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16. Abstract

Integrated Corridor Management (ICM) systems are a promising approach for managing both travel demand and network demand in normal and abnormal conditions. Traditionally, ICM is applied in an urban setting where multiple transportation modes are readily available. However, the North Carolina Department of Transportation (NCDOT) has applied ICM principles in more rural applications where fewer modal and network options are likely to exist. NCDOT has deployed ICM on 22 miles of I-85 from Mile Marker 10 to 32 near Charlotte, with a focus on managing incident-related congestion on the interstate and parallel US-74 arterial. This deployment includes traveler information on Dynamic Message Signs, activatable detour trailblazer signs for individual incidents, and incident-specific signal timing plans for intersections included in the detours.

To accurately capture the traffic diverted due to ICM activations, observations of traffic flow patterns are essential. In this project, Bluetooth and Wi-Fi traffic monitoring devices were placed throughout the corridor and used to match trips along the primary and detour routes to establish baseline Origin-Destination (O-D) patterns which can be compared to ICM activations after implementation. This project also adapted an existing sketch-planning NCDOT analysis method used in the project prioritization process to compare estimated delays on primary and detour routes during ICM operation. The inputs for diversion rates and capacity benefits from ICM-specific signal timing can be updated as observations provide better estimates.

To support the monitoring and evaluation of the ICM deployment, this project developed a dashboard integrating data feeds from public and private sources and an evaluation framework that captures delay, safety, environmental, administrative, and capital impacts of ICM deployment. The implementation of the developed framework showed significant benefits to the project stakeholders, particularly in cases of high incident severity. The benefits are dependent on both the severity of the incident and the time of day, with peak periods yielding greater benefits compared to non-peak periods. The overall benefit of ICM implementation was found to be substantial. Additionally, the analysis of the 5-year and 10-year benefit-cost ratios of the I-85 ICM program indicated that the investment in ICM is likely to result in a favorable return on investment over a period of 5 and 10 years.

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Executive Summary

Integrated Corridor Management (ICM) systems offer the potential to manage both travel demand and network demand in normal and abnormal conditions (1). Through increased awareness, decision-support, and institutional coordination, ICM systems strive to change the traditional reactive model of traffic management to a proactive approach (2). With ICM, system operators take action before corridor performance degrades and, in cases where degradation has already occurred, take action to promptly restore normal conditions. Traditionally, ICM is typically applied in an urban setting where multiple transportation modes are readily available. NCDOT has applied ICM principles, but in more rural applications where less modal and network options are likely to exist. These initiatives will provide potential opportunities to measure benefits and provide guidance for future implementation of ICM elsewhere in the state.

NCDOT has deployed ICM on 22 miles of I-85 from MM 10 to 32 near Charlotte with a focus on managing incident-related congestion on the interstate and parallel US-74 arterial (3). This deployment includes traveler information on Dynamic Message Signs, activatable detour trailblazer signs for individual incidents, and incident-specific signal timing plans for intersections included in the alternative routes.

The goal of this research project is to support the I-85 ICM deployment with data collection, monitoring, development, and application of an analysis framework for Before and After analysis.

Observations of traffic flow patterns are essential to accurately capture the traffic diverted due to ICM activations. In this project, Bluetooth and Wi-Fi traffic monitoring devices were placed throughout the corridor and used to match trips along the primary and detour routes to establish baseline origin-destination (O-D) patterns which can be compared to ICM activations.

This project also adapted an existing sketch-planning analysis method used in the project prioritization process to compare estimated delays on primary and detour routes during ICM operation. This analysis then uses incident rates and time of day traffic patterns to estimate the total delay with and without ICM operation to estimate the benefit of ICM. The inputs for diversion rates and capacity benefits from ICM-specific signal timing can be updated as observations provide better estimates.

Additionally, this project developed a live dashboard integrating data feeds from public and private sources presented in a compact set of maps and graphs. NCDOT performs after action reviews of severe incidents, including those in the I-85 ICM deployment, which may use the dashboard to supplement their review. Reviewing the probe data provides a view of the experienced travel time for drivers remaining on the primary route and those detouring, while GPS data may indicate when diversion may utilize other routes when following third party device recommendations.

Last, this project developed an evaluation framework which captures delay, safety, environmental, administrative, and capital impacts of ICM deployment. For both benefits and costs, it is important to separate the incremental or specific impacts of the ICM deployment with the understanding that other projects and background traffic patterns continue to affect the corridor.

The application of the framework that was developed has shown that the ICM can provide significant benefits to stakeholders, especially when the incident is severe. The level of benefits obtained from ICM is dependent on the severity of the incident and the time of day, with more severe incidents providing greater benefits, and peak periods yielding more benefits than non-peak periods. Additionally, the

evaluation results indicate that the 5-year and 10-year benefit-cost ratios of the I-85 ICM program are likely to be 3.1 and 5.3, respectively, indicating that each unit of investment in the ICM program will result in 3.1 units of overall benefits over a 5-year period and up to 5.3 units of benefits over a 10-year period.

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1. Introduction

Integrated Corridor Management (ICM) systems offer the potential to manage both travel demand and network demand in normal and abnormal conditions. Through increased awareness, decision-support, and institutional coordination, ICM systems strive to change the traditional reactive model of traffic management to a proactive approach. With ICM, system operators take action before corridor performance degrades and, in cases where degradation has already occurred, take action to promptly restore normal conditions.

Traditionally, ICM is typically applied in an urban setting where multiple transportation modes are readily available. NCDOT has applied ICM principles, but in more rural applications where less modal and network options are likely to exist. These initiatives will provide potential opportunities to measure benefits and provide guidance for future implementation of ICM elsewhere in the state.

Actively managing the corridor from a transportation operator’s perspective implies an awareness of all the routes and the ability to accept, adjust, and deploy advisory and control strategies which can affect the entire system. From a traveler’s standpoint, ICM offers enhanced travel options including the ability to dynamically shift transportation options based on actionable information provided on traffic and road conditions.

NCDOT has deployed ICM on 22 miles of I-85 from MM 10 to 32 near Charlotte with a focus on managing incident-related congestion on the interstate and parallel US-74 arterial. This deployment includes traveler information on Dynamic Message Signs, activatable alternative route trailblazer signs for individual incidents, and incident-specific signal timing plans for intersections included in the alternative routes.

Due to impacts to NCDOT budget and COVID-19 traffic, the I-85 ICM activation occurred later than planned and the application of the developed analysis framework was postponed. The goal of this tech transfer is to apply the ICM analysis framework developed as part of the original NCDOT project (RP 2022-23) to evaluate the system impacts. The objectives of this tech transfer are:

1. Continue collecting travel data from all the sources to capture the traffic trends and incident impacts;
2. Maintain the online monitoring dashboard that can be used to review data after incidents; and
3. Apply the developed ICM analysis framework developed as part of the original research project (RP 2022-23).

The report is laid out in three sections. In chapters 2 and 3 data collection and monitoring tools are described. In chapter 4 the analysis method is applied to multiple case studies to evaluate the system impacts of ICM. Lastly, Chapter 5 discusses recommendations and lessons learned, which are recorded for future deployments.

2. **Monitoring and Data Collection**

2.1. Facility/Route Descriptions

The ICM facility includes I-85 and the parallel US-74 arterial west of Charlotte, NC. On the west side, the site starts at the boundary of the city of Kings Mountain, runs through the city of Gastonia, and ends at the vicinity of Charlotte Douglas International Airport. The I-85 study area begins east of Billy Graham Parkway (Exit 32) and extends west of US 74 (Exit 10), containing 15 interchanges along the interstate. Traffic signals along the route are owned and operated by different entities including the NCDOT Division 12, the City of Gastonia, and the Charlotte DOT.

The alternative route for the corridor, US 74, runs parallel to the main route and has 88 signalized intersections throughout the study area. The use of the alternative routes depends on the event type and the associated locations of the event. Twelve operational scenarios were developed to detour the traffic from I-85 to the US 74 in case of incidents along the freeway. Figure 1 shows a schematic drawing of the site.

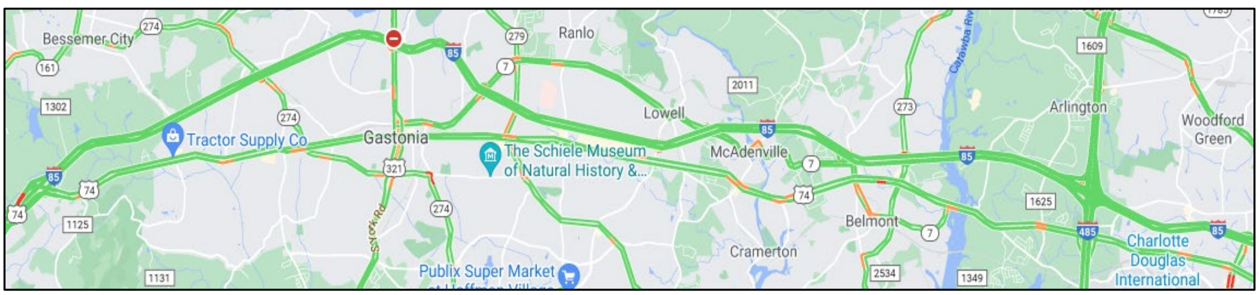

Figure 1: ICM Corridor along I-85 and US-74

2.2. Data Description

2.2.1. Clearguide

HERE was the probe vehicle data provider for this project. Clearguide (HERE’s tool), which analyzes transportation data and can be used to identify problem areas and assess the performance of a system, was used as the main tool in this project. This project used Clearguide’s two suites of products – contour maps and freeway/arterial travel times. Contour maps were used to investigate traffic levels at a macro level. This service proved an indispensable tool for assessing traffic levels post Covid-19 pandemic and helped the research team better understand the traffic patterns along the corridor. Furthermore, Clearguide travel time was used as a validation tool for incidents along the corridor, third-party travel time providers for comparison with Bluetooth and Google travel times, and was used in the estimation of vehicle hours of delay.

2.2.2. Bluetooth

Bluetooth units provided three of the most important datasets in this project. These sensors are capable of providing ground truth travel time, origin-destination information, and diversion rate estimation. Valid individual travel times obtained through Bluetooth Sensors can shape the origin-destination matrix between sensors and estimate the diversion rate for scenarios where incidents are present on the freeway. The latter is achieved by comparing sensor match rates for the day and time when an incident is present to a similar day when the incident is not present.

2.2.3. Twitter

Live incident data on the ICM corridor is gathered through the Twitter API by listening to NCDOT's Tweets. These Tweets include the incident's timestamp, roadway, mile marker, city, incident type, and number of lanes closed. A back-end script in Python automates this task of listening to NCDOT's tweets, and the script is running 24/7 with the collected data saved in the project SQL database.

2.2.4. Google Maps

Upon detection of an incident in NCDOT's tweet, the back-end script connects with Google Maps API and requests two items: detour routing information and travel time for the detour. While NCDOT's ICM will provide detour information to travelers, not all drivers will divert as instructed by the signs. Some may be using third-party apps such as Google Maps and rely on the detour information provided by them. The detour route and travel time information are crucial data points in determining the diversion rate.

2.2.5. TIMS

Incident data were acquired from NCDOT's Traveler Information Management System (TIMS). This system logs incident information on the types of events that most often cause delays on the highway systems and include major accidents, construction or maintenance projects, and natural disasters. The TIMS database contains incident attributes such as road name, direction, mile marker, start and end time, severity, number of closed lanes, coordinates, and many more. The acquired incident log is filtered temporally and spatially using the reported start times and mile markers. Furthermore, incidents with extremely long durations (hundreds of days), negative duration, and those not identified as incidents in the HCM were flagged as outliers and excluded from the analysis dataset.

2.3. Dashboard

2.3.1. ICM Dashboard Description

The Integrated Corridor Management (ICM) Dashboard is a web-based data visualization tool that visually tracks, analyzes, and displays traffic incident data at a section of the I-85 corridor in North Carolina. The dashboard is aimed at providing information to engineers and researchers on the impact of individual incidents and can be used as an additional data source for after-action reviews. It is a web-based platform developed using JavaScript as the primary language (Node.js interpreter) and MySQL database. The ICM Dashboard is hosted at ITRE's DataLab on secure state-networked servers.

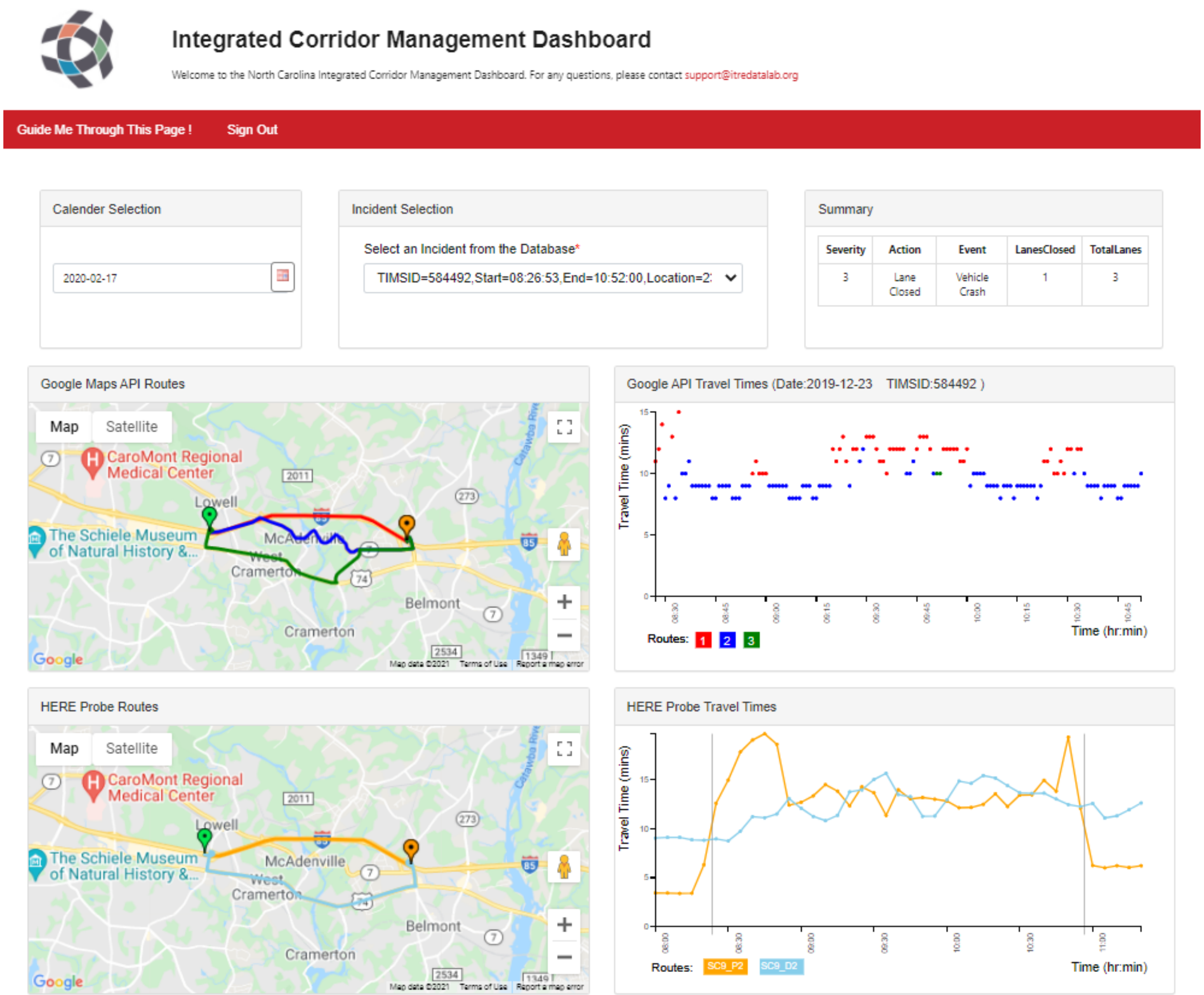

Figure 2: ICM Dashboard Example

2.3.2. Dashboard Issues Encountered During the Implementation Phase

The research team faced multiple challenges during the data collection, development, and maintenance of the dashboard to maintain up-to-date incident, and travel time data from TIMS, probe vehicle data provider, and Google Maps, respectively.

The dashboard monitors the NCDOT Twitter account. The Tweet from the NCDOT I-85 account is the trigger for the dashboard to request data from TIMS and Google maps. Upon reading a tweet that falls within our area of interest, it sends a request to TIMS API to get the details of the crash. In case of a crash, a Google travel time is requested by the code every minute until the crash is cleared.

Following are the issues that our team faced during the implementation phase of the ICM:

TIMS API Link Update

NCDOT updated the TIMS API link midway through the project which caused issues connecting to the service and as such the data collection process was interrupted and halted temporarily. Upon updating the API link, data collection was resumed. After we updated the link in the code, it was seen that the code was able to record the data but was not making a Google API request for the travel time information. This was due to the change in data format.

TIMS Data Structure Modification

It was found that NCDOT had changed the data structure and the way the data was now available on TIMS. Table 1 shows the differences between the previous and the current version of TIMS data provided by the API.

Table 1: Difference between the previous and the current version of TIMS data

Old format	New format
Direction	direction
Location	location
IncidentType	incidentType
Latitude	latitude
Longitude	longitude
Id	id
Reason	reason
Condition	condition
Severity	severity
LanesClosed	lanesClosed
LanesTotal	lanesTotal
Fatality	fatality
HazardousMaterials	hazardousMaterials
CommercialVehicle	commercialVehicle
OverturnedCommercialVehicle	overturnedCommercialVehicle
CreationDate	creationDate

Incorporating these changes in the script so that it could parse the new data format, did record the data in the local database, but the dashboard was still not getting updated as needed. This was due to a change in the format of the recorded time.

Date and Time Format Modification

Another issue that the TIMS API change caused was the Date and Time modification adding to the list of other issues preventing on time update of the dashboard. The timestamp had a "TZ" concatenated at the end. This was found to be an encoding bug. The time stamp is recorded in the UTC format and not the local time as expected by the code. When we incorporated this change, the dashboard was up and running as needed.

3. **Bluetooth Analysis**

Bluetooth sensors were a vital part of the ICM project providing the necessary means for validation of travel times along the corridor, enabling calculation of origin-destination matrix, and quantifying the diversion rate for different incident severities. The following sections provide details of the Bluetooth analysis.

3.1.1. Bluetooth Sensors Placement along the ICM Corridor

The ICM project employed 30 commercial Bluetooth sensors to cover the primary and alternative routes along the I-85 ICM corridor. The focus was to have at least one sensor at each endpoint of a given ICM scenario and place intermittent sensors along the detour routes to have a reserved option for traffic detection, taking the alternative route in case the first sensor on the facilities misses them. The Bluetooth sensors used were seventh-generation BlueMAC units manufactured by Digiwest LLC.

Units were installed on different NCDOT available infrastructures, such as gantry poles in the wide median on Interstate 85, signs, and other available roadside posts. Figure 3 shows the approximate location of most of the devices deployed in this project.

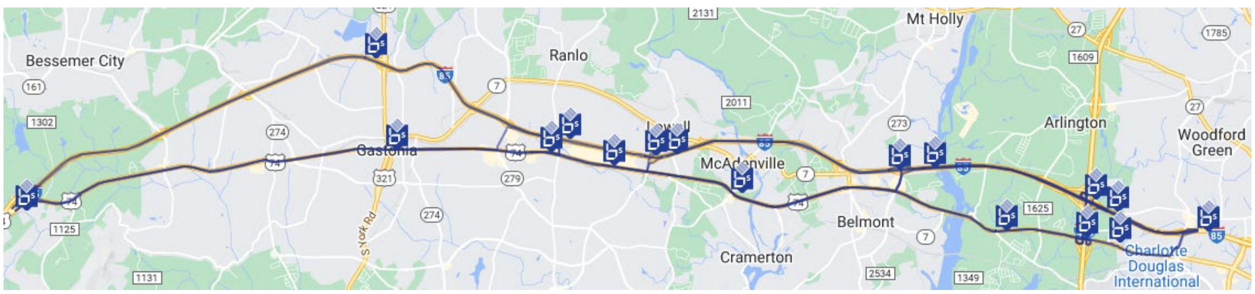

Figure 3: Location of deployed Bluetooth sensors

3.1.2. Bluetooth Data Pre-Processing

Data pre-processing related to the Bluetooth tasks for this project was divided into two parts: travel time generation and outlier detection. Two different methods were employed for the latter, depending on the facility type (freeway and signalized arterials). Details of the data pre-processing can be found in the final report for the project's first phase.

3.1.3. Diversion Rate Analysis

Diversion rate is an essential factor in the before-after analysis of any integrated corridor management study. The research team deployed Bluetooth sensors across the network to test route diversion patterns due to the ICM during different incident severities (shoulder, one-lane, and two-lane closures). These sensors allowed the researchers to find the actual level and pattern of diversion from the affected primary routes to the alternative arterial routes.

The initial step for diversion rate estimation consists of gathering the incident information and its characteristics, such as type, location, severity, number of lanes closed, and whether ICM activation occurred during the incident. This information was gathered from NCDOT's TIMS database. Figure 4 shows incident severity and frequency after ICM went live on I-85 until August 2022.

The second step comprised segregating the incidents based on their severity and ICM activation. In this step, incidents were classified into four categories (shoulder closure, one lane closure, two lane closure, and three lane closure). The diversion rate for each incident severity was obtained by comparing the Bluetooth matches on the primary route for periods where incidents were present to periods with no incidents. Care was taken to compare similar days of the week and time. The output of this process provides the diversion rates, as shown in Table 2.

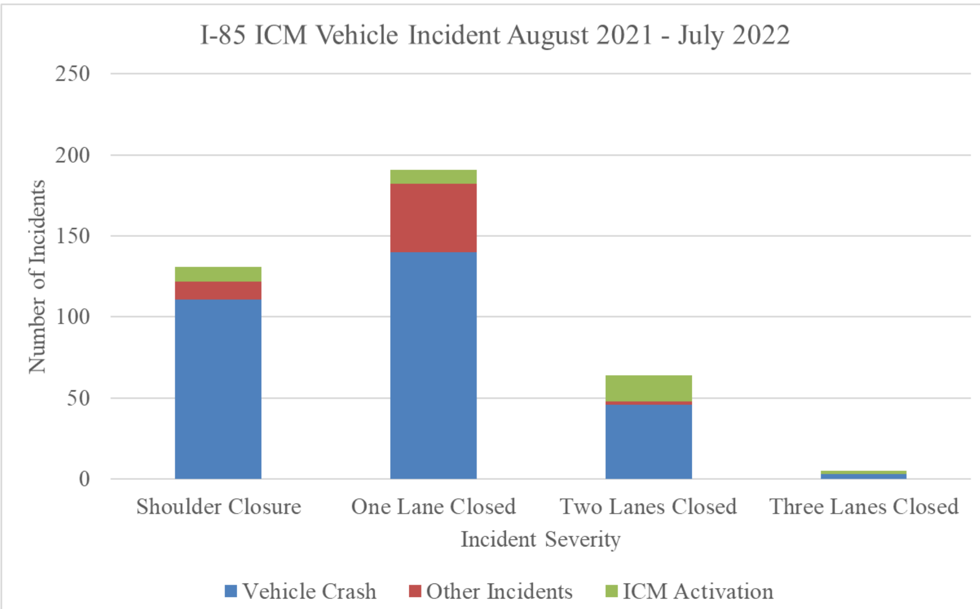

Figure 4: I-85 Incidents for August 2021 - July 2022

Table 2: Diversion Rates for the I-85 ICM Corridor

Incident Severity	Off Peak Diversion Rates	Peak Diversion Rates	Natural Diversion Rates (No ICM)
Shoulder Closure	5%	7%	0%
One Lane Closed	15%	23%	5%
Two Lanes Closed	25%	35%	15%
Three Lanes Closed	40%	50%	25%

3.1.4. Case Studies

To test the robustness of the developed methods for outlier detection both for the primary and detour routes and estimation of detour percentage, the team selected a scenario where data for both the incident and non-incident days were available. The route selection to include incident and non-incident days was deemed crucial for testing the outlier detection algorithms and analysis of the detour rate to ensure they work under both incident and non-incident scenarios. The case study is located along the west side of the ICM facility between exits 10A and 17.

Figure 5 shows the travel time on Scenario 1's primary route on July 27th, 2022. The blue squares represent valid travel times, while the red crosses show the outlier travel time times identified by the outlier detection algorithms. On July 27th, 2022, a vehicle crash occurred on mile marker 12, closing two lanes from 12:53 PM until 2:01 PM. The incident's effect is clearly shown by the travel time spike in Figure 5. As a result of this incident, travel time on the primary route increased almost four times north of 35 minutes.

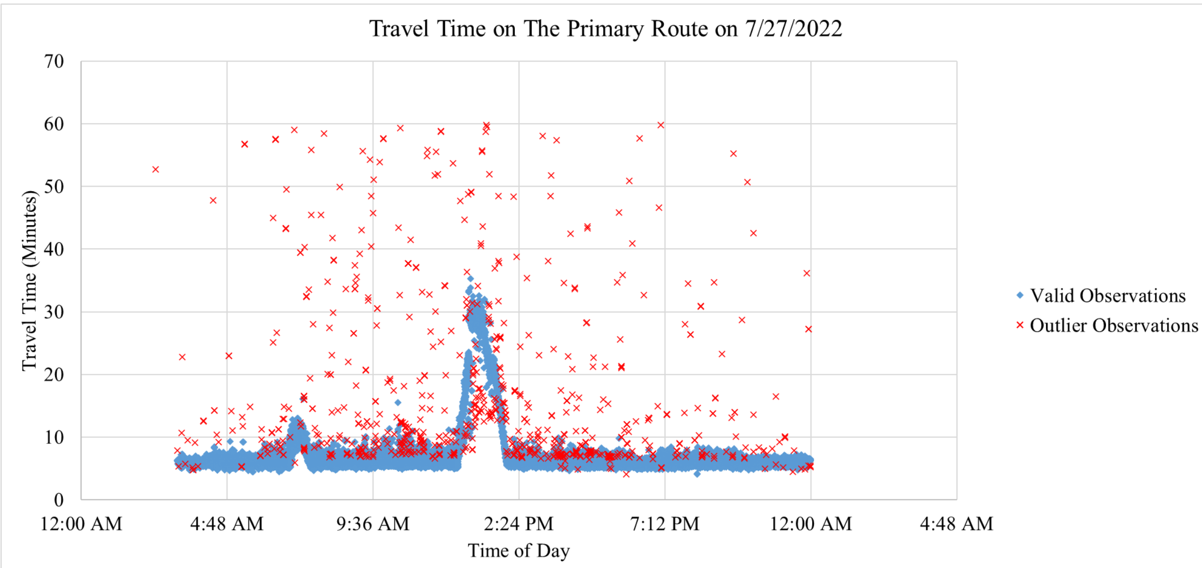

Figure 5: Travel Time on the SC1 Primary Route During the Incident of 7/27/2022

Figure 6 shows the travel time on the alternative route for scenario 1. The red triangles show the outlier travel times, while the blue circles show the valid travel time observations. Effects of the incident on the primary route are also observed on the alternative route. This is because ICM was turned on, and vehicles were re-routed to the alternative route.

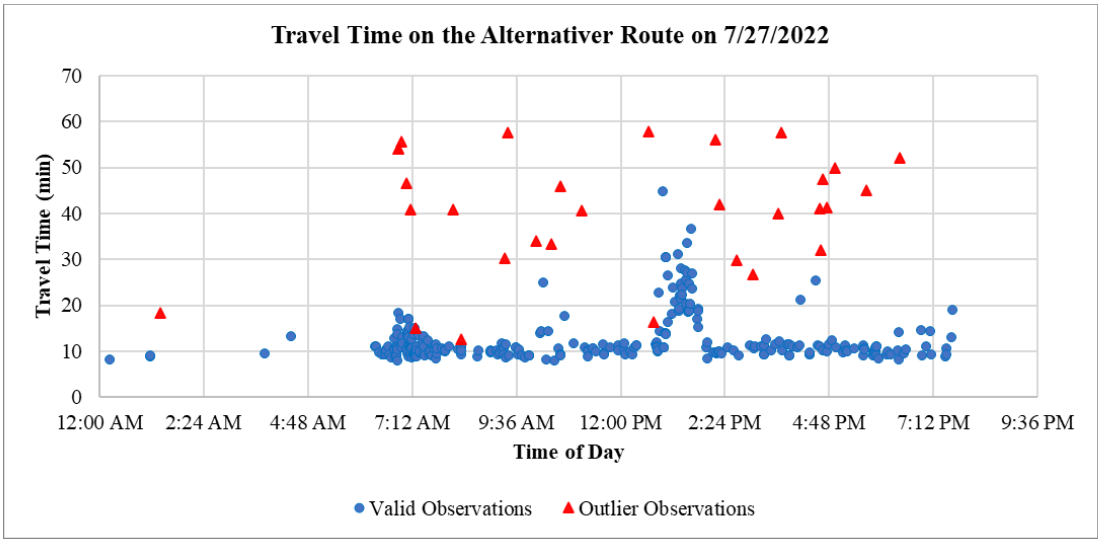

Figure 6: Travel Time on the SC1 Alternative Route on 7/27/2022

Application of the developed algorithms for outlier detection to both incident and non-incident periods revealed the robustness of the methodology. The freeway and arterial outlier travel time detection methods could flag travel times not representative of the traffic stream. The flagged travel times were removed from the analysis. The resulting travel times can be used for travel time, origin-destination, and diversion rate analysis.

4. I-85 Before and After Analysis

4.1. Incident Impact Performance Measures

Incident Severity is the maximum impact to travel lanes at the incident location, and may vary by roadway direction in cases where incidents affect both travel directions. Incidents often have varying impacts to travel lanes as responders arrive and clear the roadway, and this timeline may be considered during review of individual incidents however it is difficult to incorporate directly into an analysis of all incidents together.

Excess Incident Delay (EID) is delay incurred during incidents beyond the recurring level of congestion for a certain time of day. This accounts for the incremental impact of incidents rather than *Travel Delay* which is based only on speed limit travel time. Times of day with no recurring congestion calculate EID beyond speed limit travel time. The *Recurring Congestion Baseline* accounts for this recurring level of congestion in non-incident days at that time of day. Figure 7 shows an example of how EID can be visually interpreted.

$$Recurring\ Congestion\ Baseline\ (RCB_{tr}) = max\begin{Bmatrix} Non - Incident\ 80th\ Percentile\ Travel\ Time_{tr} \\ Speed\ Limit\ Travel\ Time_{r} \end{Bmatrix}$$

where,

t = Time of day/Day of week
r = Route

$$Excess\ Incident\ Delay\ (EID_{tir}) = max\begin{Bmatrix} TT_{tir} - RCB_{tr} \\ 0 \end{Bmatrix}$$

where,

i = Unique incident identifier

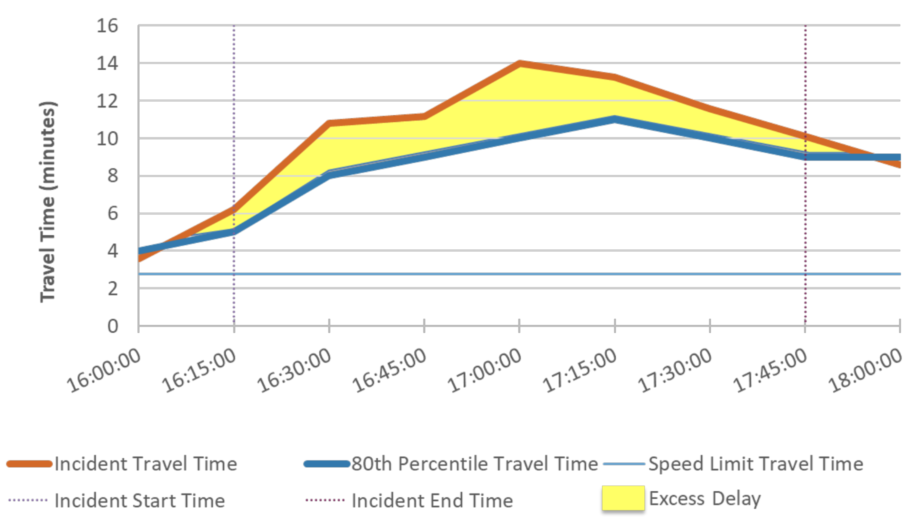

Figure 7: Illustrative example of Excess Incident Delay

As EID is calculated on per vehicle basis for each time period, volumes must be assigned to each time period. *Volume distributions* indicating the percent of daily traffic traveling at each time period of the day may be estimated or observed using sensors on the facility. The following estimation equation can be used in the absence of raw counts:

$$V_{tr} = AADT_r * D_r * K_{tr} * DM_t$$

where,

V_{tr} = Time of Day estimated Hourly Volume on Route
$AADT_r$ = the average annual daily traffic volume on route
D_r = Directional Distribution (assume 0.5 or use local value)
K_{tr} = Hourly Volume Factor for Time of Day, Day of Week and Peaking Pattern
DM_t = Daily Multiplier to convert AADT to ADT

Hourly vehicle volume distributions shown in
Figure 8 are incorporated from the 2019 TTI *Urban Mobility Report* (Source: https://mobility.tamu.edu/umr/). Daily Multipliers, found in Table 3, adjust AADT to ADT for a specific day of the week, which were obtained from NCDOT's Traffic Survey Unit.

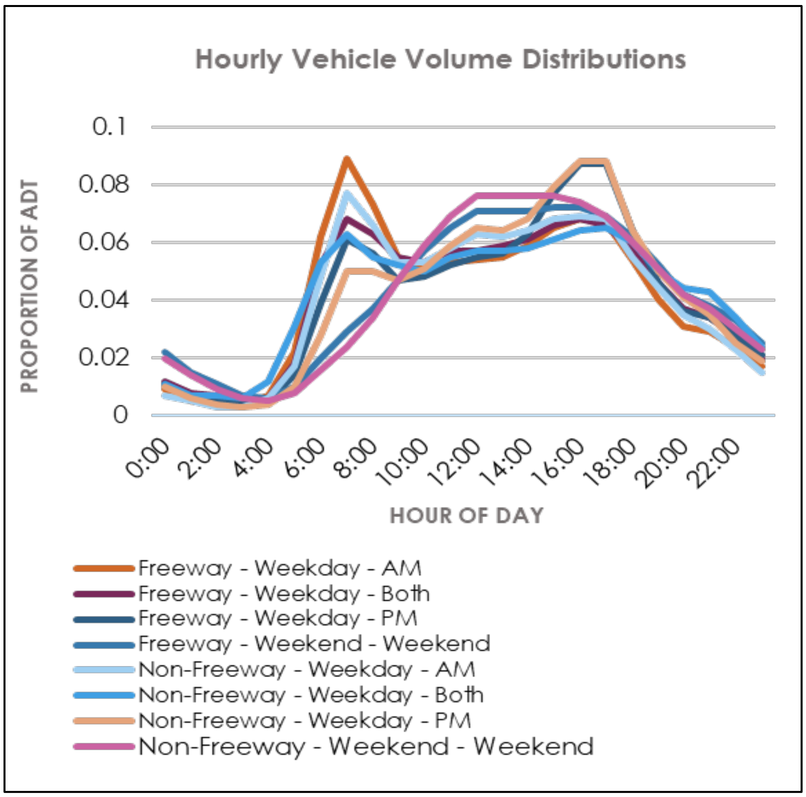

Figure 8: Hourly Vehicle Volume Distributions by Functional Classification, Day of Week, and Peaking Pattern

Table 3: Daily Multipliers to Adjust AADT to ADT

Day of Week	Daily Multiplier
Monday – Thursday	1.05
Friday	1.1
Saturday	0.9
Sunday	0.8

The equation below can be used to calculate *Incident Vehicle Hours of Delay* for a given incident. Incidents are tracked beyond the recorded start and end time to account for potential delays in incident identification at the TMC or queue discharge.

$$Incident\ VHD_{ir} = \sum_{t=0}^{T} EID_{tir} * V_{tr}$$

where: *t* varies from start of incident (t=0) to the end of the incident at t=T, with T being the total impact duration plus 30 minutes Before and after.

Diversion Percentage is the average percent of mainline traffic that diverted onto the detour route during the incident. The goal of the ICM deployment is to manage traffic flows such that the diverted traffic reduces the mainline congestion while still benefiting from the detour route travel times. This may be estimated through the matching method described in 4.3 or other methods of O-D analysis.

4.2. Benefit-Cost Methodology

The Benefit-Cost Analysis (BCA) includes the following benefits and costs which can be aggregated to net benefits or a Benefit-Cost Ratio. The analysis should also note any unmeasured or unrecorded benefits or costs which can be used to contextualize the findings. Often many institutional benefits are unable to be measured, especially for pilot deployments of new operational strategies.

4.2.1. Benefits

Travel Time and Delay Savings is calculated from the total reduction in vehicle-hours of excess delay. This excess delay is an estimate of only the incident-specific delay and accounts for recurring congestion expected on that day of week and time of day. In the case of incidents occurring in the after period, the excess incident delay must be calculated for both the mainline route and detour route, weighted by the diversion rate. Analysis should use a vehicle class weighted value of time (VOT) to estimate the user cost of delay with an average vehicle occupancy assumption.

Fuel Savings may be estimated utilizing the NCDOT methodology developed in NCDOT Research Project 2013-09. It utilizes the average price of gasoline and diesel over the analysis period, and estimates fuel consumption tied to the delay savings of the project.

Emission Savings may be estimated utilizing NCDOT's emission methodology used in CMAQ evaluation for speed improvement project types in urban counties. The CMAQ methodology estimates savings in NOx, VOC and CO based on speed improvements and idle time reduction.

4.2.2. Costs

Construction and Deployment Costs include the construction of DMS and changeable trailblazer signs as well as infrastructure upgrades that can be solely attributed to the deployment. If planned infrastructure upgrades occurred in tandem with the deployment, a justifiable percentage of these costs may be attributed to the ICM project.

Administrative and Operation Costs should include TMC staffing and salary costs of NCDOT staff needed to operate the ICM program. Similarly, these costs should be apportioned at a justifiable percentage of the total based on the portion of effort attributable solely to the ICM program. These costs should also reflect a long-term recurring cost rather than an initial higher effort that may be needed for a first pilot deployment such that the costs can be used to estimate future project costs.

4.3. I-85 ICM Results

4.3.1.1. *Overview of Valid ICM Incidents*

This research extracted the traffic incidents that triggered ICM activations to evaluate the impacts of ICM activation on corridor performance. A total of 40 valid traffic incidents were identified during the data analysis period (August 2021 to July 2022) that met a minimum duration of 15 minutes and impact on congestion beyond recurring levels. For each ICM incident, this research documented its start and end times (the time difference was assumed as the average duration of the incident), if the incident occurred during a peak period (a peak period could be either a morning peak from 6:00 to 9:00, or an afternoon peak from 16:00-19:00), average number of closed lanes, and detour route scenarios (11 detour routing scenarios). Details of each ICM incident are listed Table 4 below. In general, the majority of ICM incidents (70%) occurred during a peak period; the duration of ICM incidents ranged from 10 minutes to 1059 minutes with a mean duration of 132 minutes. In terms of average number of closed lanes, 2 incidents (5%) resulted in 3 closed lanes, 16 incidents (40%) had 2 closed lanes, 10 (25%) incidents lead to one closed lane, and 12 incidents (30%) did not result in lane closure.

Table 4: Summary of ICM incidents

TIMS_ID	Start Time	End Time	Peak Period	Duration (min)	Closed Lanes	Route
613237	2021-08-02 6:22:00	2021-08-02 8:49:00	1	147	1	SC4
613852	2021-08-12 14:46:00	2021-08-12 17:07:00	1	141	0	SC11
615095	2021-09-01 8:26:00	2021-09-01 9:20:09	1	54	2	SC4
615430	2021-09-07 20:23:00	2021-09-07 21:46:54	0	84	2	SC5
615635	2021-09-10 18:45:00	2021-09-10 19:58:18	1	73	2	SC3
615708	2021-09-13 6:46:00	2021-09-13 9:40:03	1	174	1	SC4
615909	2021-09-15 15:16:00	2021-09-15 16:23:59	1	68	3	SC7
616172	2021-09-20 14:09:00	2021-09-20 14:52:16	0	43	2	SC4
616796	2021-09-30 14:53:00	2021-09-30 16:38:13	1	105	2	SC4
616896	2021-10-01 17:02:00	2021-10-01 18:08:19	1	66	0	SC3
616951	2021-10-03 14:24:00	2021-10-03 16:24:30	0	121	2	SC4
617118	2021-10-06 9:55:00	2021-10-06 11:10:50	0	76	0	SC9
617175	2021-10-07 1:36:00	2021-10-07 3:20:28	0	104	0	SC7
617730	2021-10-14 15:02:00	2021-10-14 16:13:44	1	72	2	SC5
617732	2021-10-14 15:15:00	2021-10-14 15:48:23	1	33	2	SC8
617796	2021-10-15 14:59:00	2021-10-15 15:14:07	0	15	2	SC8
617813	2021-10-15 17:40:00	2021-10-15 19:11:44	1	92	0	SC2
618558	2021-10-27 16:32:00	2021-10-27 17:13:00	1	41	0	SC4
618564	2021-10-27 17:22:00	2021-10-27 19:07:17	1	105	0	SC5
618784	2021-10-31 14:20:00	2021-10-31 15:34:14	0	74	1	SC4
619501	2021-11-11 17:21:00	2021-11-11 18:48:23	1	87	2	SC7

620015	2021-11-19 22:32:00	2021-11-20 0:13:47	0	102	1	SC5
620208	2021-11-23 18:53:00	2021-11-23 19:04:26	1	11	1	SC5
620862	2021-12-06 18:14:00	2021-12-06 19:47:15	1	93	0	SC9
621421	2021-12-15 18:33:00	2021-12-15 19:04:43	1	32	1	SC5
622020	2021-12-29 14:53:00	2021-12-29 15:15:35	0	23	2	SC3
625544	2022-02-19 20:35:00	2022-02-20 2:27:40	0	353	2	SC8
625801	2022-02-23 9:11:00	2022-02-23 11:28:04	1	137	1	SC4
626915	2022-03-08 23:10:00	2022-03-09 16:48:32	1	1059	1	SC4
626980	2022-03-09 17:11:00	2022-03-09 18:26:12	1	75	1	SC9
628015	2022-03-22 18:11:00	2022-03-22 21:49:43	1	219	0	SC11
628143	2022-03-24 4:32:00	2022-03-24 7:47:21	1	195	2	SC2
628509	2022-03-28 18:24:00	2022-03-28 21:55:00	1	211	0	SC5
628727	2022-03-31 0:15:00	2022-03-31 4:14:14	0	239	3	SC6
629199	2022-04-05 16:11:00	2022-04-05 21:27:00	1	316	2	SC3
631492	2022-05-03 16:49:00	2022-05-03 18:26:10	1	97	1	SC2
633537	2022-05-27 5:52:00	2022-05-27 7:10:00	1	78	0	SC10
637372	2022-07-19 8:47:00	2022-07-19 11:12:30	1	146	2	SC8
637873	2022-07-25 18:11:00	2022-07-25 19:15:00	1	64	0	SC3
638036	2022-07-27 12:53:00	2022-07-27 14:01:07	0	68	2	SC1

4.3.1.2. *Benefit-Cost Ratio*

With the identified valid ICM incidents, this research compared the benefits brought by ICM activations against costs for the deployment, administration, and operation of the ICM program. In this case study, benefits refer to the overall average passenger vehicle and truck travel time and delay savings as well as fuel and emission savings. This research assumed that heavy vehicle percentage was 7 percent during excess delay incidents). The weighted value of time (VOT), which is the total cost per vehicle hours of delay (VHD), was assumed as $51.19. For each detour route scenario, the average AADT was obtained from NCDOT's AADT maps, as shown in Table 5; then, the percentage of AADT for different times-of-day (listed in Table 3) was employed to estimate the hourly traffic demand on the route during the ICM activation.

Table 5: Average AADT of Each Routing Scenario

Route	**Average AADT**
SC1	84,005
SC2	84,005
SC3	89,604
SC4	99,672
SC5	125,350
SC6	118,474
SC7	116,800
SC8	127,000
SC9	125,612
SC10	99,672
SC11	99,672

Then, for each ICM incident, this research calculated the monetized total benefits based on time-of-day traffic demand, vehicle hours of delay, and weighted value-of-time.

Table 6 compares the monetized total benefits per incident before and after the implementation of ICM. For each ICM-incident, the comparisons were made for three scenarios: total net savings with ICM activation using the expected peak and off-peak diversion rates, total savings under ideal policy with ICM where drivers **ONLY** divert during time periods with savings on the alternate route, and total net savings without ICM using minimal diversion rates drivers utilize in the literature. Overall, the grand total benefit of the 40 ICM-incident is expected to be $1.648 million under ideal policy with ICM activation. The net grand total benefit with ICM is approximately $1.26 million, which is about 23 percent lower than the savings under an ideal policy scenario. The net total benefit without ICM is approximately $0.444 million, which is 73 percent lower than the net savings with ICM.

Among the 40 ICM-incidents, all but two incidents have a positive saving under ideal policy with ICM activation; nevertheless, 13 ICM-incidents have a negative net saving, and the negative net savings with ICM are larger than without ICM. This indicates that the benefits of ICM are particularly significant under a relatively high traffic demand scenario; while during off-peak periods or when traffic demand is not heavy, the net benefits of ICM might not be as high as during peak periods.

Table 6: Comparison of Monetized Total Benefits per Incident

TIMS_ID	SUM of Net $ Saved ICM	SUM of Ideal Policy $ Saved ICM	SUM of Net $ Saved No ICM
613237	$137,888.15	$143,227.43	$29,395.56
613852	$47,028.08	$51,432.65	$-
615095	$32,695.30	$39,402.04	$17,854.13
615430	$(18,809.17)	$-	$(11,285.50)
615635	$41,996.14	$43,994.84	$22,019.11
615708	$27,226.39	$30,550.85	$6,449.05
615909	$(7,621.96)	$26,554.56	$(7,201.37)
616172	$6,124.59	$24,440.48	$3,674.75
616796	$117,676.87	$127,587.84	$62,135.58
616896	$422.84	$3,158.38	$-
616951	$17,915.86	$37,497.39	$10,749.51
617118	$(1,534.09)	$2,711.50	$-
617175	$(76.00)	$7.90	$-
617730	$(14,000.64)	$9,844.18	$(6,768.94)
617732	$(12,984.20)	$2,931.66	$(6,491.44)
617796	$(13,818.74)	$2,318.65	$(8,291.24)
617813	$28,789.66	$29,549.56	$-
618558	$2,854.15	$3,824.98	$-
618564	$12,147.71	$17,222.40	$-
618784	$15,377.51	$18,728.00	$5,125.84
619501	$38,628.84	$57,186.98	$16,411.62
620015	$(5,364.43)	$114.69	$(1,788.14)
620208	$(488.63)	$5,734.28	$(383.95)
620862	$14,644.44	$18,352.20	$-
621421	$(20,978.88)	$-	$(5,148.90)
622020	$2,788.42	$17,025.26	$1,673.05
625544	$72,659.50	$75,027.43	$43,595.70
625801	$128,027.29	$128,211.55	$41,876.03
626915	$(36,466.03)	$5,589.41	$(10,961.69)
626980	$38,673.09	$48,227.56	$8,407.19
628015	$9,798.85	$11,663.20	$-
628143	$80,421.78	$80,787.95	$35,323.28

628509	$28,362.68	$34,320.34	$-
628727	$(13,768.95)	$911.62	$(8,605.60)
629199	$427,931.45	$431,604.40	$201,030.58
631492	$63,554.43	$68,964.42	$13,816.18
633537	$19,967.81	$20,712.67	$-
637372	$(13,137.68)	$11,936.23	$(7,590.70)
637873	$7,243.07	$8,193.28	$-
638036	$(1,263.32)	$9,247.28	$(757.99)
Grand Total	**$1,260,532.19**	**$1,648,796.04**	**$444,261.72**

Finally, the benefit-cost ratio of the ICM program was calculated as the 5-year (and 10-year) total benefit divided by the total costs during the 5-year period (and 10-year period), as shown in Table 7.

Table 7: Benefit-Cost Ratio

Benefit-Cost Analysis Items		**Initial**	**Annual**	**5-Year Total**	**10-Year Total**
Benefits	Total VHD, Emissions, Fuel Savings	n/a	$1,080,456.16	$4,948,172.86	$9,216,510.23
Costs	Admin and Operations	n/a	$25,006.86	$1,603,349.11	$1,741,799.64
	Equipment	$1,442,847.00	$10,039.51		
B/C Ratio		n/a	n/a	3.1	5.3

The total benefit was calculated as annual savings in VHD, fuel, and emission totals; the total cost was calculated as the initial equipment deployment cost plus annual administrative and operation costs projected over a number of years while considering an IRR of 3%. Results show that the 5-year and 10-year B/C ratios of the I-85 ICM program are expected to be 3.1 and 5.3, respectively, indicating that each unit investment in the ICM program tends to result in 3.1 units overall benefits over a 5-year period, and the benefits could up to 5.3 units over a 10-year period. Importantly, this ratio applies for this specific implementation compared to many other potential deployments. The I-85 deployment construction and equipment costs were high due to the extensive infrastructure upgrades needed and other deployments may show much higher benefit cost ratios if they are accomplished at lower costs.

5. Conclusions and Recommendations

This project successfully demonstrated the potential of an Integrated Corridor Management (ICM) system to enhance traffic management on I-85. Through the implementation of innovative data collection methods, dashboards, and analytical frameworks, ICM solutions provided a robust system that significantly improves the effectiveness of traffic diversion strategies during incident occurrences.

The use of Bluetooth and Wi-Fi traffic monitoring devices for origin-destination and travel time data collection has proven invaluable in understanding and managing traffic flow patterns and comparison of alternative routes. We acknowledge the need for further testing and optimization of these sensors, particularly in terms of detection range and rate, to further refine our data accuracy. Consistency in sensor settings and configurations, alongside robust systems for device status monitoring, is fundamental to maintaining data integrity.

The developed dashboard, which integrates data feeds from multiple sources, presents an important tool for monitoring ICM deployments. The flexibility to utilize data from different sources, such as incident (TIMS), route data (Google Maps), probe data (ClearGuide), and travel time data (Bluetooth and Wi-Fi), enables a real-time and comprehensive overview of traffic conditions.

We acknowledge the potential of emerging data sources and technologies for traffic monitoring and recommend further exploration of these as they mature. Our framework is designed to adapt to these advancements, ensuring that the ICM solution remains useful for traffic management solutions.

The evaluation framework developed in this project has been instrumental in understanding the impact of ICM deployments. It has provided crucial insights into the operational, and planning impacts of the ICM deployment, as well as the benefits and costs associated with it.

Our analysis has revealed that ICM systems can bring substantial benefits to users and stakeholders, particularly during severe incidents and peak periods. The benefit-cost ratios calculated for the I-85 ICM program suggest a significant return on investment, with the potential for even higher returns as ICM deployments become more common and associated costs decrease.

The framework and tools developed during this project show significant promise for integration into future construction projects planned at the current site. Their adaptability and real-time data processing capabilities can provide key insights into traffic management, thereby mitigating potential disruptions caused by construction activities. The dashboard, in particular, can offer proactive management of construction-induced traffic, minimizing public inconvenience and contributing to cost-effective project execution.

The impact of this project on construction will be largely beneficial, allowing for informed construction scheduling and efficient logistics handling. As the ICM system is capable of managing and diverting traffic effectively during incidents, it will be especially valuable in a construction context, where unexpected disruptions are common. We recommend that future construction projects fully utilize these tools for optimal traffic management, thereby enhancing overall project efficiency and success.

In conclusion, the results of this project affirm the effectiveness of the ICM system in managing traffic flow and reducing delays during incidents. We anticipate that as ICM technology and strategies continue to evolve, the benefits of such systems will increase even further, providing even greater value to the NCDOT and the traveling public.

6. References

1. USDOT, “FHWA Integrated Corridor Management (ICM) Program: Major Achievements, Key Findings, and Outlook.” November 2019. [Online].
2. Petrella, M. and L. Conwell (2017). "Integrated Corridor Management Initiative: Traveler Response Panel Survey Dallas," Intelligent Transportation Systems Joint Program Office.
3. NCDOT 2019-30, "Post-Implementation Evaluation of Integrated Corridor Management (ICM) in North Carolina", 2019.