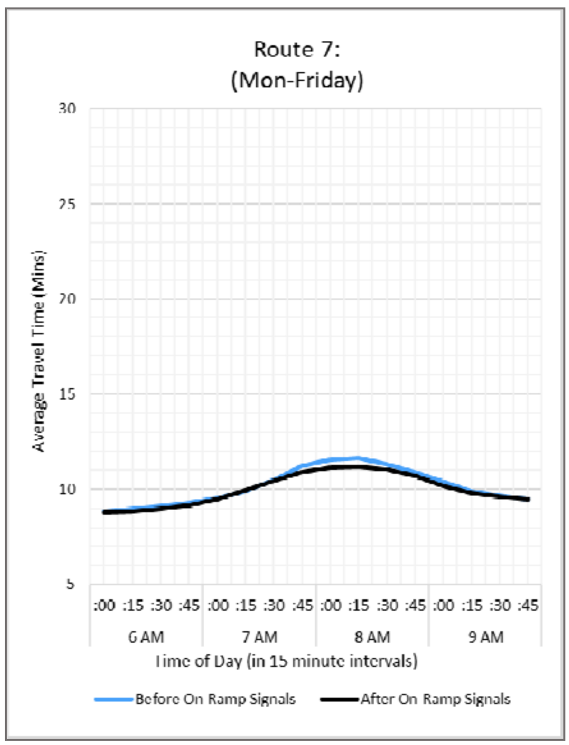
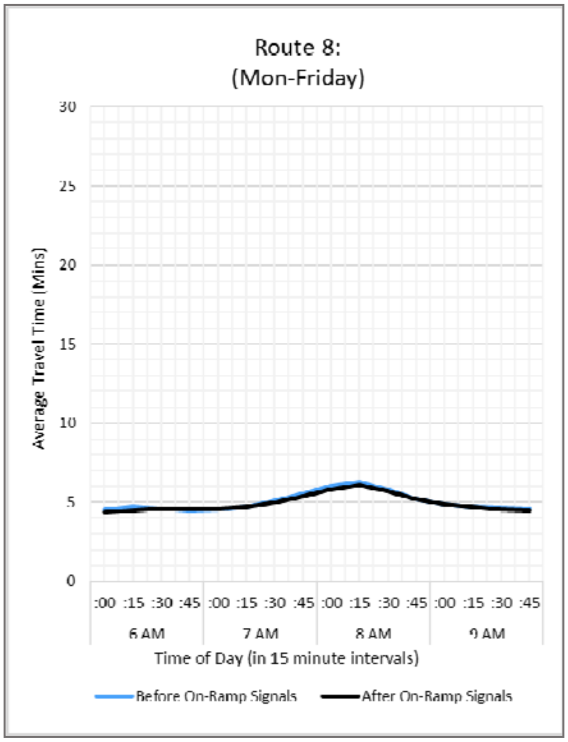
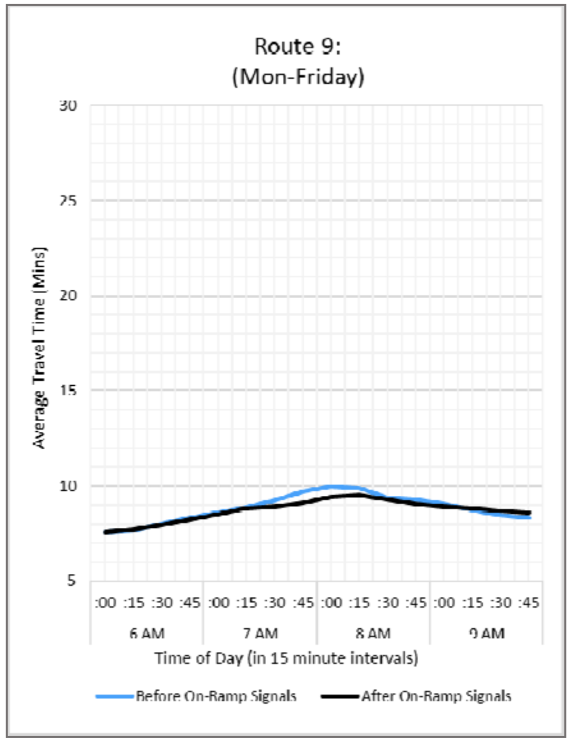


Exhibit 22: Travel Time Comparison for Route 8 (Leesville Rd. at Grove Church) and Route 9 (Leesville Rd. at Lynn)





3.6. Traffic Volume

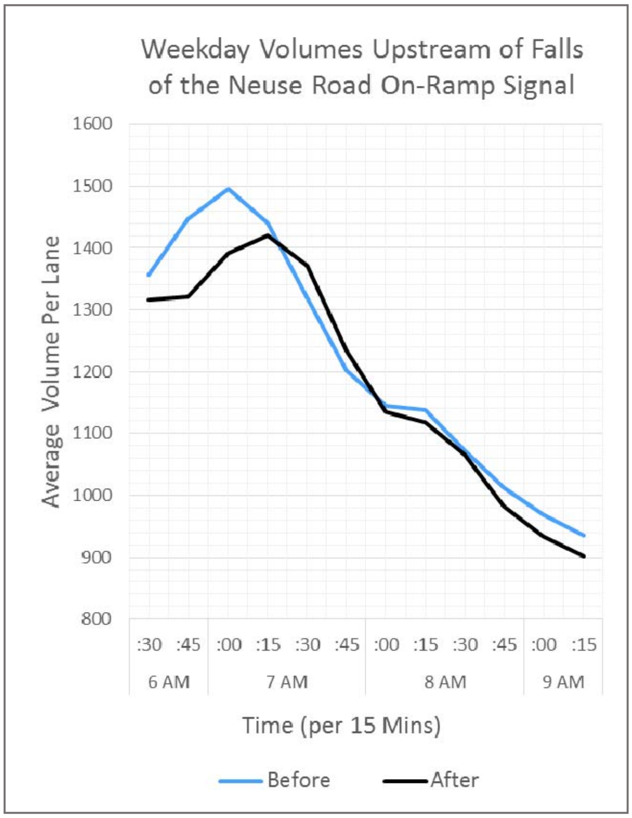
Comparing volumes on a corridor before and after a system change such as on-ramp signals can indicate how commuters have adapted to the change. For this reason, the hourly flow rates of vehicles traveling through the I-540 WB on-ramp signal corridor were compared. The primary data source used to develop this comparison are sensors upstream and downstream of the on-ramp signals. The specific locations of the two data collection points are upstream and downstream of on-ramp signal locations indicated by green stars in Exhibit 23.

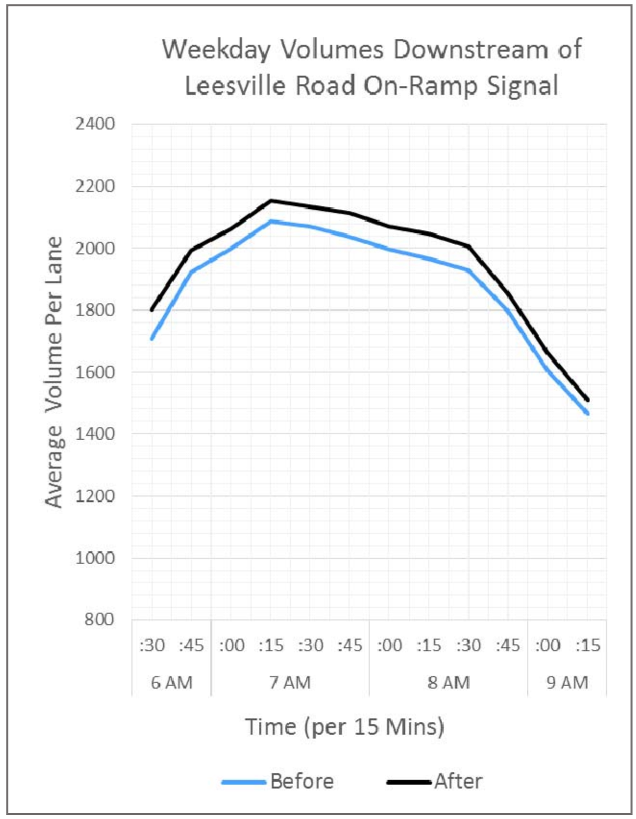
Exhibit 23: I-540 Volume Data Sensor Locations

To examine the before and after traffic volumes, the aggregated average hourly flow rates of vehicles were compared. In some cases, sensor data was supplimented with other soruces, such as manual counts, due to intermitent equipment errors. The results of this analysis are shown in Exhibit 24. The period of analysis is October 1 to September 30, with the "before" period in 2016-17 and the "after" period in 2017-18. This analysis excludes holidays and severe weather days.

The analysis results for both the up and downstream sensor locations are shown in Exhbit 24. Blue lines in Exhibit 24 show volumes for the year prior to on-ramp signals and the black lines show volumes for the on-ramp signals period. Black lines close to or above blue lines indicate that the number of drivers is the same or higher than pre-on-ramp signals conditions.

Exhibit 24: Distribution of I-540 Volumes for Both Sensor Locations for All Weekdays





This exhibit shows that hourly flow rates on I-540 WB were, on average, the same or slightly higher than pre-on-ramp signals values. Consequently, it does not appear that on-ramp signals signifcantly impacted the number of drivers using the on-ramp signal corridor during the morning peak period. This is indicated by the after period (black) lines that are consistentently near or above the before period (blue) lines in Exhibit 24.

Additionally, volumes at the upstream location peaked later in the day following the installation of the on-ramp signals, which may indicate that drivers are starting their commutes later due to increased travel time reliability. The downstream sensor seems to indicate that more throughput is consistently taking place on the freeway during the peak, increasing the effective capacity of the freeway during congested conditions.

Note: This analysis does not account for work zones in the area or other scenarios that may influence the number of drivers on I-540. This analysis incorporates NCDOT sensor data that is still in the validation process.

3.7. Vehicle Hours of Delay

Vehicle Hours of Delay (VHD), a product of delay and volume, was calculated to determine the level of delay on I-540 WB before and after on-ramp signals. The method for developing this analysis is detailed in Appendix 5.

A comparison of distribution of the sum of the annual vehicle hours of delay for the I-540 WB corridor before and after on-ramp signal is shown in Exhibit 25. This analysis uses traffic data and excludes holidays and severe weather days. The results indicate that the total annual vehicle hours of delay for the corridor decreased by approximately 8.5% after the installation of on-ramp signals, considering a 3.5% estimated annual growth in vehicle hours of delay.

Exhibit 25: Distribution of Annual Vehicle Hours of Delay Before and After On-Ramp Signals

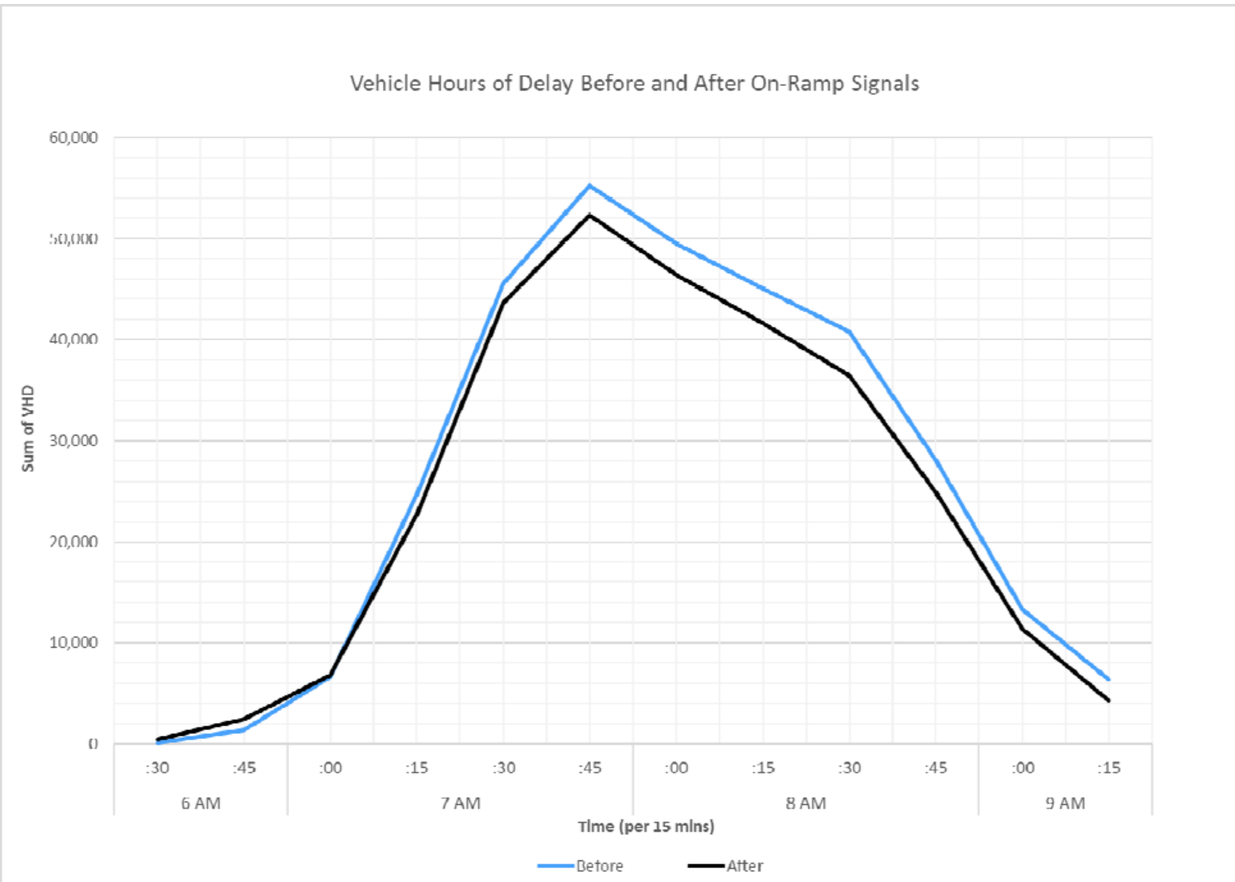


Exhibit 26 details the long-term impact of this reduction, showing the 10-year comparison of the VHDs for the on-ramp signal corridor before and after. These results indicate that over the next 10 years, on-ramp signals can reduce the vehicle delay for commuters by more than 338,522 hours, as shown in Exhibit 26. This equates to a savings of 13 hours per average daily commuter vehicle.

Exhibit 26: Comparison of Annual Vehicle Hours of Delay Before and After On-Ramp Signals

	Annual Totals for Weekday Peak Periods		
Year	**VHD w/o On-Ramp Signals**	**VHD w/ On-Ramp Signals**	**Reduction in VHD**
2017 (Installation)	330,203	330,203	-
2018	341,760	314,980	26,780
2019	353,722	323,655	30,066
2020	366,102	334,983	31,119
2021	378,915	346,708	32,208
2022	392,177	358,842	33,335
2023	405,904	371,402	34,502
2024	420,110	384,401	35,709
2025	434,814	397,855	36,959
2026	450,033	411,780	38,253
2027	465,784	426,192	39,592
Total: 2018-2027	***4,009,320***	***3,670,798***	***338,522***

These results include an annual volume growth factor of 3% and an annual increase in vehicle hours of delay of 3.5%, based on historic traffic data. The forecasted reduction incorporates these growth factors with a consideration of an 8.5% annual reduction in VHD after on-ramp signals compared to the "no build" scenario without on-ramp signals.

3.8. Benefit-Cost Analysis

The comprehensive benefits and costs of the I-540 WB ramp meters are detailed in this section. The details of the benefit-cost analysis methods applied through this study are outlined in the *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways.* This method is outlined in Appendix 3.

The research team applied similar methods to forecast the benefits and costs prior to on-ramp signal installation during the planning-level analysis was applied using actual traffic data. However, the results of the studies vary primarily due to assumptions made in the pre-installation models related to actual on-ramp signal operational parameters, which were unknown at the time.

The pre-installation study also incorporated the estimated benefits of crash cost savings. The post-installation study did not include an estimation of the monetary value of safety benefits due to the limited duration that the on-ramp signals have operated. In addition, the post-installation analysis outlined in this report includes additional considerations such as staffing costs, which were unknown during the pre-installation study.

Because the I-540 WB on-ramp signals were installed during 2017, this year is considered the baseline year, or “Year 0,” for the benefit cost analyses in this report. Most benefit-cost analysis literature refers to the installation period of a project as “Year 0.” As such, 2017 is considered the “no-build scenario”, with the idea that benefits of on-ramp signals are gained only after installation and activation. Some of the data analyses used in this benefit-cost analysis were conducted for the period of October 1 to September 30. In these cases, the 12-month periods of data are used as a proxy for a full calendar year from January 1 to December 31 in the benefit-cost analysis. For example, data from October 1, 2016 to September 30, 2017 is used to represent a full year of 2017 in some parts of the benefit-cost analysis.

The following sections outline the benefits and costs associated with the I-540 WB on-ramp signals.

3.8.1. Capital, Programming, and Operational Investments

The upfront costs associated with on-ramp signals are installation costs, or the capital funds needed to install the signal infrastructure for the first time. For the I-540 WB on-ramp signals, this cost was considered as a one-time expenditure. As shown in Exhibit 27, the estimated total capital cost of installing all four of the I-540 WB on-ramp signals was $830,170.

Exhibit 27: Individual On-Ramp Signal 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

The installation also included a one-time programming cost, which will likely only be required once in the life of the on-ramp signals. This estimated programming cost was $405,000, as shown in Exhibit 28.

Exhibit 28: 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

While a discount rate, which accounts for the changing value of money over time, is only applied to investments that occur after the year of installation. Therefore, the 3% discount rate used in this study is only applied to costs and benefits that begin after 2017. Maintenance costs associated with on-ramp signals are considered to accumulate annually and 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 (MDOT, 2015). The annual estimated cost of ongoing maintenance and operations investments for the four on-ramp signals is $29,964, as shown in Exhibit 29.

Exhibit 29: Estimated Annual Maintenance and Operations Costs

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

In addition, the on-ramp signal operations can require ongoing performance monitoring and other tasks that require transportation staff time. The long-term costs associated with the staff required to support the operations of the I-540 WB on-ramp signals are shown in Exhibit 30, which presents the total staffing investment of $356, 490, including overhead rates, benefits, and other costs, needed to support the on-ramp signals during the installation year and for the next 10 years.

These estimations are also similar to the staffing costs for future North Carolina on-ramp signal projects. These costs are not expected to increase significantly with the addition of new on-ramp signals within a system, although they may increase with the time that a given on-ramp signal system is operational. For example, additional staff may be needed if the I-540 WB on-ramp signals are operated during the afternoon peak period in addition to the morning peak.

Exhibit 30: NCDOT Staffing Costs for On-Ramp Signal Operations

Staff Support Cost	Weekly Compensaton	Annual Compensation	Total Projected for Years 2018-27*
TMC Floor Operator Compensation	$636	$32,197	$274,645
TMC Engineer	$190	$9,595	$81,845
Total	*$826*	*$41,792*	***$356,490***

*These projections are discounted into the future

The total estimated capital, programming, and operation investments required for the I-540 WB on-ramp signals are shown in Exhibit 31. The total anticipated cost is $1,655,560 over 10 years

Exhibit 31: Total Capital, Programming, and Operational Investments

Cost	Installation Year 2017	Total Projected for Years 2018-27*
Installation (Four On-Ramp Signals)	$830,170	N/A
Programming	$405,000	N/A
Operations and Maintenance	N/A	$63,900
NCDOT Staff Support	N/A	$356,490
Facility Replacement**	N/A	$0
Total Cost for 2017-27		***$1,655,560***

*These projections are discounted into the future
**It is not expected that the facility will need to be replaced until after 10 years

3.8.2. Value of Decreased Driver Delay

On-ramp signals can help reduce the net delay of roadway users by decreasing and smoothing congestion (USDOT, 2016; Zhang and Levison, 2010; WisDOT, 2006). Because traffic delays can come at a high cost to commuters, policy analysts commonly monetize delay using a measure called value of travel time (VDOT, 2013).

In this analysis, delay was valued at $33.58 per vehicle per hour. This value of travel time figure incorporates several considerations. Texas A&M Transportation Institute estimates the value of an hour of time for passenger and heavy vehicles at $17.67 and $94.04, respectively (Schrank, Eisele, Lomax, and Bak, 2015). Data for the I-540 WB on-ramp signal corridor shows that heavy vehicles comprise approximately 5% of traffic during the morning peak, for a corridor average of $21.49 per hour (95% passenger vehicles, 5% heavy vehicles), per vehicle on the corridor.

Because some of these vehicles may include more than one passenger, 1.25 was applied as the standard vehicle occupancy. This vehicle occupancy rate is the same as the average proposed by Schrank, Eisele, Lomax, and Bak (2015), and considers the behavior of average I-540 WB commuter. Therefore, the total value of travel time per vehicle per hour used for this analysis is $33.58 ($21.49 x 1.25). As described in the method detailed in Appendix 3, the delay experienced on the I-540 WB on-ramp signal corridor was monetized by applying the value of travel time to the before and after vehicle hours of delay (VHD) shown in Exhibit 26.

The 10 year (2018-2027) monetized values of these differences in vehicle hours of delay are shown in Exhibit 32. The resulting values reflect the difference in vehicle hours of delay and corresponding the costs before on-ramp signals compared to the “no build” scenario without on-ramp signals. Positive VHD numbers and monetized values indicate a decrease in VHD and delays after the I-540 WB on-ramp signals. Note that these costs are discounted at a rate of 3% annually to account for the changing value of money overtime, similar to inflation.

Exhibit 32: Monetary Value of Vehicle Hours of Delay Difference Over 10 Years

	Annual Totals for Weekday Peak Periods				
Year	VHD w/o On-Ramp Signals	Cost of Delay w/o On-Ramp Signals	VHD w/ On-Ramp Signals	Cost of Delay w/ On-Ramp Signals	Difference in Cost of Delay
2017 (Installation)	330,203	$11,086,818	330,203	$11,086,818	N/A
2018	341,760	$11,140,637	314,980	$10,267,682	$872,955
2019	353,722	$11,194,718	323,655	$10,243,167	$951,551
2020	366,102	$11,249,061	334,983	$10,292,891	$956,170
2021	378,915	$11,303,668	346,708	$10,342,857	$960,812
2022	392,177	$11,358,540	358,842	$10,393,065	$965,476
2023	405,904	$11,413,679	371,402	$10,443,516	$970,163
2024	420,110	$11,469,085	384,401	$10,494,213	$974,872
2025	434,814	$11,524,760	397,855	$10,545,156	$979,605
2026	450,033	$11,580,706	411,780	$10,596,346	$984,360
2027	465,784	$11,636,923	426,192	$10,647,784	$989,138
Total: 2018-2027	*4,009,320*	*$113,871,779*	*3,670,798*	*$104,266,677*	***$9,605,102***

In total, these results show a savings of $9,065,102 in delay costs for I540 WB drivers over 10 years with on-ramp signals. Considering volumes for the I-540 WB on-ramp signal corridor, this equates to $38 a year in delay savings for the average daily commuter vehicle. This means that a commuter that typically drives the on-ramp signal corridor each weekday will save $369 over 10 years.

3.8.3. Total Benefits of On-Ramp Signals

In total, as shown in Exhibit 33, the total net benefits forecasted to accumulate over the ten years after the installation of the on-ramp signals is $7,949,541. This benefit calculation excludes safety benefits, which cannot be determined without additional years of before-and-after data.

Exhibit 33: Total Forecasted I-540 WB On-Ramp Signal Costs and Mobility Benefits Over 10 Years

Type of Benefit/Cost	First Year Costs in 2017*	Total Costs Projected for 2018-27*	Total Benefits Projected for 2018-27*
Installation (Four On-Ramp Signals)	$830,170	N/A	N/A
Programming	$405,000	N/A	N/A
Operations and Maintenance	N/A	$63,900	N/A
NCDOT Staff Support	N/A	$356,490	N/A
Reduction in Delay	N/A	N/A	$9,605,102
Total Net Benefits 2017-27			***$7,949,541***

*These projections are discounted into the future

These findings exclude estimations of the cost savings associated with safety benefits, which cannot be determined without additional years of before-and-after data. Given the results of ramp meters in other parts of the United States, it is likely that the I-540 WB on-ramp signals will result in long term safety benefits values (Zhang, 2007; Fontaine and Miller, 2010). As part of the 2016 pre-installation study, the on-ramp signals were forecasted to result in an additional $1.4 to $4.1 million in benefits over 10 years due to a reduction in traffic crashes.

4. Conclusion and Recommendations

Since September 2017, the first four on-ramp signals in North Carolina, positioned on the westbound lanes of I-540 in Wake County, have been regularly activated Monday to Friday from 6:30 - 9am. This report focused on the impact of these on-ramp signals. The results identified are the product of data collected in the I-540 WB area over multiple years from numerous sources, both before and after on-ramp signals. When feasible, the costs and benefits of the on-ramp signals were monetized using benefit cost analysis methods.

In addition, the analytical methods updated and developed through this study will provide NCDOT with planning and evaluation frameworks that can be readily applied to future on-ramp signal projects. In the future, NCDOT can use the planning-level tools to evaluate the potential of implementing on-ramp signals in other locations in the state and apply the evaluation tools to assess the impacts of the on-ramp signals after installation. Ultimately, the methods, processes, and lessons learned delivered with this study can help North Carolina make faster and more accurate decisions about future on-ramp signal projects.

Key conclusions and recommendations are outlined in the following sections, with the key methods detailed in the Appendices.

4.1. Key Outcomes

A comparison of before and after traffic conditions during morning weekday peak hours from shows that following results, on average, after the installation of on-ramp signals. *

Decreased Delay Benefits

- **$9.6 Million in driver delay savings over 10 years** for the on-ramp signal corridor, excluding arterial roadways
- **13 hours of delay savings over 10 years for the average daily commuter vehicle** using the on-ramp signal corridor, excluding arterial roadways
- **8.5% annual decrease in vehicle hours of delay** for the on-ramp signal corridor, excluding arterial roadways
- **$38 a year in delay savings for the average daily commuter vehicle** using the on-ramp signal corridor, excluding arterial roadways

Travel Time Reductions

- **84% of commuters experienced shorter drive times** in the on-ramp signal area each week, including arterial roadways
- **Up to 2 minutes (7.3%) decrease in drive time per day for a commuter** using the on-ramp signal area, including arterial roadways

Congestion and Volume Improvements

- **9% decrease in reoccurring congestion** along the I-540 on-ramp signal corridor, excluding arterial roadways
- **12-minute decrease in the congested period per day** along the I-540 on-ramp signal corridor, excluding arterial roadways
- **Overall increase in driver volumes** on I-540, indicating that the majority of drivers are not deterred by the on-ramp signals

The net mobility benefits forecasted to accumulate over the ten years after the installation of the on-ramp signals is $7,949,541 over 10 years. This value does not include consideration of additional types of benefits such as decreases in emissions and reduction in crash number and severity, as a longer before-and-after comparison is needed to monetize these outcomes.

These mobility improvements accrued during the morning weekday peak period despite an annual average 3-4% growth in traffic volumes. According to a 2018 U.S. Census report, 63 people move to Wake County each day, around 23,000 new residents each year. Many of these individuals use the I-540 corridor, and traffic congestion in the area continues to grow with the additional traffic. Yet, in the first year of the on-ramp signal, traffic flow in the area of the on-ramp signals was smoother and congestion and breakdowns were reduced. Given these results, it is anticipated that drivers will continue to experience benefits of on-ramp signals into the future as the technology mitigates the impacts of growing traffic in the area.

The cost savings associated with safety benefits cannot be determined without additional years of before-and-after data. Given the results of ramp meters in other parts of the United States, it is likely that the I-540 WB on-ramp signals will result in long-term safety benefits. As part of the 2016 pre-installation study, the on-ramp signals were forecasted to result in an additional $1.4 to $4.1 million in benefits over 10 years due to a reduction in traffic crashes.

**Note: These results were calculated using the approaches described in the Methodology and Guidance Development section, and are limited by the scope of the analyses conducted through this study and the available data.*

4.2. Lessons Learned

Through the current study, experiences and lessons learned were documented to enhance future planning and implementation approaches to on-ramp signals in North Carolina. These lessons learned are outlined in a white paper in Appendix 6. These lessons learned also reflect the limitations of this study.

4.3. Sensitivity Analysis

The research team conducted sensitivity analyses on data to help increase the confidence in the accuracy of results. These analyses involved examining multiple traffic data sources as well as examining how inputs such as the volumes growth factor impacted results. Through these processes, the research team developed more robust and methodologically sound research approaches and analyses, given available data.

4.4. Influence of Project Characteristics

The benefits and cost associated with on-ramp signals may vary by project, such as:

- Location selection – Factors like level of congestion, configuration, and capacity of a facility may impact benefits. For example, implementing on-ramp signals in areas with more severe reoccurring bottlenecks may provide the opportunity for more significant decreases in delay and safety issues.
- Ramp configurations – Minimal ramp storage may reduce the opportunity for mobility benefits, while more significant configuration changes that may require planning exceptions and more construction but may offer more significant mobility benefits.
- Resources applied – The level of internal resources applied to support operations needs to be estimated and negotiated during the project planning phase. Roles between NCDOT, the on-ramp signal vendor, and contractors, along with associated costs, need to be defined clearly during the project planning phase.

Evaluating and estimating the impact of these factors during the project planning phase will help ensure that a given on-ramp signal implementation is as optimally efficient and effective.

4.1. Additional Benefits

As previously referenced, the monetized benefits identified through this study focus on mobility outcomes. Additional benefits related to other outcomes such as decreases in emissions and reduction in crash number and severity may also accrue into the future due to the on-ramp signals. However, the research team did not monetize benefits beyond mobility as part of this report because cost savings associated with types of outcomes cannot be determined without additional years of before-and-after data. For example, to further examine the benefits of on-ramp signals, NCDOT should conduct a full safety study of the on-ramp signal area once 3-5 years of post-installation crash data is available.

4.2. Future Research

The post-installation evaluation of the I-540 WB on-ramp signals detailed in this report, provides conclusions based on the available data and specific conditions of the I-540 on-ramp signal area. Therefore, the results of on-ramp signals at other locations may vary and the before-and-after results of this study are not transferable to similar North Carolina projects. However, NCDOT can readily the resources provided through this study and the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* study to more effectively plan and evaluate future on-ramp signal projects.

These projects will provide an opportunity to further refine these methods and processes to better reflect North Carolina operations. Consequently, it is recommended that NCDOT collect lessons learned and conduct impact evaluations for each future on-ramp signal project. With these findings, NCDOT can continue to further enhance the resources developed through this study to better address on-ramp signal needs specific to North Carolina.

NCDOT may also benefit from exploring additional variables beyond those explored in this report. Long-term studies of the I-540 WB on-ramp signals or studies of on-ramp signals at future locations may include variables beyond those examined in this report. Examples include additional performance measures related to safety, fuel use or idling, improvements in quality of life due to reduced stress related to highway congestion, system-level travel time reliability, and operating and ownership costs (MDOT, 2015; WisDOT, 2006).

In addition, there is an opportunity to build upon tools like the I-540 WB on-ramp signal online dashboard, which NCDOT can use to gain operational data on-demand in real-time. In the future, NCDOT can adapt such tools to assess on-ramp signals in different locations around the state.

In conclusion, this study provides a strong foundation on which NCDOT can apply to more effectively and efficiently plan and evaluate on-ramp signal projects into the future.

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6. Appendices

6.1. 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 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.

6.2. 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.

6.3. Appendix 3: Life Cycle Cost Analysis Guide

This methodology is designed to monetize the outcomes of on-ramp signals. 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.

Pre-Installation Evaluation (Before)

1. Identify Discount Rate and Years of Analysis
    a. Identify multiple years of "before" data in accordance with the guidance outlined in the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* report. At least three years of data is recommended for more accurate forecasts.
    b. 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.
        i. The assumption is 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).
        ii. 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).
        iii. Below is the equation to use for the discounting calculation.

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

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

    c. Decide how many years of data will be monetized.
        iv. For example, ten years would include monetized estimations for 2017 to 2026.
        v. 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, replacement, and forested staffing 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 cost 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.

v. Staffing cost
   a) Develop estimates for annual staffing cost for operating ALL ramp metering location in the system.
   b) This annual cost should be included for the first year of operation and every year after. See the Capital, Programming, and Operational Investments section in this report for the estimated costs of operating four sequential ramp meters.

b. Project the total for all installation, maintenance and operations, replacement, and forested staffing 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 the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* report 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 the NCDOT website.
   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 the References section of this report.
   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 to apply this equation:

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

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

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, one needs to be developed based on historic traffic data before proceeding.

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 the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* report.
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. For safety and user delay, compare the estimated monetized "before" conditions of the ramp metering facility area to the "after" conditions.
b. Add the total monetized values for all costs and benefits as calculated above.
c. Conduct separate analysis for both the low and high CRFs to create a range of benefits.

Post-Installation Evaluation (After)

1. Identify Discount Rate and Years of Analysis
    a. Ensure that at least one full year of “after” traffic data and at least three years of “before” traffic are available before proceeding.
    b. Select the discount rate that will be used to adjust for the changing value of money over time. Use the same discount rate and method, as outlined in the Pre-Installation Evaluation.
2. Calculate installation, maintenance and operations, replacement, and forested staffing costs. Unless revised numbers are available, use the same values and method outlined in the Pre-Installation Evaluation.
3. Calculate User Delay Benefits/Costs
    g. Identify values to be used to monetize user delay. Unless revised numbers are available, use the same values and method outlined in the Pre-Installation Evaluation.
    h. Analyze NCDOT geocoded data in ArcGIS to identify the average percent of heavy vehicles for the selected temporal and spatial parameters. Unless revised numbers are available, use the same values and method outlined in the Pre-Installation Evaluation.
    i. Select the standard value of user travel time. Unless revised numbers are available, use the same value outlined in the Pre-Installation Evaluation.
    j. Select the number of people that will be expected to occupy each vehicle, on average. Unless revised numbers are available, use the same value outlined in the Pre-Installation Evaluation.
    k. Establish an annual traffic volume growth factor (VGF) for the facility. Unless revised numbers are available, use the same values outlined in the Pre-Installation Evaluation.
    l. Utilize delay data from pre-installation analysis, making sure that it incorporates:
        i. Future volume estimations developed by applying an annual traffic volume growth factor (VGF) for the facility area.
        ii. Vehicle hours of delay (VHD) projections, ensuring that VHD calculations are annualized for each year of the time of analysis. For more details, see the method in the 2016 *Planning Level Evaluation of the Effects of Ramp Metering on North Carolina Freeways* report.
    m. Utilize delay data from the post-installation analysis, making sure that it incorporates:
        i. Future volume estimations developed by applying an annual traffic volume growth factor (VGF) for the facility area. These volumes should compound over time in the forecasted analysis.
        ii. Vehicle hours of delay (VHD) projections, ensuring that VHD calculations are annualized for each year of the time of analysis. For more details, see Appendix 5: Vehicle Hours of Delay Methodology.
        iii. Compare the sum of VHD values before and after ramp metering for the entire area of analysis using the method in Appendix 5: Vehicle Hours of Delay Methodology. The percent difference between the sums is the projected reduction in VHD after ramp meter installation.
        iv. Calculate the total change in VHD per year that will be used in the benefit calculations, accounting for the annual VHD with versus without ramp meters.
    f. 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.
4. Estimate Total Benefits
   a. For user delay, compare the estimated monetized "before" conditions of the ramp metering facility area to the "after" conditions to assess the forecasted benefits.
   b. Add the total monetized values for all costs and benefits as calculated above.

6.4. Appendix 4: 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 observational data 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 3 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 3.
    d. Output: The LCCA will estimate the overall savings due to ramp meters.

6.5. Appendix 5: Vehicle Hours of Delay Methodology

Vehicle Hours of Delay (VHD) is the product of delay and volume. The delay is calculated as the actual travel time minus the free flow travel time, using data pulled from RITIS, with free flow time being determined by the length of a Traffic Message Channel (TMC) segment multiplied by the ratio of 65/60.

To inform volume estimations using available sensor data, NCDOT AADT values and segments were adjusted to align with the length of the corresponding TMC segment(s). The AADT value for each segment was divided by the AADT value for the segment with the sensor, giving a proportion. This proportion was then multiplied by the volume data. The entire result of both parts was divided by 60 to convert from minutes to hours. The formula is shown here:

$$\widehat{VHD} = \frac{\left(t_a - \frac{l * 65}{60}\right) * \left(\frac{A_i}{a_s} * V_j\right)}{60}$$

Where t_a denotes the actual travel time, *l* denotes the length of the TMC segment, A_i denotes the i^{th} element of the vector A, which is the vector of AADTs for all segments, as denotes the AADT value for the segment containing the sensor, and V_j denotes the j^{th} element of the vector V, which is the vector of Volume data across dates and times. This value is floored at zero, and all calculations were done using SAS statistical software.

A note on l: The length of the TMC segment can change depending on how the segment is defined. For this study, the length used was the length as defined in late 2018. However, small changes in the length can greatly affect the data, as a miniscule positive VHD value can become negative if the TMC segment is defined to be longer. Since VHD is floored at 0, many of these values drop out of the sums, causing the sum of the VHDs (and consequently, the average) to drop. For example, using 2014 data with lengths as defined in 2014 produces a total sum of VHD ~ 262,000 car hours. Using the same 2014 data over the same timeframe but with lengths as defined in 2018 yields a comparatively measly 117,000 car hours. Before any comparisons from one study to another incorporating this method can be made, it is imperative to ensure that the TMC lengths are defined identically.

The expected value of VHD is

$$E(VHD) = \frac{\left(\bar{t}_a - \frac{l * 65}{60}\right) * \left(\frac{\bar{A}}{a_s} * \bar{V}\right)}{60}$$

In terms of verification, the lack of bias in this VHD can be demonstrated by subtracting the expected value above from the estimate. For example,

$$E(\widehat{VHD}) - E(VHD) =$$

$$E[\frac{\left(t_a - \frac{l*65}{60}\right)*\left(\frac{A_i}{a_s}*V_j\right)}{60}] - \frac{\left(\bar{t}_a - \frac{l*65}{60}\right)*\left(\frac{\bar{A}}{a_s}*\bar{V}\right)}{60} = 0$$

Additionally, the estimator can be shown to be consistent by taking the limit as n, the sample size, approaches infinity. In this case, n approaching infinity can be conceptualized in two ways. Either the study period is increased indefinitely, or the intervals at which measurements were taken are decreased such that data is collected constantly.

$$\lim_{n\to\infty}[\frac{\left(t_a - \frac{l*65}{60}\right)*\left(\frac{A_i}{a_s}*V_j\right)}{60}]$$

The limit of the constant terms are themselves, so the only three limits which need to be considered are t_a, A_i, and V_j. The limit of t_a will approach $E(t_a)$, as the sample size is independent of the time it takes cars to traverse the segment. The number of cars on the road, likewise, are not affected by the sampling, and so the limit will approach the expected value in both the case of A_i and V_j. Thus:

$$\lim_{n\to\infty}[\frac{\left(t_a - \frac{l*65}{60}\right)*\left(\frac{A_i}{a_s}*V_j\right)}{60}] = \frac{\left(\bar{t}_a - \frac{l*65}{60}\right)*\left(\frac{\bar{A}}{a_s}*\bar{V}\right)}{60} = E(VHD)$$

This shows that $\widehat{VHD}$ is a consistent and unbiased estimator for *VHD*.

6.6. Appendix 6: Lessons Learned White Paper

Prepared by the Institute for Transportation Research and Education

February 2019

6.6.1. Purpose

This document was prepared as part of *NCDOT Research Project No. 2018-19: Post-Installation Evaluation of the Effects of Ramp Metering in North Carolina*. This white paper documents the lessons learned through the planning and implementation process for the four ramp meters on I-540 westbound. The following sections outline these lessons and provide suggestions that can be integrated into the planning and implementation process for future ramp meter projects in North Carolina.

6.6.2. Data Collection Planning

Collecting as much traffic data as possible before on-ramp signal installation, and ensuring the same data collection methods are applied after installation, is essential. Similarly, collecting diverse types of data, like traffic volumes and travel times, is key to correcting errors and conducting sensitivity analyses to help ensure the analyses results are accurate. This data should then be thoroughly analyzed and modeled to estimate the benefits of implementing ramp meters on the desired corridor.

Data Collected

To ensure reliable data collection in the I-540 WB project, Intelight placed Bluetooth travel time sensors throughout the I-540 corridor six months before the project started. The Bluetooth sensors were used to gather speed and travel time data for the project. These sensors are used in addition to the loop data sensors.

Additionally, NCDOT microwave side-fire radar detectors were used to measure speed and traffic counts. Using these multiple sources allowed for more robust and accurate analyses, rather than using one source to evaluate traffic conditions. In an effort to collect precise and accurate data, it is recommended that law enforcement are contacted and asked to suspend speed enforcement operations at the beginning of the peak travel period during the initial months of on-ramp signals.

For the best evaluation results, the data outlined in Exhibit 34 needs to be collected both before and after on-ramp signal activation using this guidance. Collecting this data is essential to understanding the traffic patterns that exist prior to the installation of on-ramp signals to make sure that the evaluation of the results of on-ramp signals are accurate.

Exhibit 34: Data Collection Guidance for On-Ramp Signals in North Carolina

Data Type	Data Source	Optimal Collection Locations	Optimal Collection Timeframes	Data Use	Considerations and Instructions
Probe-based travel times	NCDOT uses HERE.com: https://www.here.com/	Develop route comprised of TMCs including: several miles upstream to downstream of on-ramp signal system beginning and end, arterial routes that drivers typically use as part of commute through on-ramp signal area	3-5 years of "before" installation data and at least 1 year of "after" installation data, accounting for seasonality	Travel time comparison and Monitoring	Full method in Appendix 1 of the post-installation final report
On-ramp signal data	Vendor software	All On-Ramp signal locations	1 month for calibration, Monitor throughout deployment	Metering Calibration and Monitoring	Utilize Software logs to track actual metering rates
Radar-based traffic counts	Vendor or NCDOT equipment	Freeway in advance of On-Ramp, Stop bar and upstream on ramp	As much "before" period possible, 1 month for calibration, Monitor throughout deployment	Volume Validation and Monitoring	Beneficial to verify these values using other data sources
Annual Average Daily Traffic (AADT)	NCDOT AADT maps	Collect for each Freeway segment, each On-Ramp, each Arterial at metered interchanges	At least 5 years historical data	Volume Trends	Full methods in Appendices 1,2, and 3 of the post-installation final report
Bluetooth travel times	BlueMAC, BlueToad, other Vendor	Top of each On-Ramp, after merge point of each acceleration lane, at boundary of Freeway route	As much "before" period possible, 1 month for calibration, Monitor throughout deployment	Ramp Travel Times, Origin Destination	May be substituted for Probe O-D Data
Traffic monitoring video	NCDOT Traffic Monitoring Cameras	At least one view of each merge area and each Arterial at metered interchanges	Continuous monitoring	Volume Validation, Incident Monitoring	Is not required to be recorded
Probe-based O-D Data	HERE, Streetlight, other Vendor	Develop route similar to Travel Time method to track changes in driver route choice	3-5 years of "before" installation data and at least 1 year of "after" installation data, accounting for seasonality	Ramp Travel Times, Origin Destination	May be substitued for Bluetooth

Collection Location
Such data sources are valuable assets that should be installed at multiple points in the study area. Data should be collected at multiple points throughout the mainline, adjacent arterials that crosses an on-ramp signal area, and any roadway that may be used as alternate route.

As such, the location of data collection equipment should be planned in advance. Collecting diverse data at multiple points in the impact area is essential because traffic conditions may change as people enter and exit ramps, use alternate routes, and change their behavior due to incidents on roadways. This includes count and turning movement data for both the freeway and nearby arterials that may be impacted by on-ramp signal operations.

Near on-ramps, this baseline data should include video monitoring to allow for visual confirmation of traffic data results. Video cameras should be placed to face the on-ramp signals, in an area that is not obscured by trees or other barriers. These guidelines will allow for regular monitoring of operations. Additionally, video cameras will allow for manual counting of traffic volumes, if necessary.

Collection Schedule
Ideally, baseline data for the corridor should be collected at least a full year prior to on-ramp installation, as traffic conditions will vary by season. This data should be evaluated and verified throughout the collection process to ensure any intermittent equipment errors are corrected as early as possible. Similarly, data for area arterials should also be collected in advance to enable an analysis on the impact of on-ramp signals on diversions, congestion, and other variables.

Both before and after on-ramp signals are installed, the same data collection methods are applied, using the same placement of the data collection equipment. Developing a robust before-and-after data collection pattern as early as possible in the project planning process will save staff time and money long-term and will allow for more accurate planning and evaluation of the on-ramp signals.

6.6.3. Design and Detector Placement

In terms of on-ramp signal operations, the ramp vehicle storage capacity and stop bar placement can impact traffic conditions. During the I-540 WB on-ramp signal project, the research team found that the stop bar at least one of the on-ramp signals was creating additional queuing at a nearby arterial roadway and was creating merging issue on the mainline. Similar issues occurred at time due to the limited storage capacity of the on-ramp.

To prevent these issues from occurring with future on-ramp signal projects, the design of the ramp should consider on-ramp functionality plans. This includes how drivers may behave in relationship to the stop bar location and the ramp geometry. Otherwise the design of the ramp metering system must be adjusted to compensate for ramp geometry limitations. A possible design that could alleviate this issue would be to ensure the location of the lane drop arrow is farther downstream of a potential meter stop bar.

Refer to NCDOT and vendor designs for the I-540 WB on-ramp signals for visual examples of the limitations and opportunities associated with design and freeway detector placement.

6.6.4. Ramp Queue Detectors

Placing intermediate queue detectors on the ramps may improve the overall effectiveness of the on-ramp signal system, as they can provide additional data that can improve operations. Including intermediate queue detectors can allow for the ramps to achieve complete traffic storage before the system raised the metering rates and forced traffic onto the mainline. For optimal results, it is beneficial to place excessive queue detectors further back, almost to the street intersection.

However, at on-ramps that have separate feeder ramps by turning movement, the queue detectors should be wired separately. Wiring queue detectors separately will allow operators to set lower thresholds or higher metering rates to respond to a queue in the left-turn feeder ramp, to avoid traffic backup into the intersection. An accessible and reliable wiring diagram is essential to making quick adjustments if needed.

Refer to NCDOT and vendor designs for the I-540 WB on-ramp signals for visual examples of the limitations and opportunities associated with ramp queue detector placement and wiring.

6.6.5. Staffing and Operations

The staffing level needs will be higher at the beginning of any on-ramp signal project. Prior to on-ramp signal installation, staff should be trained on monitoring signal operations as well as using the on-ramp signal software. This training will enable operators to adjust on-ramp signals more quickly and effectively for better traffic results. Software training should include education on how to both read and analyze the system reports and settings.

For the first 2-3 months of a project, staff should document all changes to on-ramp signal operations, outages, and other variables which may influence regular traffic operations. This documentation can help inform operational decisions for the given project and future projects. Note that the costs of on-ramp signal operations outlined in this report are not expected to increase significantly with the addition of new on-ramp signals to a system, unless the time that the on-ramp signals operate increases significantly.

6.6.6. Arterial Signal Timing

The operation of roadways surrounding the ramp meters can also impact the level of benefits and costs experienced both on the freeway and the roadways themselves. As such, it is key that NCDOT develop plans for adjusting arterial signals before the installation of on-ramp signals.

These plans should include a timeline for when and how the signals operations will be analyzed during different stages of on-ramp signal implementation. These plans should also include forecasts for when arterial signals will be retimed based on traffic data to help ensure that the on-ramp signal area, including arterials, is running as effectively as possible.

For optimal results, signals surrounding the on-ramp signals should use time of day plans that are re-evaluated and re-timed as needed every 3-6 months in the first 1.5 years of on-ramp signal operations. These signals should also be prioritized for re-timing evaluations into the future as traffic grows, as the flow of traffic onto the freeway will impact the operation of the operation of the on-ramp signals as well as the arterials nearby the entrance ramps.

A preliminary review of current signal timing prior to installation may be performed in order to asses potential critical failures for activation. For instance, if the current signal phasing would allow for traffic to back up from the ramp and into the right turn lane to block opposing left turns, changes to phasing or RTOR restrictions may be used to ensure that some of the left turn phase is utilized during spillback conditions.